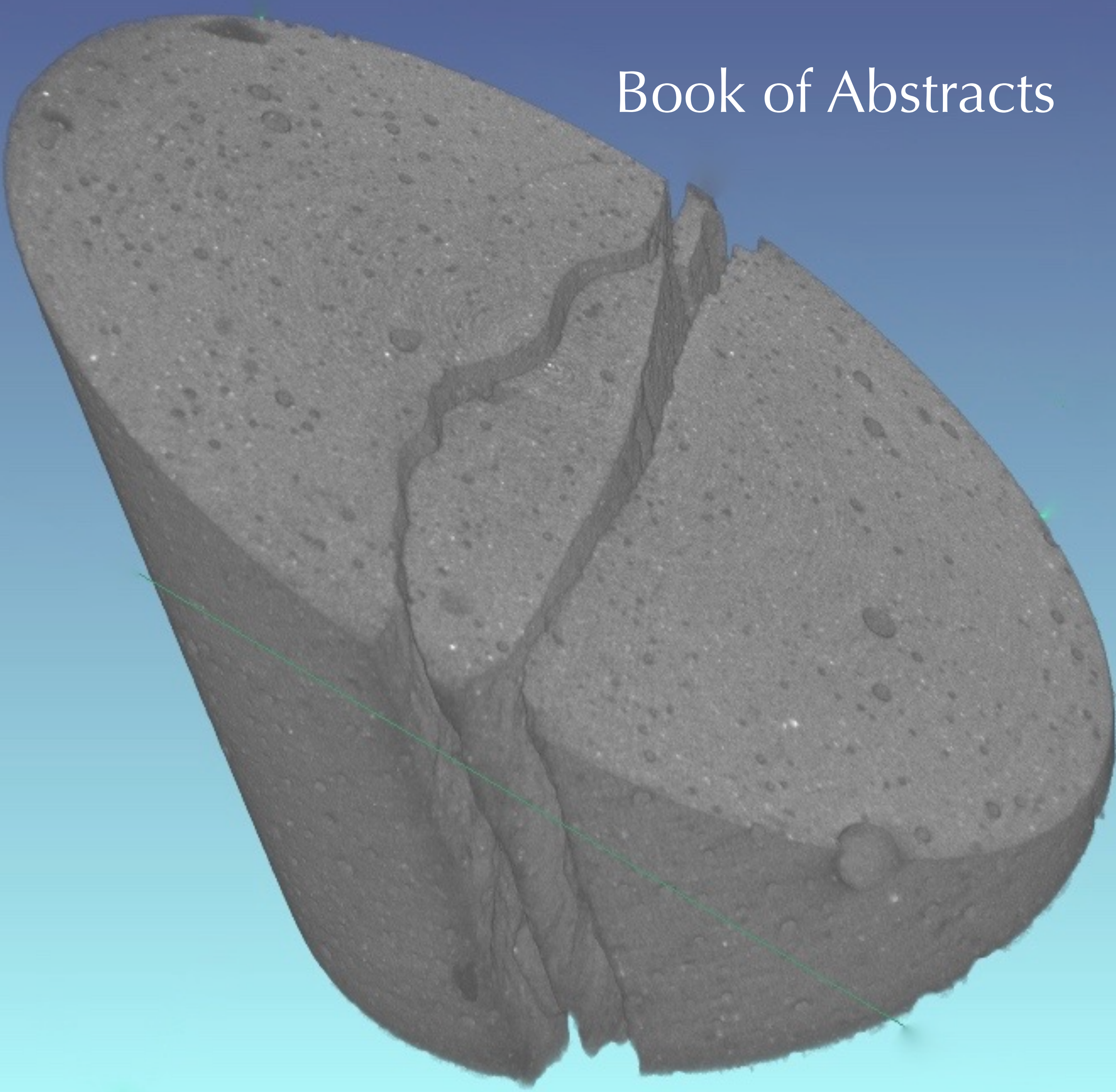
# FraMCoS-9

## The 9th International Conference on Fracture Mechanics of Concrete and Concrete Structures

May 29 - June 1, 2016, Berkeley California, USA

IA-FraMCoS

# Book of Abstracts



**FraMCoS-9** The 9th International Conference on Fracture Mechanics of Concrete and Concrete Structures

*May 29-June 1, 2016; Berkeley California, USA*

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# Plenary Lectures

# Induction healing of concrete reinforced by bitumen-coated steel fibres

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## ABSTRACT

An experimental study of a new self-healing concrete is presented. Bitumen, used as the healing agent, is introduced in fresh fibre-reinforced concrete as the coating of steel fibres. The mechanism exploits induction energy to heat up the steel fibres inside the cracked concrete matrix; the bitumen then melts and finally flows into the cracks, sealing them. The aim of the research is to set up the main parameters affecting the performance of the healing mechanism as well as its efficiency.

In order to achieve this goal, the microstructure of healed specimens has been studied through ESEM and Light Microscope. Mechanical properties of the samples, before and after healing, were also checked. Moreover, electrical measurements have been carried out to better predict the success of the mechanism. Several parameters have been varied in the tested specimens. The achievement of the percolation threshold on fibre reinforced cement-based composites [1][2] strongly depends on the amount of fibres as much as on their size; less determinant but still used as parameter is the composition of the concrete matrix, specifically the sand-cement ratio. The amount of healing agent, in terms of thickness of the coating, was also varied and the penetration class of bitumen was carefully chosen.

Results point out the potentiality of the proposed self-healing mechanism. Cracks 100µm wide were partially filled with bitumen; filling amount varied upon the thickness of the coating layer and the presence of fibres bridging the crack. Finally, it is shown that recovery of the mechanical properties is influenced by the changes on the bond conditions at the interface between steel fibres and concrete matrix after the healing process.

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# Behaviour and assessment of massive structures: an overview of the French research programs CEOS.fr and VeRCoRs

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## ABSTRACT

Beyond stability and strengthening capacity, most concrete structures have to fulfil a number of additional functions, which involve behavioural requirements for: reinforced concrete cracking, deformability, water and air leak-tightness and sustainability.

Actually, the standard rules (EC2, Model Code,…) do not fully address the case of massive elements, for which Thermo-Hydro-Mechanical (THM) effects, scale effects and structural effects induce specific response and preliminary cracking. Furthermore, for massive slabs, walls and containment, shrinkage and creep are prevalent at an early and long-term age.

To address these concerns, the French civil engineering community decided in 2008 to launch a national research program project, CEOS.fr [1], with the aim of making a significant step forward in engineering capabilities for predicting the expected crack pattern of special structures under anticipated in-service or extreme conditions. Experiments on large specimen (monotonic, cyclic and THM loadings) and related modelling were performed [2] in order to improve engineering design practices.

In the wake of CEOS.fr, and in view of addressing the concrete containment ageing issue, EDF launch in 2013 the VeRCorRs program [3]. It consists principally of a 1/3 scale mock-up of reactor containment, now standing at EDF-Lab Les Renardières site near Paris. The main objectives of the program are to study:

- the structural behavior at early age and when ageing,
- the ageing effects on leak tightness,
- the behavior under severe accident conditions for which the thermo- mechanical loading is maintained for several days.

The presentation intend to address the main results obtained from CEOS.fr and the preliminary results obtained during the first VeRCoRs test campaign, for which, international benchmarks are in progress.

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# Multi-Scale Seismic Simulation of RC Building Coupled with Drying Shrinkage and Steel Corrosion

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## ABSTRACT

This paper is to apply the multi-scale thermo-hygro modeling to full-scale RC structural systems under combined long-term ambient and short seismic actions.

First, the multi-scale modelling, which may deal with micro-cracking caused by moisture migration and corrosion, is experimentally verified by using corroded RC columns under high axial compression. Second, the steel corrosion is computationally reproduced to a multi-story RC building under long-term fictitious ambient conditions.

The seismic ground motion is subsequently applied to the corrosion damaged mock-up tested on the huge shaking table. Beforehand, the effect of drying shrinkage and cracking, which is inevitable for thin structural concrete in air, is discussed so as to clarify the pure corrosion impact to the whole structural system.

The steel corrosion deteriorates the ductility of seismic resistant members, but as a global influence, steel corrosion is validated to reduce the base-shear input of floors owing to the decayed stiffness by corrosion.

Through these case-studies, the authors raise the points of discussion to take into account the local and global effects of corrosion induced micro-fracture all at once for seismic performance assessment, and that the knowledge solely on the capacity of corroded RC members cannot lead to an engineering solution, but the fracture mechanics aspect is to be incorporated.

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# Lattice models for coupling of fracture and transport

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## ABSTRACT

The response of geomaterials, such as soil, rock and concrete, is governed by complex fracture and mass transport processes, which often interact with each other. Examples are hydraulic fracturing of rock, slope stability of soils and durability of concrete.

The mathematical modelling and computer simulation of these processes using continuum approaches can be challenging due to the heterogeneity of the materials and the discontinuous nature of the processes. On the other hand, discrete techniques, in which the material response is described by an assembly of discrete elements, are known to be suitable for modelling situations in which discontinuities dominate the system response. Among these discrete techniques, lattice models stand out for being computationally efficient in analysing processes involving small displacements.

I will present recent progress in developing lattice models for coupling of fracture and mass transport and their application to the analysis of fluid pressure induced fracture, which is a continuation of recent work published in [1].

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# Behaviour of Strain-hardening Cement-based Composites (SHCC) under force-controlled cyclic loading

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**ABSTRACT**

The safe use of Strain-hardening Cement-based Composites (SHCC) for structural and non-structural applications often requires a solid knowledge of the mechanical performance of this material under cyclic loading. In the previous investigations the behaviour of SHCC subjected to a deformation-controlled tension regime was studied.

The article at hand presents the experimental results obtained from the fatigue tests performed with a fixed force level for the upper (in tension) and lower reversal points of the loading cycles. The varying parameters under investigation were the upper and the lower stress levels. Moreover, two different definitions for the upper force level were applied. In the first approach the upper force level was fixed as a value related to the average first crack stress of the particular series (for example 80 % of that average value). In the second approach the upper reversal point was individually defined in relation to the first crack stress of the specimen under investigation in the course of the testing process (i.e., for example 80 % of the first stress measured on this particular specimen). The lower reversal point varied between tension and compression.

The experiments were performed on uniaxially loaded dumbbell-shaped prisms. It was observed, that, as expected, the number of load cycles to failure decreased with increasing upper stress level. Additionally, the strain capacity increased with decrease in the upper stress level from 80 % to 60 % of the first crack stress. A further reduction of the upper stress level caused no change in the failure strain level. After mechanical testing, the crack patterns on surfaces of the specimens were analysed and optical investigations of the SHCC fracture surfaces were performed to provide insights into the failure mechanisms specific for the fatigue behaviour of SHCC. Finally, the experimental results were discussed in particular with respect to the identification and description of the decisive mechanisms determining the material performance under force-controlled loading.

# Session MS01: Multi scale Modeling of Brittle Damage Processes

# The Scaled Boundary Finite Element Method for Efficient Modelling of Linear Elastic Fracture Problems

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## ABSTRACT

In this work, a study of computational and implementational efficiency is presented, on the treatment of Linear Elastic Fracture Mechanics (LEFM) problems. To this end, the Scaled Boundary Finite Element Method (SBFEM) [1], is compared against the popular Extended Finite Element Method (XFEM) [2] and the standard FEM approach for efficient calculation of Stress Intensity Factors (SIFs). The aim is to examine SBFEM's potential for inclusion within a multiscale fracture mechanics framework.

The XFEM scheme mitigates a number of drawbacks, which are inherent to the standard FEM, i.e., computational cost associated with the need to mesh and remesh the crack surfaces as well as the reduced accuracy due to the introduction of mesh dependant projection errors. However, a priori assumptions commonly based on Westergaard's solution to the exact stress field of a uniform plate as well as the corresponding modifications to the pre-processing are still required, which may lead to problematic conditioning of the system [3]. On the other hand, the SBFEM comprises a semi-analytical scheme, wherein an analytical solution in the radial direction achieves reduction of the problem dimension by one, similar to the Boundary Element Method (BEM). As a result, the method lends itself naturally to the homogenization of large regions. Additionally, the analytical solution in the radial direction allows to directly extract the SIFs in post-processing based purely on their definitions and without a priori assumptions. Furthermore, this enables the use of established stress recovery techniques to not only increase accuracy but also introduce an effective error estimator.

The above features will be exploited to solve a series of benchmarks in LEFM comparing XFEM, SBFEM and commercial FEM software to analytical solutions. The extent to which the SBFEM lends itself for inclusion within a multiscale framework will further be assessed.

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# Correlation during the fracture process analysed with the help of Ripley's functions

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## ABSTRACT

The degradation of quasi-brittle materials encompasses micro-cracks propagation, interaction and coalescence in order to form a macro-crack. These phenomena are located within the Fracture Process Zone (FPZ). This paper aims at providing a further insight in the description of the FPZ evolution with the help of statistical analysis of damage.

The statistical analysis relies on the implementation of Ripley's functions [1], which have been developed in order to exhibit patterns in image analyses. Ripley's functions allow exhibiting a correlation length between fracture events from which a parallel can be drawn with the internal length entering in non-local models [2]. In the present approach, the analyses are carried out with the help of a lattice approach, which has been shown [3-4] to be representative of fracture of concrete, including size effect tests on notched and unnotched specimens [5].

First, three point bending tests on notched concrete specimens are considered. Ripley's analysis is compared with experimental data from acoustic emission. Comparisons between experimental and numerical evolutions of extracted correlation lengths are performed and they reveal that the lattice model captures very well the correlation of damage events observed experimentally. Then, numerical analyses are performed on specimens of different shapes and with different loads. It is shown that the correlation length can be very different depending on the geometry and boundary conditions, which suggests that the internal length in non local model should not be constant, but depends on how damage initiates (notch effect/boundary effect) especially.

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# Study on the Structural Behavior of Serrated Cast-in Channels Subjected to Longitudinal Loading Close to the Edge

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## ABSTRACT

The structural behavior of cast-in anchor channels located close to the edge and loaded in longitudinal direction is not clear. In addition, recent design guides [1,2] rely on approaches for calculation of single and grouped headed anchors connected by anchor plates. The explicit applicability of the calculation methods on anchor channels has rarely been validated by physical experiments. The lack of clarity motivated the presented physical experiments and numerical simulations on serrated anchor channels for filling this information gap. Test series on serrated anchor channels were scheduled to determine the structural behavior under longitudinal loading and to determine how this is influenced by the edge distance. The anchor channels were installed in concrete close to the specimen's edge and positioned orthogonal to the edge, at a prescribed distance and at the edge level. Each anchor channel was equipped with two bolted anchors. Loading was applied via serrated bolts. The anchor channels were loaded until failure. Special attention was paid to the crack formation during loading. Of particular interest was the point in time when the load was redistributed from the front to the rear anchor. For a deeper understanding of the failure mechanisms Finite Element simulations were performed. The challenge was, beside generating the complex mesh geometry, to model the physical behavior of the concrete and the structural steel respectively as a composite realistically. The interaction between the brittle concrete and the ductile structural steel raised the scientific demands. Numerical calibration experiments with the structural steel members were performed until a good convergence of the numerical calculations was achieved. The numerical setup was adopted from [3]. Load-deflection curves obtained from physical experiments were used to calibrate the composite model. The contact properties of the interface between concrete and structural steel were set according to [4]. The distance to edge was varied in order to evaluate its influence on the failure mechanism. It could be shown that the resistances calculated according to the current design guides are on the conservative side. The distance to the edge and the failure mechanism are not coupled. No critical distance to the edge could be observed.

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# A Weakest Link Failure Model of Polycrystalline MEMS Structures

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## ABSTRACT

MEMS devices typically need to be designed against a very low failure probability, which is beyond the capacity of histogram testing. Therefore, the understanding of the probabilistic failure of MEMS devices is essential. Currently available probabilistic models for predicting the strength statistics of MEMS structures are based on classical Weibull statistics. Significant advances in experimental techniques for measuring the strength of MEMS devices have produced data that have unambiguously demonstrated the inadequacy of the Weibull distribution. This paper presents a robust probabilistic model for the strength distribution of polycrystalline silicon (poly-Si) MEMS structures. The overall failure probability of the structure is related to the failure probability of each material element along its sidewalls through a weakest-link statistical model. The failure statistics of the material element is determined by both the intrinsic random material strength and the random stress field induced by the sidewall geometry. Different from the classical Weibull statistics, the present model accounts for structures consisting of a finite number of material elements, and it predicts an intricate scale effect on the overall failure statistics. It is shown that the model agrees well with the measured strength distributions of poly-Si MEMS specimens of different sizes. The present model also explicitly relates the strength distribution to the size effect on the mean structural strength, and therefore provides an efficient means of determining the failure statistics of MEMS structures.

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# Multiscale Modeling FRC Composites

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## ABSTRACT

Mechanical properties such as ductility, strength and load bearing capacity of cementitious materials can be considerably improved by the addition of reinforcing fibers. These reinforcing fibres fibers improve the fracture toughness of the unreinforced cementitious matrix by arresting micro-crack growth which, if unhindered, will coalesce and form a macro-crack eventually leading to material and structural failure. The strengthening mechanism is dependent on the properties of the fiber and its interaction with the matrix material characterized by the interface behaviour.

In order to understand the macroscopic counterpart of these complex micro-mechanisms and support material design, we propose a multiscale model that is a combination of semi-analytical and computational sub-models specified at multiple scales. At the scale of the single fiber, a semi-analytical model is developed, taking the type of fiber (hooked end, straight) and the angle of the fiber w.r.t. crack direction into account. On the level of individual micro-cracks, based upon this model, the influence of fiber bundles on micro-crack evolution is taken into account within the framework of the Linear Elastic Fracture Mechanics. Upscaling to the macroscopic level is achieved by using continuum micromechanics [1]. For plain concrete, a continuum damage model is used, which can be related to the microcrack-density and the micro-crack topology. The proposed model allows to characterize the influence of the bond behavior on micro-crack evolution realistically.
Selected numerical experiments provide insight into the role of the interface property, resulting – on the macroscopic level - in a brittle, softening behaviour in case of weak bond and a rather ductile, hardening behavior in case of a relatively strong interface bond. Furthermore, the model predicts an increasing microcrack density and microcrack arrest with increased fiber content.

At the structural level, the Finite Element Method is used, applying the Strong Discontinuity approach [2] to capture propagating cracks. The interface behavior across opening cracks are obtained from hybrid crack bridging laws developed on the basis of the single fiber-pullout models [3].

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# A Multiscale Approach to Fracture in Brick-Mortar Masonry Composites

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**ABSTRACT**

This study focuses on the fracture behavior in heterogeneous masonry composed of clay brick units that are bonded by mortar joints. There are three main levels of observation to deal with the layered material system in which adhesion of brick- mortar interfaces plays a critical role in fracture initiation and inter/intra fracture propagation in the brick and mortar material system. At the micro/ meso level of observation the disparate fracture processes are governed by the mismatch of the constituent properties which introduce curious interactions such as tension in the stiffer brick units under far-field compression, a remarkable feature of the so- called prism test. In contrast, the so-called triplet test of double lap shear leads to delamination of the brick and mortar interfaces and finally to fracture of the stronger brick substrate. The so- called wrench test is used to evaluate the tensile capacity of adhesive bond that governs separation of bricks from their adherent mortar bed joints. Thereby tension experiments indicate that adhesive debonding is not necessarily a surface dominated process when porous clay bricks are bonded to cement-based mortars.

The paper includes experimental observations of the different fracture processes which are interpreted at the micro-, meso- and macro- scale levels of observation in form of (i) fracture-informed lattice models, (ii) fracture energy based interface models of zero- vs. finite thickness. The response predictions of the two level computational models will be compared and assessed with regard to their predictive limitations and shortcomings to deal with the composite material tests mentioned above and their extension to full scale masonry walls and masonry structures.

By this means, the arguments of fracture initiation and fracture propagation will be the central issue how to separate tensile debonding from shear slip in a mixed mode fracture mechanics problem with dilatancy effect, and how to upscale the underlying fracture properties from a lattice-based network of springs in terms of energy release rates and crack extension patterns to a fracture dominated interface properties in form of a finite thickness cohesive zone model as well as a fracture based zero thickness interface model. As a final step, considering localization based XFEM strategies the embedded degrading interface properties are incorporated into an equivalent anisotropic framework of a layered material system that accounts for the composite mesostructure of brick and mortar masonry assemblies.

# Effects of Microcracks in the Interfacial Zone on the Macro Behavior of Concrete

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## ABSTRACT

Concrete being one of the most widely used construction material, is treated as homogeneous from a design perspective. However, on a closer examination it is observed that concrete is heterogeneous which consist of coarse aggregate and fine aggregate. Also, there exists an interfacial region called interfacial transition zone (ITZ) which bonds the aggregate to the cement paste whose strength dependents on the microstructural characteristics. This interfacial region neither possesses the properties of aggregate nor of the cement paste.

Interface being the weakest zone, the microcracks are likely to initiate here when the local major principal stress exceeds the initial tensile strength of the interface [1]. When these microcracks reaches certain critical length, termed as the critical microcrack length, in this study, it propagates and coalesce with the existing macro crack to form a major crack resulting in the failure of bond. The microstructural character of the interfacial zone governs the mode I crack propagation in conventional concrete [2]. The material behavior of concrete is influenced by the geometry, the spatial distribution and the material property of the individual constituents and their interactions. Hence, the failure of concrete can be viewed as a multiscale phenomenon.

In this work, the effects of microcrack present at the ITZ on the overall behaviour of concrete are studied. This is done by estimating the critical microcrack length using the principles of linear elastic fracture mechanics. Also, a procedure to determine the material properties such as the elastic modulus and fracture toughness at the interface by knowing the concrete mix proportion is explained. Using the information of the critical microcrack length, an analytical model is proposed through a relationship between the applied stress and crack opening displacement to obtain the macro behavior of the material. This model is validated using experimental data published in the literature for normal, high strength and self consolidating concrete. Furthermore, since various parameters are involved in the determination of critical micro crack length, which are randomly distributed, an analysis is done to study the most sensitive parameter which affects the size of microcrack.

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# Mesoscopic Simulations of Concrete Fracture Based on X-ray $\mu$CT Images of Interial Structure

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## ABSTRACT

In the paper, concrete fracture was experimentally and theoretically investigated at aggregate level. Three-point quasi-static bending tests with notched beams were performed. During tests, fracture was observed with the x-ray micro-tomographSkyscan 1173 [1], representing a new generation in high-resolution desktop x-ray micro-tomography systems. In addition, the interfacial transitional zones (ITZs) between aggregate and cement matrix zones were by means of the scanning electron microscope (SEM) with the magnification factor of 1'000.

The experimental crack above the beam notch was strongly curved and depended on concrete micro-structure. It mainly propagated through ITZs between the cement matrix and aggregate. The crack might rarely propagate through a weak aggregate particle. Some small crack branches were also visible. The crack shape was different along the beam depth. The width of ITZs varied between 30 and 50 μm. Their porosity was strongly uniform.

In order to describe the 3D experimental fracture process, the discrete element method (DEM) was used [2], [3]. The calculations were performed with the three-dimensional spherical discrete model YADE, developed at University of Grenoble which takes advantage of the of the so-called soft-particle approach [4]. Concrete was modelled as random heterogeneous 4-phase material composed of aggregate particles, cement matrix, interfacial transitional zones (ITZs) and air voids [3]. The concrete microstructure was taken directly from micro-tomograph images. A linear normal contact model under compression was used. The contact tangential forces and normal forces satisfied the cohesive-frictional Mohr-Coulomb equation using the inter-particle friction angle. Aggregate was simulated as clusters of spheres. The material constants were assumed based on uniaxial tension and compression tests [2]. The numerical outcomes were directly compared with the experimental results. A satisfactory agreement between calculations and experiments was achieved. In addition, the effect of properties of ITZs was studied in detail.Attention was also paid to micro-structural events during crack branching.

The DEM results presented significant perspectives to follow in detail the fracture development including micro- and macro-cracks.

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# Lattice Discrete Particle Modeling of Shear Failure in Scaled Reinforced Concrete Beams without Stirrups

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**ABSTRACT**

This paper discusses the calibration of a concrete lattice discrete particle model (LDPM) [1], and its validation for the case of shear failure in scaled RC beams without stirrups. First, the model parameters were preliminarily defined based on: (a) the design of the concrete mixture that was used to fabricate scaled beam specimens; and (b) a literature database of concrete meso-scale parameters [2]. Second, the calibration was refined to reach satisfactory agreement between numerical and experimental uniaxial compression stress-strain curves obtained by testing concrete cylinders in accordance with ASTM C469. The calibrated concrete LDPM was further assessed by numerically simulating different fracture tests, and verifying that the numerical fracture energy lies within a plausible range based on test data available in the literature.

The calibrated model was then used for the numerical simulation of shear failure in scaled RC beams without stirrups, reinforced either with ductile (steel) or non-ductile (glass fiber-reinforced polymer) bars, and having a shear span-to-effective depth ratio equal to 3.1 and an effective depth in the range 146-883 mm. To provide experimental evidence for the validation of the computational model, several scaled RC beams were fabricated using the reference concrete mixture design, and load tested (e.g., [3, 4]). The beam computational models were validated and discussed vis-à-vis experimental data based on different criteria, including elastic response, post-cracking stiffness degradation and damage progression, strength as well as scaling thereof, and failure mode.

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## Damage evolution in disordered media as a Markov process

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### ABSTRACT

The continuum damage mechanics framework is widely used to model progressive failure of materials. It is based on introduction of a damage variable $D$, which is related to degradation of secant stiffness of the material. However, this deterministic formulation is understood as the effective behaviour at the representative volume element (RVE) size. In highly disordered materials like composites, rocks, concrete, paper, etc. the mechanical behaviour is strongly affected by the interplay of disorder and long-range elastic interactions. This coupling leads to strong sample-to-sample variations and size-effects, especially when the mesoscale of the sample is below the RVE size. Such effects can be incorporated in continuum damage mechanics by treating damage evolution as a stochastic process. The objective of this study is to formulate damage evolution as a Markov process with the aid of a vast amount of data from discrete spring lattice models.

The discrete models of failure such as the fiber bundle model (FBM), random fuse model (RFM), random beam model (RBM), and their derivatives are inherently suited to model disorder-induced statistical effects such as size-effect, damage localization, crack surface roughness, avalanches etc. Such models naturally account for the microstructural disorder and effectively capture nucleation, interaction, and coalescence of microcracks. Therefore, the damage parameter extracted using such models not only has an inherent stochastic character, but it is also linked with the underlying microstructural details. The ensemble averaged damage evolution from such models has been extensively studied in the past and is shown to have a scale-dependent character. In this study, the focus is on using the damage evolution data to extract transition probability density functions which describe damage evolution as a Markov process.

Starting with the simple case of FBM under displacement-controlled conditions, which is solvable analytically, the evolution of damage is analysed as a Markov process in models with increasing complexity such as the FBM under force-controlled boundary conditions, an anti-plane spring lattice model, and an in-plane spring lattice model. The proposed approach is demonstrated for cases where damage is treated as a scalar, however, extension of the framework to $2^{nd}$ rank or $4^{th}$ rank tensorial representation of the damage variable can be performed on similar lines. Such microstructure-inspired scale-dependent stochastic damage evolution laws naturally capture the scatter observed in material responses of disordered materials.

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# Session MS02: Modeling Time-Dependent Behavior and Deterioration of Concrete

# Analysis of Cracking Due to Shrinkage Restraint on the Mechanical Behaviour of Reinforced Concrete

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## ABSTRACT

Delayed strains (shrinkage and creep) of concrete can be of crucial importance for the assessment of the behavior of concrete structure. In partially prestressed concrete structures, they participate to the prestress loss. If shrinkage strains are restraint, tensile stresses appear and can lead to cracking. The restraint may be "intern", i.e. due to gradients of temperature/relative humidity or "extern", i.e., due to the previous casting of structural member, like raft foundations, in the case of concrete lift etc. A lot of studies in the literature deal with these issues.

However, in reinforced concrete structures, shrinkage restraint by steel rebars, in a similar way that shrinkage of cement paste is restrained by aggregates, has not been deeply investigated. It induces a self-equilibrated state of stress: tensile stresses in concrete and compressive stresses in steel rebars in the case of uniform shrinkage (as for autogeneous shrinkage). It may lead to cracking of concrete, partial debonding at the steel/concrete interface, or just initial tensile stresses in concrete around the rebar. In any case, it should affect the behavior of reinforced concrete structures, especially in structures submitted to tension or in bending: loss of stiffness and bearing capacity. Besides, since drying is not uniform, gradient of drying shrinkage induces tensile stresses at the surface equilibrated by compressive stresses in the core. The prediction of this initial state of stress needs the characterization of drying, shrinkage, creep, elastic and fracture properties. Besides, for bending test, the unilateral behavior must be also known, since in the upper part of the beam, tensile stresses are first induced by shrinkage, but compressive stresses appear during the mechanical loading.

In order to investigate the effect of shrinkage restraint, an extensive experimental program has been carried out: pull-out tests, reinforced concrete ties in tension and bending tests on Partially Prestressed Concrete (PPC) beams, as well as shrinkage and creep tests. In addition, numerical simulations have been undertaken in order to assess the residual properties in tension and bending: rigidity, bearing capacity and crack openings (assessed by Digital Image Correlation). The numerical simulations in concrete ties and PPC beams show that, without taking into account shrinkage restraint, the stiffness and the force corresponding to the onset of cracking are overestimated. However, when drying shrinkage is taken into account without the effect of basic and drying creep, an opposite result is obtained. Therefore, shrinkage and creep should be taken into account in the analysis. Indeed, tensile stresses of a few MPa are found in the concrete around the rebars and superficial cracking are predicted in concrete ties and PPC beams, which reduce the bearing capacity of concrete.

# Shrinkage Cracking of Thin Irregular Shotcrete Shells Using Multiphysics Models

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**ABSTRACT**

Tunnels in good quality hard rock are normally reinforced with a combination of fiber reinforced shotcrete (sprayed concrete) and rock bolts. The thickness of the shotcrete may be as low as 50 mm. However, due to restrained movement, cracks can occur within the first months of service, due to the strain-softening behaviour of shotcrete it usually leads to wide cracks.

Shrinkage and strength development of shotcrete is a complex problem, where it depends on factors such as: water-cement ratio, variations in relative humidity and temperature and is highly influenced by the creep behaviour. The rapid development of bond strength between shotcrete and rock will restrain movements due to shrinkage and thermal effects. Shrinkage of shotcrete is normally considered as uniformly distributed and applied to the structure as an uncoupled field. Using coupled multiphysics models could be one way to better understand and simulate the cracking due to restrained movement.

This paper aims to highlight the difference in simulated shrinkage cracking of thin irregular shotcrete shells, considering if a multiphysics or uncoupled mechanical model is used. The mechanical response of the multiphysics model is based on Microprestress-Solidification theory [1] and includes coupled behaviour with moisture and temperature. The experiments by Bryne et al. [2] regarding end-restrained shrinkage of shotcrete slabs will be used for verification of the numerical material models. The variation of crack location and the stress build-up before cracking will be studied and evaluated with respect to variation in internal and external conditions.

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# An experimental and numerical method to investigate the oxide behavior in corrosion of reinforced concrete

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## ABSTRACT

Corrosion of the reinforcement reduces the service life of concrete structures, due to the consequent decrease in cross-sectional area of the steel, loss of bond, and cracking of the concrete cover [1]. In the prediction of corrosion-induced cracking, the mechanical behavior of the oxide has been proved to be crucial. However, there are many uncertainties about the oxide parameters, due to the difficulty to perform direct in place measurements, and their values have to be assumed in the models.

To gain further knowledge about the oxide behavior, an experimental and numerical method was developed and is presented in this work. Accelerated corrosion tests have been carried out in concrete prisms reinforced with a tube to record information close to the oxide layer. During the tests, the width of the main crack, which forms at the cover, has been recorded by standard means, and the variation of inner diameter and the variation of inner volume of the tube have been measured using special instruments [2]. After corrosion, the crack pattern of the specimens has been investigated in slices of the specimens impregnated under vacuum with fluorescent resin. In parallel, numerical simulations of the tests have been carried out using a model that combines expansive joint elements, to reproduce the mechanical action of the oxide [3], and elements with an embedded cohesive crack, to reproduce fracture of concrete [4]. Then the influence of the model parameters on the curves of crack width, inner diameter and inner volume has been analyzed. From the joint analysis of the experimental and numerical results, relevant conclusions about the oxide behavior have been disclosed, and values for the oxide parameters are proposed, with satisfactory results for the simulation of corrosion-induced cracking.

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# Parametric Damage of Concrete Under High-Cycle Fatigue Loading in Compression

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## ABSTRACT

The progressive deterioration of concrete parameters such as strength and stiffness occurs due to the continuous application of compressive fatigue loads on concrete elements. Hence, the irreversible deformations or induced concrete strains evolve. As such, the progressive increase in concrete strain result in a corresponding increase in the reinforcing bars strains, especially at the intersections with concrete cracks.

In order to verify if the fatigue resistance verification of deep beams as specified in the literature is conservative, experimental investigations were conducted to study the behaviour of four small-scale reinforced concrete deep beams, with shear-span to effective-depth ratio of 1.0. Concrete damage models which account for salient fatigue influencing factors, were also developed from compression fatigue tests conducted on concrete cylinders. The principal compressive strain evolutions from the beam struts were measured progressively, and compared with the predicted strain evolutions. Each predicted strain evolution was obtained by substituting the initial strut stress estimated from the static analysis of the fatigue load, into a strain evolution model from the literature. The comparison between the measured compressive strain evolution from the experiments and the predicted strain evolution model indicated that the design approach is conservative. However, this was attributed to the neglect of the fatigue resistance contribution from the tensile strength of concrete in design.

In order to predict a more realistic behaviour of a reinforced concrete element under fatigue loading, a rigorous analytical approach which, involves a modified strut-and tie method for the fatigue resistance verification of deep beams, was proposed by modifying the constitutive models for concrete with the proposed fatigue damage models. The progressive crack growth of steel reinforcement resulting from the evolving stresses is accounted for, using an equivalent cycle concept with the Paris crack growth model. From the proposed algorithm, failure is expected when the evolved stress approaches the residual strength of the steel at its intersection with concrete crack.

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# Plastic shrinkage of inert and cement-based materials: characterization and comparison

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## ABSTRACT

Understanding of plastic regime behaviour is of main interest for cement-based materials, as cracking may occur in this early-age stage. Although all mechanisms are not yet described at microscale, the phenomena at mesoscale are quite well understood: (i) water bleeding occurs simultaneously to material segregation, (ii) when bleeding water disappears due to drying, menisci appear at material surface and capillary pressure increases into the material, (iii) leading eventually to cracking.

This study focuses on finding a simple approach to compare the risk of plastic cracking for different materials. In a first part, five types of inert fillers, known to have different plastic cracking risks, have been considered. Four laboratory tests have been performed: early-age shrinkage, air entry pressure, oedometer test, crack-band tests. The experimental results validate the use of a simple Cam-Clay-based model to describe the plastic regime. We show that the identified model parameters can be correlated to the risk of plastic cracking for these materials.

In a second part, two cement-based materials are considered. The main difference with the inert materials is that material properties evolve with material hydration, hence making it more complicated to perform the experiments. For these materials, we succeed into capturing the evolution of the material properties over time, especially those measured with the oedometer test. Finally, using the relationship found for inert materials, we propose a strategy to classify the materials according to their risk of plastic cracking.

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# Bond Degradation of Corroded Reinforcement: An Experimental and Numerical Study

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## ABSTRACT

Corrosion of rebars in concrete is a major source of deterioration of structures exposed to extreme environmental conditions. It is one of the main life time limit states for many infrastructures. In addition to the well understood effect of section capacity reduction due to reduction of steel cross section, the loss of bond between rebars and concrete enables larger deformations that are not easily understood nor expected. To understand the problem, a series of accelerated corrosion experiments were conducted. Multiple rebars sizes were cast inside concrete cylinders, then exposed to corrosion conditions. To accelerate curing, the specimens were cured in water for 7 days at 55 ◦C. After curing, specimens were immersed in 2% NaCl solution and constant current was passed through the rebars. Rebars were coated and only exposed over the contact are to guarantee a uniform corrosion profile along the concrete-rebar interface. Different corrosion levels were achieved by imposing electric current over different intervals.

Following the accelerated corrosion tests, rebar pull out tests were conducted in order to quantify the change in bond strength due to rebar corrosion. The free end displacement was measured against pull out force and bond-slip curves were developed. The corroded area was at the end of the rebar not in the middle, thus, the measured force represented only bond-slip behavior of corroded bar with no non-corroded rebar length passing through as opposed to most tests in literature. Finally, the whole bond-slip behavior was modeled using the Lattice Discrete Particle Model and a corrosion dependent Bond-Slip model was formulated. Results show excellent agreement between experimental and numerical simulations.

# Study of cracking risks of alkali-activated slag mortars due to shrinkage restraint at early-age

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## ABSTRACT

Alkali-activated slag materials are being increasingly used as alternative to classical cement-based matrices in some particular applications: external chemical attacks, radioactive waste confinement, etc. Once mixed with the activating solution, this category of construction materials undergoes a series of reactions recalling the exothermal hydration reaction of ordinary Portland cement. Consequently, some deformations can appear generating stress within the matrix once subjected to restraints. In fact, on one hand, the temperature elevation causes thermal strains, and, on the other hand, autogeneous shrinkage can induce stresses if they are restrained. Yet, the mechanisms beyond these volume changes may differ from ordinary Portland cement ones.

However, few studies on this topic are available in the literature. Thus, an experimental and modelling research program is currently undertaken in order to assess the cracking risk of this type of materials that can be induced by internal (i.e. effects of temperature gradients) and external shrinkage restraints at early-age in autogenous conditions.

First of all, an experimental campaign was developed in this project in order to identify important material parameters governing the delayed behaviour (hydration, shrinkage, creep, evolution of quasi-static mechanical properties, etc.) of an alkali-activated slag mortar. The evolutions of these material properties show that existing model based on hydration degree approach (e.g. [1]) cannot be used due to their slow development. Therefore, an equivalent time approach must be used and has been developed. The thermo-chemo-mechanical model includes the description of the most important phenomena occurring in autogenous conditions: thermal and autogenous shrinkage, basic creep, hydration and release of heat, evolution of Young modulus, tensile strength, etc.

An experimental work has been performed in order to validate the developed approach. Digital Image Correlation is used to assess the displacement fields of a small mock-up sampling an alkali-activated slag application used in civil engineering. Furthermore, a parametric study was conducted to analyse the numerical model sensitivity to changes in its input parameters.

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# Effect of Loading Rate on the Double-*K* Fracture Parameters of Concrete

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## ABSTRACT

This work studies the effect of the loading rate on the double-*K* parameters in concrete fracture. These two parameters are the fracture toughnesses $K_{Ic}^{ini}$ and $K_{Ic}^{un}$, related with the crack initiation and the limit of the stable crack propagation, respectively, which are calculated using data from a load-crack mouth opening curve, $P$-$w_M$ [1]. Double-*K* parameters and methodology were introduced by Profs. Reinhardt and Xu in the late 90s and have generated abundant scientific literature since then. They are fairly used by many researchers and practitioners around the world, especially in China, where there is already a standard to regulate the determination of the double-*K* parameters [2]. Nevertheless, the methodology so far only copes with strictly static tests, while there is concern about the rate-effects coming from not-so-slow tests or from unstable portions of $P$-$w_M$ curves obtained when the control of the machine cannot follow fast variations of the load or snap-back in some of the signals, which is likely to happen in big specimens. Besides, rate-effects couple with the ones deriving from the size of the specimen [3], especially in the case of wedge-splitting (WS) tests.

The introduction of rate-effects in the double-*K* methodology is made following the approach of Rosa *et al.* [4], who developed a viscous-cohesive model which was implemented in the so-called 'smeared crack-tip superposition scheme' to obtain an exact cohesive solution. It gives the cohesive stresses as a function of both the crack opening and the crack opening velocity. This model is now adapted to WS tests and calibrated with a series of tests on compact specimens of five sizes performed in Zhejiang University and others in the scientific literature. The same viscous-cohesive model is also used in the double-*K* methodology to compute rate-dependent double-*K* values and to derive the corresponding *R*-curves, which are compared with those coming from the experiments and from the exact viscous-cohesive solution.

Our results show that both $K_{Ic}^{ini}$ and $K_{Ic}^{un}$ increase with the rate of loading, the rate dependence being slightly weaker for small specimens than for large ones provided the tests are done at a constant crack mouth opening displacement velocity. This amplifies the size effect on double-*K* parameters, which is pronounced for small sizes and mild for big sizes at strictly static tests. The numerical methodology also allows for reproducing peaks/valleys in the curves generated by sudden changes in the loading rate. Likewise, *R*-curves for various rates are easily calculated with the viscous-cohesive model.

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# Life-time prediction for anchorage system

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*Keywords:*

Anchor, concrete, sustained load, concrete creep, extreme event

*Abstract:*

The efficient and permanently safe design of anchor systems requires a thorough understanding of complex load carrying mechanisms and processes. Considering the required design life time of at least 50 years in combination with the demanded small failure probability, especially for the ultimate limit case, a suitable framework for the service-life prediction and assessment is critical. In general, accurate modelling concept for all involved materials and processes, taking into account the associated model and prediction uncertainties, should be utilized. However, simplified system models can provide acceptable estimates. In this paper, the framework (a) for predicting the life-time of an anchor subjected to a sustained load as well as extreme events, and (b) for quantifying it's life-time robustness, is presented. This simplified approach is based on the damage evolution or the effective time during the extreme events. It is clear that damage resulting from an early occurrence of the extreme event will influence the behaviour under sustained load. Contrariwise, the behaviour during an extreme event will be influenced by the sustained load effect up to this point in time. For the purpose of this study a Poisson process is used to describe the occurrence of extreme events. After introducing the problem and framework a simplified case study is presented and discussed.

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# Modelling Corrosion of Steel Reinforcement in Concrete: Natural vs. Accelerated Corrosion

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## ABSTRACT

Chloride-induced corrosion of steel reinforcement in concrete is one of the major causes for deterioration of reinforced concrete (RC) structures. RC structures exposed to aggressive environmental conditions, such as structures close to the sea or highway bridges and garages exposed to de-icing salts, very often exhibit damage due to corrosion. Principally, the computation of corrosion current density requires modeling of the following physical, electrochemical and mechanical processes: (1) Transport of capillary water, oxygen and chloride through the concrete cover; (2) Immobilization of chloride in the concrete; (3) Crystallization and dissolution of free chloride as a consequence of drying and wetting of concrete as well as related hysteretic property of sorption curves; (4) Transport of $OH^-$ ions through electrolyte in concrete pores; (5) Cathodic and anodic polarization; (6) Transport of corrosion products in concrete and cracks, (7) Creep, shrinkage and swelling of concrete and (8) Damage of concrete due to mechanical and non-mechanical actions.

In the present work the recently developed 3D chemo-hygro-thermo-mechanical model for concrete is briefly discussed. The model is implemented into a 3D FE code and it is here used to simulate the corrosion of steel reinforcement in concrete under natural and accelerated conditions.

In order to speed up corrosion of reinforcement in concrete experimental tests are almost always accelerated by imposing external electric potential and by adding chlorides to concrete mix. Therefore, the corrosion rate becomes much faster than the fastest corrosion rate in the nature, which can have significant consequences on the non-mechanical and mechanical processes related to the corrosion of reinforcement, i.e. the experimental results can lead to unrealistic conclusions.

To further improve and calibrate the numerical model, and to investigate the influence of the accelerated corrosion on corrosion induced damage an extensive test program, in which the reinforced concrete cylinders of different sizes, were exposed to accelerated corrosion was carried out. The experimental tests for different corrosion conditions were supported by numerical simulations using the above mentioned model. Based on the results of the experimental and numerical studies it is shown for which range of the imposed electric potential the resulting corrosion phase can be taken as realistic. Moreover, the influence of creep, swelling and drying of concrete on the corrosion induced damage is also investigated.

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# Development of a computational multi-physical framework for the use of nonlinear explicit approach in the assessment of concrete structures affected by alkali-aggregate reaction

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## ABSTRACT

This paper proposes an innovative methodology for the use of the explicit approach in the assessment of concrete structures affected by alkali-aggregate reaction (AAR). Efficiency of the explicit approach has been proven in previous works for the case of large concrete structural models with high degree of nonlinearity. In the proposed methodology, the strain is decomposed into mechanical, thermal, creep, shrinkage and AAR strain components. The AAR component is computed according to Saouma and Perotti [1] model for the anisotropic distribution of the volumetric expansion and according to Larive model [2] for the AAR kinetics. One advantage of the approach is that it can be used with any existing concrete model that has undergone a rigorous verification and validation (V&V) process for the mechanical part. In this work the EPM3D [3] concrete model implemented as a user-subroutine in Abaqus-Explicit is used. The general methodology is based on three different finite element analyses: thermal implicit, hygral implicit and the final nonlinear multi-physical explicit analysis. Theoretical formulation to address the problem of time scale difference between the implicit and explicit approaches is presented. A new incremental numerical formulation is presented to correctly handle the dependency of the AAR kinetics on the temperature field in case of cyclic temperature variation. Quantitative validation examples are presented at the material level, along with qualitative assessment of the cracking pattern of an existing hydraulic structure affected by AAR. This last application at structural level demonstrates the efficiency of the suggested methodology and the feasibility within an industrial context.

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## Self-consistent chloride diffusivity upscaling in cement paste

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### ABSTRACT

Chloride ingress into concrete is a major cause for material degradation, such as cracking due to corrosion-induced steel reinforcement swelling. Corresponding transport processes encompass diffusion, convection, and migration, and their mathematical quantification as function of the concrete composition remains an unrevealed enigma. Approaching the problem step by step, we here concentrate on the diffusivity of cement paste, and how it emerges from the microstructural features of the materials, and the chloride diffusivity in the capillary pore spaces. Therefore, we employ advanced self-consistent homogenization theory as recently used for permeability upscaling [1], based on the resolution of the pore space as pore channels being oriented in all space directions. This results in a surprisingly simple analytical (yet implicit) relation between porosity, pore diffusivity and the overall diffusivity of the cement paste. This relation is supported by experiments, and re-confirms the pivotal role [2] that layered water most probably plays in pore diffusivity reduction with respect to that found under the chemical condition of a bulk solution.

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# Multiscale Analysis of Alkali Silica Reaction in Concrete: A Homogenization Approach

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## Abstract

Alkali silica reaction (ASR) is one of the main reasons that cause deterioration in concrete structures, such as dams and bridges. ASR is a chemical reaction between alkali ions from cement paste and the available non-crystalline silica inside each aggregate piece. ASR gel, which is the product of this reaction, imbibes additional water causing swelling and cracking, which leads to degradation of concrete mechanical properties. ASR, a complex multiscale chemo-mechanical problem, is derived by various environmental factors including humidity and temperature. Diffusion and permeability inside the concrete structure play a fundamental role in defining the kinematics, rate and extent of ASR.

Lattice Discrete Particle Model (LDPM)[1] is a meso-scale discrete model, which simulates concrete at the level of coarse aggregate pieces using realistic aggregate size distribution function. LDPM has shown strong abilities in reproducing concrete response in different experiments, such as tensile fracturing, confined and unconfined compression, torsion, and shear tests. ASR effect has been successfully modeled by LDPM[2] through calibration and validation of the model parameters using available experimental data. Volumetric expansion, expansion anisotropy under applied load, non-uniform cracking distribution, concrete strength and stiffness degradation, and temperature effects of concrete subjected to ASR, are some of notable ASR effects that are precisely simulated.

This paper employs the ASR-LDPM model to solve large-scale structures through multiscale homogenization approach. The basic idea of the homogenization technique is to represent each integration point in the macroscopic domain by a representative volume element (RVE), in which the related material heterogeneity is modeled, while the material is assumed to be homogeneous at the macroscale. Theoretical derivation of homogenization method is first developed based on the idea of asymptotic expansion of field variables. Next, LDPM homogenization framework is used to reproduce experimental data of different laboratory test in terms of capturing the stress effects, cracking pattern, and volumetric expansion.

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# CREEP OF CRACKED POLYMER FIBER REINFORCED CONCRETE UNDER SUSTAINED TENSILE LOADING

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**Key words:** Creep, Fiber Reinforced Concrete, Tensile Creep, Crack Growth, Polymeric Fibers

**Abstract.** In fiber reinforced concrete (FRC), fibers are added to the fresh concrete mix in order to improve the residual tensile strength, the toughness and/or durability of a concrete element. Currently, structural applications remain relatively scarce as the time-dependent behavior of FRC is still poorly understood. The proposed paper reports on the first results of an experimental campaign into the creep of cracked polymer FRC. In the test setup, cylindrical, notched FRC specimens are considered. The concrete is reinforced with structural polymeric fibers for use in load-bearing applications. In a first step, the material is characterized according to the European Standard EN14651. Furthermore, a short-term direct tension test is performed as well. Secondly, the samples are precracked to localize the creep deformations and to monitor the crack growth in time. The samples are subjected to a sustained tensile load, whereby different load levels with respect to the individual residual strength are considered. The results of the first months of creep loading will be detailed and discussed in the paper.

# Fundamental Study of Crack Propagation of External Sulfate Attack with Mesoscale Analysis System for Coupled Chemo-Mechanical Behaviours

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## ABSTRACT

In this study, three dimensional numerical analysis systems, which can consider the change in physico- chemical property and mechanical behaviours due to sulfate attack, was constructed in order to evaluate the process of expansion crack propagation. This analysis system was coupled with numerical analysis for sulfate attack with RBSM. Sulfate attack analysis was constructed by cement hydration model, mass transfer model and chemical reaction model and it can describe the change in cement hydrate and precipitations, diffusion and consumption of sulfate ions and the change in pH. In addition, RBSM is one of the discrete analyses that can directly evaluate crack width and crack propagation.

In this analysis system, both of truss network model for mass transfer and chemical reaction and springs for mechanical behaviours were introduced to analytical model so that mass transfer, chemical reaction and mechanical behaviour were described by being coupled with both of spatial-temporal information. Furthermore, expansion pressure was calculated as a function of the amount of ettringite calculated by sulfate attack analysis and introduced to each springs of RBSM to evaluate the process of expansion crack propagation.

With this analytical system, expansion crack propagation analysis was conducted to evaluate that the kind of cement and mix proportion influence to expansion crack propagation. As results, it was confirmed that this analytical system can describe signature expansion crack propagation due to sulfate attack and the amount of ettringite changed by the amount of $Al_2O_3$ in monosulfate could affect the expansion crack.

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# A coupled multi-physics model for creep, shrinkage and fracture of early-age concrete

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## ABSTRACT

The behaviour of concrete at early-age is a complex phenomenon that necessarily includes interaction of multiple physical fields, such as temperature and moisture, to characterize its mechanical response. Perhaps the most prominent phenomenon is the exothermic reaction of cement hydration, which for massive concrete structures may result in a significant temperature increase and thereby an increased risk for thermal cracking. Furthermore, the hydration reaction consumes water leading to a moisture sink, self-desiccation, which causes autogenous shrinkage of the solid matrix. If the concrete is not cured properly this can lead to severe cracking, especially for concrete with low w/c-ratios. Furthermore, the rate of hydration is highly influenced by the state of temperature and moisture, which affects the evolution of mechanical properties such as strength. [1]

In this paper, a numerical model is presented that couples the evolution of temperature and moisture during the early-age of concrete with a mechanical model. This model accounts for volumetric changes due to temperature and moisture variations as well as evolution of material properties during and after the initial hydration. Furthermore, the model also accounts for cracking through an isotropic damage model and creep by employing the Microprestress-Solidification theory [2]. Similar coupled models for early-age concrete can be found in the literature, e.g. the model presented by Di Luzio and Custasis [3].

The presented model is implemented in the commercial FE code Comsol Multiphysics. The implementation allows for a two-way coupling between the different physical fields, which enables the model to consider e.g. the influence of cracking on moisture movement. To validate the capabilities of the model, it is analysed and compared to relevant experimental data found in the literature. Results show that the model is in good agreement with the experimental data. Finally, a structural example of a massive concrete structure with a high risk for thermal cracking is analysed to highlight the how the model performs in a structural setting. Results from the structural analysis are presented and discussed.

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# Effective Ageing Linear Viscoelastic Properties of Composites with Phase Precipitations: Comparison Between Numerical and Analytical Homogenization Appoaches

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## ABSTRACT

Dissolution and precipitation processes are present in key phenomena affecting the behaviour of cement-based materials. At early-age, due to hydration process, new phases are formed within capillary pores; at late ages, the material can be submitted to degradation processes in which hydrated phases dissolve. These processes reflect in an ageing behaviour of the material.

Cement–based materials exhibit viscoelastic behaviour. Recently, analytical homogenization tools have been developed to upscale the effective properties of composites in an ageing linear viscoelastic framework [1,2]. Taking advantage of these tools, an extension of Bazant's original solidification theory [3] was proposed in a 3D tensorial context [4].

In this paper, we propose to benchmark these analytical approaches by comparing with numerical homogenization to estimate the behaviour of ageing composites in different scenarios. To this end, 3D numerical samples are generated by randomly distributing inclusions of various sizes and shapes in a box [5,6]. The standard finite element method is then applied to solve the problem involving different phase behaviours and external loadings. Here, classical creep and relaxation loadings are considered. The effects of the phases contrast on the response obtained by both numerical and analytical approaches are discussed. Also, whilst analytical homogenization is often limited to spheroidal forms, numerical homogenization can deal with more complex geometries. We compare the response of solidification in two main morphologies: spherical and convex polyhedral inclusions. In the latter case, samples with flattened and elongated polyhedral aggregates of different aspect ratios are generated so as to investigate the influence of their shape.

The results provided here go towards a better description of the dissolution precipitation processes, which is an important feature in the description of cement-based materials ageing behaviour.

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# Subcritical Crack Growth Induced by Stress Corrosion in Hardened Cement Paste

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## ABSTRACT

For concrete structures a primary driver of deterioration shortening their lifespans is the damage growth resulting from coupled chemo-mechanical attack. Under sustained service load coupled with corrosion, stress corrosion cracking will lead to subcritical crack growth (SCG) in concrete members. In this study, the kinetics of crack growth in cement paste under concurrent mechanical and chemical attacks will be investigated experimentally and numerically. To obtain the complete crack velocity-stress intensity factor (K-v) curve, tests will be designed for the experimental characterization to track the subcritical crack growth. In the test the specimens, which are immersed in a corrosive solution of high concentration, will be subject to sustained loading. To record the crack propagation as well as strain/stress distribution around crack tip, a high-resolution microscopic system and a non-contact 3D digital image correlation system will be used to scan the specimen surface. Using the experimental results as benchmark, numerical simulations based on lattice model will be carried out. To capture the heterogeneity of hardened cement paste at meso-scale, the specimen will be mapped on a lattice system so as to separate the lattice elements representing different constituents. Another advantage of the proposed mapping technique is to assign transport property to the lattice elements to approximate the effect of corrosion kinetics. Based on the numerical simulations, a parametric exploration is undertaken to probe the correlation between SCG kinetics and the coupled chemo-mechanical parameters.

# Experimental and Numerical Study on Cementitious Materials Degradation under External Sulfate Attack

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## ABSTRACT

External sulfate attack is one of the situations that may cause gradual but severe damage to cementitious materials, which may lead to cracking, increased permeability and strength loss. In this paper, the thin-walled hollow cylinders [1] with wall thickness of 2.5mm were made considering the slow penetration process of sulfate ions in immersed environment. Also the vacuum saturation method using different sodium sulfate concentrations was adopted, with tap water as the reference. Three types of restraint were applied on the cement paste hollow cylinders with a spring or a steel bar in the middle to build the unrestrained, low restrained and high restrained conditions. The expansion was measured, and also the generated stress was calculated. Changes in sulfur distribution along the attack direction and pore size distribution were investigated by EDS (energy dispersive X-ray spectrometer) and MIP (mercury intrusion porosimetry). Meanwhile, ESEM (Environmental Scanning Electron Microscope) and EDS were used for microstructure and reaction products analyses.

A three-dimensional lattice model was built to simulate the cement paste hollow cylinder expansion. The expansion is mainly due to the formation of ettringite in small pores. The filling amount and filling size of pores were calculated based upon MIP tests. The values of internal stress caused by ettringite formation were assumed based on crystallization pressure theory related with pore size [2]. Then the internal stress values were transferred to the lattice model [3]. Finally, the model was validated by the experiment results, which supports the crystallization pressure theory for explaining external sulfate attack mechanism.

**Key words:** External Sulfate Attack, Expansion, Crystallization Pressure, Lattice Model

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# Meso-scale Modeling of Irradiation Damage in Pressurized Water Reactor Concrete Biological Shields

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## ABSTRACT

Safe and economically viable long-term operation of commercial nuclear power plants (NPPs) beyond 60 years requires the structural assessment of irreplaceable reinforced concrete components such as the concrete biological shield (CBS) encircling, and often supporting the reactor pressure vessel (RPV). Esselman and Bruck [1] found that the neutron exposure at 80 years of operation of 2-loop and 3-loop pressurized water reactors (PWRs) exceeds $10^{19}$ n.cm−2 (E > 0.1 MeV), which is admitted as the approximate threshold for inducing irradiation damage to concrete [8,2].

In previous research, the effects of radiation-induced volumetric expansion (RIVE) on the formation of damage in concrete specimens tested in high-flux reactors were studied using micromechanics [5] or meso-scale modeling [3]. Simplified simulations of the CBS structural behavior show the formation of important biaxial elastic stresses in the region subjected to high fluence [4]. Because of strong gradients of neutron fluence [7], relative humidity [6] and moderate gradient of temperature, aggregate RIVE is concurrent to paste shrinkage and creep occurring at rates different from those in test reactors. This paper present the meso-scale numerical simulations, performed with AMIE, of the inner portion of the CBS exposed to severe irradiation conditions, accounting for the aforementioned time-dependent mechanism on concrete degradation.

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# Crack-gel Interaction on the Static and Fatigue Failure of ASR-Damaged RC Slabs

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**ABSTRACT**

Research target of this study is degradation of punching shear strength due to Alkali Silica Reaction (ASR) in Reinforced Concrete (RC) slab members. At first, punching shear strength of ASR slabs were examined experimentally. 6 RC slab specimens were made with reactive aggregate and cured in a saturated salt water pool for about 1 year. Deformation of slab specimens due to ASR strongly depended on bar arrangement, i.e., large expansion and large curvature were observed in case of single rebar layer, while small expansion and little curvature were observed in the case of double layer. Static punching shear strength also depended on bar arrangement. While significant reduction in punching shear strength was found in case of the single layer of reinforcement, no reduction was observed in case of the double layer bar arrangement regardless of the degree of induced expansion.

In addition to the static experiments, the cyclic loading was carried out in both dry and wet conditions. The punching shear fatigue strength of ASR- damaged specimen was reduced according to the reduction in the static punching shear strength, but the further strength reduction was not observed even in case of the wet condition unlike the normal reinforced concrete slabs.

As the next step, the authors conducted the multi-scale chemo-hygral simulation with ASR gel generation and migration. The poro-mechanics based multi-phase modelling succeeded to simulate deformation during the expansive reaction and the structural performance of ASR-damaged slabs by considering the quasi-hydro static pressure of created ASR gels in concrete. Stress contour in cross sections clarify that the restraint condition is greatly different between single layered specimen and the double especially in the bending compressive zone. Tensile restraint leads to large expansion and weakens concrete matrix. Because the degree of restraint is necessary to estimate the remaining structural performance of ASR damaged RC slabs, the numerical simulation is expected to solve the problem in view of asset management and maintenance.

# Session MS03: Micro- and Nano-Scale Testing of Concrete/Rock/Cementitious Materials

# Experimental study of failure mechanisms in brittle construction materials by means of X-ray micro focus computed tomography.

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## ABSTRACT

X-ray computed tomography (XCT) is a powerful tool in the 3D visualisation of fracture initiation and propagation in brittle materials, based on the attenuation of X-rays [1]. As test samples are small, the balance between sample size and image resolution is an important issue. The minimum sample size is related to the representative volume element (RVE) for the material and failure mechanism under investigation.

Aim of this paper is to present the experience obtained at the Building Materials and Building Technology research group in using XCT for the experimental study of failure mechanisms in brittle construction materials during three test programs. The resolution limit of the applied system is in the order of micro meters (microCT). Several types of in-house-made loading stages were applied for observation of step-wise induced failure mechanisms. Common goal of the presented experimental programs was to analyse the material's inner structure and fracture propagation at microscale, in support of studying local failure mechanisms and developing numerical models. The presented test programs concern:

- The triaxial behaviour of mortar joints with different mortar composition (lime, cement, hybrid binders), and thus varying relative mortar-brick stiffness.
- Fracture growth in two types of ferruginous sandstone samples (low and moderate cementation), which were subjected to stepwise compressive loading in dry and water-saturated conditions [2].
- Influence of flow distance on fibre distribution and orientation in two types of steel fibre reinforced self-compacting concrete (medium and high viscosity, but with similar slump-flow value).

For each test program, setup optimization and resulting failure modes will be discussed. As a general conclusion, most test results supported the theoretical framework relevant to the effects of varying conditions (relative stiffness, pore saturation, viscosity) on the observed failure modes. However, sample size / image resolution balance remains an important focus point. In further research, the obtained experimental data will be coupled with numerical modelling.

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# Combined investigation of Low-scale Fracture in Hydrated Cement and metal alloys Assessed by Nanoindentation and FIB 9th International Conference on Fracture Mechanics of Concrete and Concrete Structures – FraMCoS-9

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## ABSTRACT

Fracture mechanisms and fracture energy are of central importance for models that deal with the inelastic phenomena in brittle and quasi-brittle materials including cement and concrete. Fracture properties are traditionally assessed on macroscale from relatively simple laboratory tests (e.g. tension or three-point bending setup) in which specimens fail by a single localized crack crossing throughout the whole specimen. Therefore, the energy calculation is simplified and the fracture energy can be well estimated.

As the scale goes down the situation starts to be more complicated since the fracture paths and extent are no longer straightforward. In recent years, nanoindentation has become a standard technique for assessing elastic and plastic properties of individual material phases at scales below one micrometer. However, evaluation of fracture properties requires proper knowledge of the exact failure mechanism in terms of crack patterns and crack dimensions.

In nanoindentation experiment, the fracture toughness or critical strain energy release can be determined for brittle solids in which the crack geometry is well estimated from top of the specimen (radial cracking) [1]. This is not the case of either cementitious materials or some metal alloys where multiple cracks are located at the circumference of the indentation imprint and their exact length and depth cannot be readily observed. To overcome this difficulty, semi-quantitative energetic methods that try to decouple total indentation work into elastic, plastic and fracture parts have been developed [2]. Assumptions of these methods are, however, too simplified to be quantitative and are not well applicable to cementitious materials. Therefore, direct visualization and measurements of the crack system under the indent is necessary.

In this work, nanoindentation is applied to introduce fracture deformations into hydrated cement and metal alloy (mostly magnesium based, serving as a benchmark material) in the scale of a few micrometers. Crack patterns and crack extent is determined with the aid of focused ion beam (FIB) milling and imaging in the indentation affected volume under the tip after unloading. Fracture parameters are identified by combining work of nanoindentation (from load-penetration curves) and cracks reconstruction derived from FIB images. Deformation mechanisms are compared and unique low-scale parameters are derived for individual hydrated phases in cement paste.

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# Nano-characterization of Type-G Cement Slurry Incorporating Nanoclay Cured under High Temperature and High Pressure Conditions

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## ABSTRACT

Type-G Cement slurry with various admixtures commonly used in oil/gas well cementing incorporating 1, 2 and 3% nanoclay particles by weight of cement were produced. A water/cement ratio of 0.44 was used and the mixes were subjected to a temperature of 290° F and a pressure of 4666 psi for 48 hours. Elastic and viscoelastic characteristics of the cementitious mixes were characterized using nanoindentation. The nanoindentation tests enabled evaluating the maximum indentation depth, plastic depth, and the reduced elastic modulus. Furthermore, dwell time of 60 seconds was used to evaluate creep compliance of the cement mixes incorporating nanoclay. Furthermore, Scanning electron microscope (SEM), X-ray diffraction (XRD) and Nuclear Magnetic resonance (NMR) microstructural analyses were conducted to explain the results observed using nanoindentation.

The experimental observations showed that the effect of incorporating nanoclay is very sensitive to the nanoclay content. It is presented that 1 and 2% nanoclay resulted in a small reduction to insignificant increase (-24 to +18%) of the reduced modulus compared with neat cement. However, a high content of 3% nanoclay resulted in significant increase (+53%) in the reduced elastic modulus and a significant reduction in creep compliance compared with neat cement. XRD analysis of cement mix with nanoclay shows that the incorporation of nanoclay in the cement mix transforms the CH phase to calcium silicate hydrate (C-S-H). Furthermore, increasing the nanoclay content resulted in increasing the level of silicate polymerization in the cement mix. It is apparent that increasing nanoclay resulted in formation of highly dense CSH that provides increase in elastic modulus and reduction in creep compliance. SEM micrographs show the difference in capillary porosity of neat cement and cement mixes incorporating nanoclay up to 3%.

# Micro-mechanisms of concrete failure under cyclic compression: X-ray tomographic in-situ observations

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## ABSTRACT

To explore the localised failures of the concrete, a small scale mechanical testing under compressive loading has been done in in-situ X-ray computed tomography (XCT) facility. Concrete consists of the coarse aggregate and cement. A 20x20x20 mm3 size of the specimen is used in the cyclic compression test to achieve a good resolution of 16.5μm in XCT images. Load is applied in three cycles and specimen is scanned after the completion of each stage in the cyclic (e.g. after loading and unloading). This test has given the insight to the micro-mechanisms such as crack opening and closing, crack tip extension and diversion, crack tip blunting, and elastic recovery of the crack openings and closures. Finally, the digital volume correlation (DVC) is utilised to get the displacement map during each cycle. Displacement contours have shown the anisotropy in the specimen.

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# Experimental and theoretical investigation of the fracture behaviour of glass beads/epoxy compositions using microscratching

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## ABSTRACT

As civil engineers one of our major concerns is the building of functional environments (i.e., buildings and infrastructure) which survive during and after any disruptive events. Concrete, ceramic, and other quasi-brittle materials contain pre-existing cracks and complex material structure on various internal length-scales. There is room for a better understanding of fracture behavior of these quasibrittle materials when considering multiple length scales of preexisting defects and inclusions. To selectively study the impact of microstructure on micro-scale fracture parameter this article presents an experimental and theoretical investigation of the fracture toughness of a representative composite material consisting of glass beads embedded in epoxy. By controlling the arrangement and the volume fracture of glass beads (representing an inclusion) in the matrix of the composite material, it is possible to control the amount, or direction, of crack development and reduce the stress concentration within the material during loading [1]. As a result, an increase in the fracture toughness of the composites and improved fracture properties is obtained. This investigation is carried out with glass beads embedded in epoxy with four different volume fractures of microspheres ranging from 0%, 5%, 25% and 50%. By using the micro scratch technique to investigate the failure mechanism it is possible to and determine the fracture parameters at the micro scale while controlling the crack path [2]. By augmenting linear elastic fracture mechanics analysis of scratch data with spatial statistics of the microstructure, a theoretical formulation agreeing with the experimental results was derived. The resulting theory may be applied as a constraint to control crack branching and propagation in the design of heterogeneous materials.

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# Fracture Toughness of Synthetic C-S-H with Varying C/S Ratio

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**ABSTRACT**

Calcium Silicate Hydrate (C-S-H) governs key characteristics of concrete such strength, durability and dimensional stability. When mixing water and cement, a number of hydration by-products such as calcium hydroxide (CH) and tri calcium sulfoaluminate (ettringite) are formed with C-S-H. This makes it challenging to characterize the mechanical and fracture characteristics of C-S-H using hydrated cement with good certainty. Furthermore, mechanical behavior and cracking of C-S-H were proven to be dependent on the CaO to $SiO_2$ (C/S) ratio and on mixing and curing conditions.

In this work, C-S-H was synthesized in the lab by mixing Calcium Oxide (CaO denoted as C) and Silicate ($SiO_2$ denoted as S) with varying C/S mixture ratios ranging from 0.7 to 2.0. For each ratio, the C-S-H powder was filtered and dried to a relative humidity of 11% and then compacted at 400 MPa to produce porosity similar to that produced in standard hydrated cement. Nanoindentation tests incorporating time-dependent effect (creep) were performed on polished C-S-H specimens using Berkovich indenter tip. A recently developed approach by the authors was used to evaluate the fracture toughness of C-S-H. In this approach, the experimental observations of nanoindentation is integrated with a viscoelastic-plastic finite element model to enable separating cracking energy from viscoplastic energy observed during dwell time. A viscoelastic creep model was also implemented to account for viscoelastic behavior of C-S-H. The proposed approach showed that increasing the silica content (low C/S ratio) reduces the fracture toughness of C-S-H. The significance of silica polymerization on fracture toughness of C-S-H was examined using NMR measurements.

# Session MS04: Nonlocal Models for the Simulation of Fracture in Concrete

# Isogeometric Implementation of the High-Order Microplane Model for Softening and Localization

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## ABSTRACT

In this study, a recently developed higher order microplane (HOM) model for softening and localization [1], is numerical implemented within a finite element framework based on isogeometric analysis. The HOM model was derived directly from a three dimensional discrete particle model and it was shown to be associated with a high order continuum characterized by independent rotation and displacement fields. Furthermore HOM model was demonstrated to possess two characteristic lengths: the first associated with the spacing of flaws in the material internal structure and related to the gradient character of the continuum; and the second associated with the size of these flaws and related to the micropolar character of the continuum. The displacement-based finite element implementation of this type of continua requires C1-continuity both within the elements and at the element boundaries. This motivated the implementation of the concept of isogeometric analysis which ensures a higher degree of smoothness and continuity [2]. NURBS based isogeometric elements were implemented in a 3D setting and with both displacement and rotational degrees of freedom at each control point. The performed numerical analyses demonstrate the effectiveness of the proposed HOM model implementation to ensure optimal convergence in both elastic and softening regime. Particularly, the proposed approach prevents strain localization and spurious mesh sensitivity known to be pathological issues for typical local strain-softening constitutive equations..

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# Spectral Localization Analysis in Nonlocal Softening Materials

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## ABSTRACT

The paper shows that spectral wave propagation analysis reveals in a simple and clear manner the effectiveness of various regularization techniques for softening materials, i.e., materials for which the yield limits soften as a function of the total strain. Both plasticity and damage models are considered. It is verified analytically in a simple way that the nonlocal integral-type model with degrading yield limit depending on the total strain works correctly if and only one adopts an unconventional nonlocal formulation introduced in 1994 by Vermeer and Brinkgreve, which is here called, for the sake of brevity, -over-nonlocal- because it uses a linear combination of local and nonlocal variables in which a negative weight imposed on the local variable is compensated by assigning to the nonlocal variable weight greater than 1 (this is equivalent to a nonlocal variable with a smooth positive weight function of total weight greater than 1, normalized by superposing a negative delta-function spike at the center). The spectral approach readily confirms that the nonlocal integral-type generalization of softening plasticity with an additive format gives correct localization properties only if an over-nonlocal formulation is adopted. By contrast, the nonlocal integral-type generalization of softening plasticity with a multiplicative format provides realistic localization behavior, just like the nonlocal integral-type damage model, and thus does not necessitate an over-nonlocal formulation. The localization behavior of explicit and implicit gradient-type models is also analyzed. A simple analysis shows that plasticity and damage models with gradient-type localization limiter, whether explicit or implicit, have very different localization behaviors. In Di Luzio and Bažant (2005) all the details can be found.

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# Bi-dissipative Thick Level Set (TLS) damage model for quasi-brittle materials

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## ABSTRACT

The Thick Level Set (TLS) approach applied to damage models allows for a non-local treatment that prevents from spurious localization problems. This approach to model damage growth and strain localisation in solids was first presented in [1]. In previous works (e.g. [1,2,3]), isotropic damage models with a single scalar parameter were adopted. Under these conditions, a single level set was used to separate the undamaged zone from the damaged zone, and damage growth was expressed as a level set propagation. Schematically, in the damaged zone, the damage variable directly depended on the level set though an explicit function. Beyond a critical length, material was assumed as fully damaged, thus allowing for a natural transition from damage to localized cracking (i.e., strain localisation). From a numerical viewpoint, once this condition was attained, crack was explicitly modelled using the eXtended Finite Element Method (XFEM).

In this paper, the TLS approach is extended to "bi-dissipative" isotropic damage models [4]. In the adopted formulation, degradations of material properties under prevailing compressive/tensile loading conditions are separately treated. Two distinct damage variables and activation criteria are used. This allows taking into account stiffness recovery upon tension-to-compression loading transition (i.e., unilateral effect) and the degradation of material properties in tension due to compressive damage. Furthermore, two independent internal lengths can be introduced [5].

In the article, the local damage model and its mathematical properties are discussed first. Several strategies for dealing with bi-dissipative damage in the framework of a TLS approach are then discussed. Some numerical results of 2D and 3D quasi-static simulations of quasi-brittle fracture are finally presented.

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# Strain localisation from isotropic and anisotropic Eikonal Non-Local (ENL) damage formulations with damage dependent internal length

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## ABSTRACT

Integral nonlocal techniques are often used to regularise damage models in the presence of strain softening laws. Some questions concerning the identification of the internal length, its possible evolution during damage process and the need for special treatments of non-locality operators near the boundaries (e.g. edges, cracks) are however still open.

A physical request is that material points separated by a crack or highly damaged zones should not interact (despite what is done in standard nonlocal integral theories). This can be obtained by introducing an evolving internal length [1,2,3,4] depending on mechanical fields (e.g. damage, strain, stress, …), thus representing a progressive transition from Continuum Damage Mechanics to Fracture Mechanics when crack localises.

A novel interpretation of evolving nonlocal interactions was recently introduced by [1]. Based on the Wentzel-Kramers-Brillouin approximation for high-frequency wave propagation in a damaged medium, [1] defined the interaction distances as the solution of an isotropic/anisotropic Eikonal equation.

From a numerical viewpoint, for each Gauss point of the finite element mesh, Fast Marching approaches [6] are used to compute non-local interaction distances from each other gauss point pertaining to its neghborhood. Geodesic distances are then used to define the kernel of Gaussian weighting function to be used in integral nonlocal regularisation.

The present work investigates and discusses numerical implementation and properties of such a regularisation technique. Several numerical results of quasi-static simulations of quasi-brittle fracture in isotropic and anisotropic media are presented.

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# Discontinuous-Based Approach for Meso-Scale Modeling of Concrete Under High Temperature

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## ABSTRACT

The action of high temperature in concrete is a field of much interest and attention due to its crucial influence in strength, durability and serviceability conditions of structural components. Long-term exposures to high temperature fields strongly affect the most relevant mechanical properties of concrete materials such as cohesion, friction, stiffness and strength [1].

In this work, the failure behavior of concrete subjected to elevated temperature effects is analyzed at the mesoscopic level of observation, whereby three phases are explicitly considered: large aggregates, mortar and aggregate-mortar interfaces. While the aggregate are modelled by means of thermo-elastic formulations, the degradation of the mortar and of the joints between mortar and aggregates are modelled through non-linear fracture energy-based thermoplastic interfaces, in the framework of the discrete crack approach. This interface formulation, see [2], takes into account the degradation of strength and fracture energy properties, both in mode I and II, due to coupled termomechanical actions. In this analysis, the interface and continuous model formulations are further extended to account for the porosity features of concrete and of the influence of both the porosity and the humidity conditions on the overall response behavior. In the framework of this extension, the non-linear interface response is activated not only under cinematic or temperature jumps, but also in case of jumps in the hydraulic conditions.

This contribution focuses on the analysis of finite element predictions of failure behavior of concrete members subjected to different thermo-mechanical and also hydraulic conditions at the mesoscopic level of observation. In particular, the variation of failure mechanism and ductility, in pre- and post-peak are evaluated, as well as the influence of the aggregate/mortar ratio, and of the involved humidity/porosity in the overall failure behavior [3].

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# A constitutive law with improved continuous-discontinuous description of fracture in concrete

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## ABSTRACT

Fracture in concrete is responsible for the both strength and stiffness reduction and it precedes the the structural failure. At the beginning of loading, a region with several micro-cracks is formed. Later these micro-cracks create a macro-crack. An adequate description of fracture in numerical FE calculations is extremely important to obtain physically realistic results. Within continuum mechanics, there exist two main approaches to describe fracture. The first one describes it in a smeared sense as localized zones of micro-cracks with a certain finite width. As an alternative, displacement jumps (discontinuities) along cracks may be introduced while keeping the remaining region as a continuous one. A smeared approach is more appropriate when describing a micro-crack formation process while a discontinuous one allows for a more realistic simulation of discrete macro-crack propagation. Usually, only one approach is used to simulate a fracture process in concrete during the entire deformation process. A combination of continuous and discontinuous approaches make it possible (as in experiments) to realistically capture all stages of fracture

The continuous-discontinuous constitutive law presented here is an improved version of the model earlier formulated [1, 2]. The original one links a continuous and discontinuous description of fracture defined within continuum mechanics. In a continuum regime, two constitutive laws are used alternatively: an elasto-plastic one with a Rankine criterion and an isotropic damage one formulated within continuum damage mechanics. Both laws are equipped with a characteristic length using an integral non-local theory. Discontinuous displacement jumps are described with XFEM. An special algorithm is responsible for transferring a softening from bulk points into a newly created crack segments. The proposed extension introduces a transfer function which allows for a gradual switch from a continuous (smeared) to discontinuous (discrete) softening process. By extending a crack with a new segment, nodes and finite elements located in a band perpendicular to this segment are doubled. The width of a doubled zone covers the width of a localized zone. Both doubled element sets share the same nodes along zone boundaries. As a consequence no special algorithm is required to a force transfer of the softening mechanism. Such modification overcomes some convergence problems observed in simulations with the original model. The effectiveness of the proposed formulation is verified on several tests including uniaxial stress states (tension and bending tests) and multiaxial stress conditions (Nooru-Mohamed problem and single-edge notched beam by Schlangen).

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# Multiscale analysis of crack-induced diffusivity of concrete: a phase-field approach

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## ABSTRACT

A variety of durability problems in cement and concrete are the results of the interaction of diffusion processes combined with chemical reactions, such as the attack of chloride ions. Crack have large impact on increasing the diffusivity of cementitious materials since they provide low-resistance pathways for chloride ions, such that the attack process of chloride ions is accelerated.

Phase-field modeling is a very powerful and reliable tool to predict cracking phenomena. The objective of this work is to develop phase-field modeling coupled with diffusion for describing the effect of cracking on diffusivity of cementitious materials. The proposed model satisfies the consistency of the second law of thermodynamics. The analysis starts from the cement paste. Anisotropic diffusivity is accounted for, which is calculated by the phase-field parameter together with the vectors parallel to the crack. By comparing numerical and experimental results for the brazilian test, the local relationship between phase-field parameter and diffusivity is calibrated. The obtained relationship is then applied to the mesoscale of concrete, including cement paste and aggregates. In this work, the mesostructure of concrete is obtained by CT-Scan. Comparisons between numerical and experimental results for concrete are also illustrated in this work.

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## Session MS05: Computational Failure Modeling at Various Length Scales

# The Homogenization of a Masonry Unit Cell Using a Lattice Model: Uniaxial Tension Case

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## ABSTRACT

This study provides an explanation on how a lattice model might be employed in homogenizing a heterogeneous anisotropic masonry unit cell made of brick, mortar and their interface using energy equivalence concepts. The direct tension test was only considered in this study. Other loading scenarios like shear and compression may also be included using the same approach. The purpose is to obtain a post-peak scalar damage parameter of a homogenized isotropic finite element from the fracture energy results of a lattice masonry unit cell.

A 2-D plain strain lattice formulation was implemented to evaluate energy release rate values of the masonry unit cell. Discretization of the continuum brick and mortar domains were based on Voronoi tessellation. Different strength failure criteria were assigned to brick, mortar, and interface strength material properties that were mapped on top of the mechanical model of the lattice according to their geometric locations. An energy method was subsequently employed to obtain the energy release rate of the lattice mesh as the crack propagates which was obtained by the change in the global stiffness matrix of the lattice model before and after of strut removal [1].

Elastic properties of the homogenized finite element, i.e., equivalent Young's modulus and Poisson's ratio, can easily be obtained from the linear elastic behavior of the lattice unit cell in $\sigma_y - \varepsilon_y$ and $\sigma_y - \varepsilon_x$ planes, respectively. It was assumed that the total strain energy released in the lattice masonry unit cell in direct tension as the crack propagates equals the total strain energy dissipated in the equivalent homogenized isotropic continuum finite element under the same loading. Since these dissipated energy values correspond to the crack propagation and the damage incurred in the masonry unit cell, a scalar damage parameter can be defined based on the dissipated strain energy and energy release rate values during the analysis. The scalar damage parameter at each increment was calculated from the accumulated dissipated strain energy values up to that increment divided by the total strain energy dissipated throughout the analysis. These damage data in terms of displacements could be used to model the nonlinear behavior of a homogenized isotropic continuum finite element which is equivalent to the anisotropic masonry unit cell under direct tension based on damage formulations.

The homogenization technique mentioned may be regarded as a bridge between the micro-scale lattice analysis and macro-scale masonry wall. The homogenized continuum finite element with the post peak damage data obtained from the lattice approach can be employed in a homogenized macro-scale masonry wall which has an equivalent Young's modulus and Poisson's ratio with the same damage data of the heterogeneous masonry unit cell, in the context of Finite Element formulations.

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# Identification of Constituve Relationships for Concrete Using Discrete and Finite Element Framework

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## ABSTRACT

Sustainability issues of concrete structures are mainly linked to their durability and water tightness capabilities. These features are evolving along with time due to cracking of concrete which is an unavoidable behaviour regarding the design of such structures. Cracking has two main consequences: at the microscale, the permeability and diffusion processes directly depend on crack's opening, spacing and tortuosity whereas at the macroscale, the homogenized degradation of the constitutive material leads to stiffness loss, modification of the internal forces distribution and loss of the load bearing capacities. Considering those different scales and phenomena, the models used to describe the cracked behaviour of concrete cannot be of the same type. The aim of this contribution is to present different tools, used at their relevant physical scales as well as their mutual enhancement for a global structural approach.

A discrete element model (DEM) is presented, introducing within an implicit framework, local nonlinear mechanisms such as brittle failure, contact, frictional sliding and scale effects. Such a local model will help one, through virtual testing procedures to express constitutive laws allowing for a refine description at the representative volume element (RVE) level of constitutive relationship based on coupled plasticity-damage models. Original developments will be presented accounting for regularized crack effects on cyclic behaviour of brittle materials. Structural computations at the large-scale civil engineering structural scales are robustly achieved using this model. The interpretation of damage fields in terms of quantitative cracking are realized thanks to zoom procedures on region of interest (ROI) by weak kinematic coupling with local DEM. Based on a structural case-study, the relevancy of the full analysis chain will be presented during the conference.

# Fracture Energy Method in Predicting Crack Spacing of Reinforced Concrete Structures

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## ABSTRACT

The crack spacing of reinforced concrete structures has a major influence on structural performance. The fracture energy criterion of crack formation was employed to predict the crack spacing of concrete based on the linear elastic finite element model. This method employs three dimensional finite element model to investigate the strain energy release rate of concrete and employs the fracture energy criterion to predict the crack spacing of concrete. The energy release was obtained by building up finite element models of the concrete subject to uniform bond stress and dividing the model into two parts and re-examine the strain energy. The difference between two models is defined as energy release. It is assumed that only if the energy release exceeds the fracture energy of the effective cracking area, the micro crack will grow into cracking. The calculation results fit well with test results. It is proved that if the average crack spacing is lower than 120mm, the fracture energy method coincide with the non-slip method in that the crack spacing increase linearly with cover thickness. If the average crack spacing exceeds 120mm, the fracture energy method could explain the underestimation of crack spacing of the non-slip method. It is reported that the crack spacing decrease with increasing concrete strength, the influence of concrete strength to the crack spacing is also well explained by this method. Based on the analytical calculation method listed above, a simplified formula is put forward to predict the crack spacing of reinforced concrete structures. Thus, a fracture energy method in predicting crack spacing of concrete is solidly established.

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# Lattice Discrete Particle Modeling (LDPM) of Flexural Size Effect in Over Reinforced Concrete Beams

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## ABSTRACT

At the macroscopic scale, concrete can be approximated as statistically homogeneous. Nevertheless, its macroscopic behavior shows quasi-brittleness, strain softening, and size effects evidencing a strong influence of material heterogeneity. A model naturally accounting for material heterogeneity is the Lattice Discrete Particle Model (LDPM). LDPM replaces the actual concrete mesostructure by an assemblage of discrete particles interacting through nonlinear and fracturing lattice struts. Each particle represents one coarse aggregate piece. Since the initial development, LDPM has shown superior material modeling capabilities.

In this presentation, LDPM is used to simulate the flexure failure of three groups of over reinforced concrete beams. The groups represent 1D, 2D and 3D geometric similarities. The geometry is generated based on concrete mix design and the calibration was only guided by the experimentally provided compressive strength. In order to reduce the redundancy of the calibration process, the fracture properties of concrete were estimated using relevant data from the literature. Finally, the rebar reinforcing system was connected to the LDPM mesh using penalty type constraints and the rebars were modeled using 1D beam elements. Numerical results show excellent agreement with experimental data suggesting a good ability of LDPM in predicting the type of failure mechanisms involved in the failure of over-reinforced concrete beams.

The simulation of the failure behavior of over-reinforced concrete is important in practice especially for existing old structures that were designed according to design guidelines not accounting for ductility requirements as requested by modern design procedures.

# 3D Mesoscopic Modeling of Crack-Permeability Interaction in Fracture Concrete

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## ABSTRACT

Modeling of transport processes in fractured porous materials is an important issue for many industrial applications. For concrete structures, understanding the fluid flow mechanism is important for assessing the leak-tightness.

Cracks occurring in concrete structures increase their permeability allowing more fluid penetration. Therefore it is significant to assess the coupling between the evolution of the cracking process and the permeability. Our interest is focused on the intrinsic permeability related to the solid porous material which does not depend on the properties of the fluid. Based on the experimental observations, many governing laws have been developed to evaluate the Crack - Fluid flow interaction depending on how the cracking process is represented [1][2]. The crack description (geometry, opening ..) is a hard task. Many approaches dealing with the fracture-permeability interaction account for the fractures implicitly. An explicit description of the fractures could also be achieved.

In the present work, a coupled mechanical-hydraulic-based approach is proposed for numerical modeling of the interdependent mechanical and hydraulic behavior of fractured concrete. The proposed model is developed within the framework of the non linear poromechanics. A damage plastic model is used to describe the mechanical behavior of the solid phase (the solid skeleton). Crack estimation is therefore performed using a post-processing method based on the fracture energy regularization [3]. The hydraulic behavior is governed by the Darcy's law for the uncracked material. After cracking, the flow through fracture is driven by the cubic law and an anisotropic description of the material permeability is therefore assumed.

The validation is performed on a splitting test where a real time crack-permeability interaction is assessed. The numerical simulations are performed at a meso-scale level. The capability of the proposed model to accurately reproduce the experimental results is proved.

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# Energy approach for multiple cracking in beams made of quasi-brittle material under pure bending

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## ABSTRACT

For beams made of quasi-brittle materials, the moment can increase after a crack starts to propagate so the formation of multiple cracks is possible. In this paper, an energy minimization method is proposed to determine the pattern of multiple cracking in such kind of beam under pure bending. For the quasi-brittle material, the fracture behavior is described by the cohesive zone model (CZM) with a linear softening law. Assuming the presence of periodic and parallel crack array in the beam, the effects of crack spacing and beam curvature on the total energy per unit length of the member is obtained through finite element (FE) analysis. In the FE model, only a representative segment of the beam with only one crack needs to be considered, so the modeling is simple and computationally efficient. After performing a series of analyses on a bending beam, the crack spacing corresponding to the lowest energy is found at different curvatures and this crack spacing vs. curvature curve is used to describe the crack pattern evolution of the member. Normalization is conducted and the effect of the tension-softening behavior on the cracking process is also studied, which shows that multiple cracking behavior is determined by only one dimensionless parameter. As the crack pattern derived from the proposed energy approach has a sound physical basis, it can potentially be used as a reference for checking if the multiple cracking pattern obtained by other computational methods is proper or not.

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## Session MS06: Fracture and Damage of Confined Concrete

# Impact Resistant Performance of Ductile Fiber Reinforced Cementitious Composites (DFRCCs)

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## ABSTRACT

The aim of current study is to investigate the impact resistant performance of ductile fiber reinforced cementitious composites (DFRCCs) containing 1.5 % volume fraction of polyvinyl alcohol and steel fibers subjected to high velocity impact of steel projectile (the diameter of 19.05 mm and the mass of 28.13 g). To investigate the impact resistant performance of DFRCCs, gunpowder impact facility was used for impact tests, and the impact velocity was from about 450 to 750 m/s except for the plain specimens (non-fiber reinforced cemenetitious composites). The dimension of a specimen is a square of 300 mm and a thickness of 100 mm. The specimens with and without fibers after high velocity impact tests were damaged in various failure modes, which are penetration, scabbing, and perforation. For DFRCC specimens, the failure modes were limited to the penetration grade under the impact velocity of about 700 m/s, which is more than two times of the plain specimen. Additionally, DFRCC specimens did not caused critical damage such as scabbing and perforation, up to the impact velocity of 725 m/s. The mass loss of the plain specimen was proportional to the impact velocity of steel projectile, while DFRCC specimens were not significantly affected by the impact velocity of steel projectile. Moreover, DFRCC specimens have superior capacity on the scabbing limit, and slightly bulged in the back side under the impact velocity of 700 m/s. In perforating, the debris of the plain specimen has significantly scattered from a position of the front side in the cross section of the specimen. Hence, the damaged area has spread widely from the front side through the back side of the specimen. However, the debris of DFRCCs slightly scattered around a position of the back side in the cross section of the specimen as compared with the plain specimen. This is due to the perforated time was delayed by reinforcing fibers. It can be seen from the test results that DFRCCs have superior impact energy absorbing capacity under high velocity impact of projectile. Consequentially, in this study, we examined that principal fracture characteristics of DFRCCs subjected to collision of steel projectile, and verified that impact resistant performance was improved by reinforcing polyvinyl alcohol and steel fibers.

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# EFFECT OF ACTIVE CONFINEMENT ON SHEAR BEHAVIORS FOR PILE CAP PRESTRESSED LATERALLY

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## ABSTRACT

Recently, the shear and flexural capacities of piles have drastically improved and the ultimate design is also required for the pile foundations of medium and high-rise buildings, as well as for the superstructures. As a result, the pile head joint (hereafter, pile cap) to be sufficient for the required ultimate strength increases in dimensions or causes the overcrowding arrangement of reinforcements. In the previous studies, the element experiment of pile foundation was conducted to investigate the fracture behavior of pile cap [Kokusho et al. 1983]. According to this experiment, the maximum capacity is determined by the widening of the cracks developing in the diagonal direction corresponding to the direction of compression strut in the pile cap. In order to control this crack widening, the introduction of lateral prestress to the pile cap may be effective because the shear crack strength and shear capacity of the reinforced concrete (hereafter, RC) column was greatly improved by introducing the lateral prestress [Shinohara et al. 2004]. The objectives of present study are (1) to verify the validity of analytical models in analyzing the specimens of pile caps mentioned above using 3D FEM approaches and test results, and (2) to investigate the improvement of the shear crack strength and shear capacity by introducing lateral prestress to pile caps to control the diagonal cracks based on the triaxial state of stress. The analytical results show that lateral prestress controls the shear crack effectively and increases the shear capacity by over 30 percent. However, some vertical tension reinforcements yield in this analysis, therefore the introduction of vertical prestress in addition to lateral prestress to the pile cap may prevent yielding of vertical reinforcements and further improve the shear capacity.

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# Crack Growth in Concrete Under Uniaxial and Confined Conditions

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**ABSTRACT**

This paper compares the results of the experimental compressive stress-induced microcracks and numerically simulated compressive microcracks in concrete under uniaxial and triaxial loading condition. An alloy with a low melting point was used to preserve the microcracks in concrete as they exist under load. Scanning electron microscope was used to capture images from the cross sections of concrete specimens. These images were then used to determine length, orientation, and density of the compressive stressed-induced microcracks in concrete specimens. A crack growth simulation model was used to generate and propagate microcracks for uniaxial and triaxial loading conditions. The crack growth simulation model revealed results similar to that obtained from the experiments.

# Drop Test of Thick-Walled Concrete Cylinder Subjected to Shrinkage and Expansion

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## ABSTRACT

Degradation of concrete is an issue since it may limit the service life of structures. Shrinkage due to moisture transfer in the early age of concrete and expansion due to thermal effect and Alkali-Silica Reaction (ASR) may degrade the concrete structures. In this point a long- thick-walled cylinder is selected to perform some drop tests from a distinct distance. Shrinkage strain is calculated based on the latest model of RILEM called “B4” [1] which considers the autogenous shrinkage and drying shrinkage separately. ASR forms in concrete with expanding of ASR gel between aggregate and cement paste and reduces the stiffness and strength of concrete and may cause cracking of concrete. Larive [2] made a substantial experimental work to evaluate the ASR expansion in concrete and propose 0.2% strain after one year for concrete structures. From this point of view the outer and the inner surface of concrete are subjected to negative strains due to shrinkage and positive strains due to expansion of concrete while the other elements are in self-equilibrium.

Two different samples including confined cylinder with external pressure and non-confined cylinder of the concrete structure are selected for drop test. With regard to confinement, the performance of these structures is compared during 4 cases including shrinkage and expansion. The simulation takes place in LS-DYNA [3] which is suitable to perform high dynamic rate problems in form of explicit time integration. MAT_159 which is available in material library of LS-DYNA, is applied to the structure. The cylinder has an external radius of 25 inches and thickness of 10 inches and height of 80 inches. The contact happens on a rigid pad. During this impact problem, effective plastic strain and damage of concrete are examined during these scenarios and they are compared in the form of failure modes of concrete.

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# Experimental analysis of the shear behaviour of concrete under high confinement

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## ABSTRACT

During seismic loading, penetration of projectiles into concrete, blasting and many other severe loadings, various localized effects including cratering, tunneling and spalling are observed. Many tests have been developed for determining the behavior of concrete under confined or unconfined conditions. A recent experimental technique was developed to study the shear fracturing in mode II. Luong [1] used cylindrical samples with centered coinciding circular notches drilled on top and bottom surfaces leaving a cylindrical shear ligament. More recently, Bakers et al. [2] conducted laboratory PTS tests and finite element modeling on three different types of rock (granite, marble and limestone) subjected to up to 70MPa of confining pressure to measure Mode II fracture toughness. The specimen was first subjected to a hydrostatic pressure and then an axial load was applied to punch through the central portion of the core. They concluded that fracture toughness increases linearly with confining pressure and reaches a constant value at confining pressures higher than 20-35 MPa. Montenegro et al. [3] observed an increase of dissipation of energy associated to mode II fracture in confined conditions and concluded that shear strength increases and dilatancy effect decreases with higher confinement. Forquin [4] conducted experiments on dry and wet concrete samples with passive confinement cells and with radial notches to avoid self-confinement of the sample peripheral part. The author observed higher strength with dry samples than with wet ones and with the steel ring rather than with the aluminium on. He also studied the behavior of concrete under high strain rates and concluded that both sets of concrete (dry and wet) have very small sensitivity to strain rates up to /100s in mode II fracturing. In the existing literature, most of the available experimental tests deal with moderate confining pressure. In the present work, PTS tests have been conducted with a high-capacity triaxial press (Giga Press). A cylindrical sample with two cylindrical notches is first subjected to hydrostatic pressure up to 150MPa, and then an axial displacement is applied in order to generate the shear stresses in the ligament. First, numerical parametrization analysis done with FEM software (Abaqus) to obtain optimal sample geometry is detailed. Then, the experimental set-up is described. Finally, comparison between first experimental results and numerical simulations is presented.

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# Size Effect on Confining Force of Circular Concrete Filled in Steel Tube under Axial Compression

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## ABSTRACT

Size effect is one of the main mechanical properties of concrete under uniaxial compression. Size effect on performance of confined concrete under axial compression also has been one of the main concern in the area of size effect on concrete. Core concrete of concrete-filled steel tube is subjected to tri-axial compression, because of the fully enclosed confinement by the surrounding steel tube. The confining force provided by steel tube to the core concrete is the most representative in all kinds of confined concrete. Size effect on concrete under uniaxial compression has been investigated and provided the corresponding rules of size effect. However, size effect on concrete under tri-axial compression has been not sufficiently studied. To fill the gap, size effect on confining force of concrete filled in steel tubular under axial compression was discussed, and the calculation method of confining force considering size effect was provided. 4 groups of circular short columns of concrete filled in steel tube were conducted under monotonic axial compression. The diameters of the specimens were 219 mm, 426 mm, 630 mm, and 820 mm respectively. The ratios of diameter to thickness of the specimens were 88. The grade of concrete was C30. The damage characteristics of the specimens with different sizes was described. The final failure modes of all specimens were shear failure, and the shear angle of the specimens increased gradually with the increasing of the diameter of the column. Size effect on stress distribution of steel tube in transverse and longitudinal directions was discussed. Based on horizontal and longitudinal strain of steel tube obtained from measuring points arranged within the scope of one-third of the specimen height in the middle of the specimens during the test, the longitudinal and transverse stress - strain curve of each measuring points were calculated. The method to evaluate longitudinal and transverse stress of steel tube of the overall specimen was established to get the stress - strain relation of overall steel pipe in longitudinal and lateral directions. Therefore stress - strain relation of confining force and confined concrete was obtained. The analysis results indicated that when the peak load was achieved, the ratio of the vertical stress to the yield strength of the steel tube was enlarged with the diameter of the specimen increased; the ratio of the transverse stress to the yield strength of the steel pipe decreased with increment of the diameter of the specimen; the confining force provided by steel tube to the core concrete also reduced with the enlargement of the size of the column. All the variation degree gradually slow down when the size of the column enlarged. The confinement action to the concrete has size effect obviously. Based on the theory of limit equilibrium and test results, calculation model of confining force considering the size effect was built, and results calculated by the model were in good agreement with experiment results. The results provided a reference basis for the study of size effect on tri-axial compressive concrete.

# Session MS07: Cracking and Fracture Behavior of HPFRCC

# Cracking of SHCC due to reinforcement corrosion

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## ABSTRACT

Reinforcement corrosion is the most important deterioration mechanism affecting reinforced concrete infrastructures. After corrosion starts, expansive pressures are exerted onto the surrounding concrete, causing cracking and spalling of the cover concrete. The onset of cover cracking can possibly be delayed by using strain hardening cementitious composites (SHCCs). In this work, the ability of strain hardening cementitious composite to resist cracking due to corrosion of reinforcement is studied [1].

An accelerated corrosion experiment is performed to speed up the process. Micro-computed X-ray tomography technique (CT-scanning) was used for monitoring rust formation during accelerated corrosion of reinforcement and subsequent cover cracking. Development of cracks in SHCC specimen was compared to a reference specimen. While the SHCC specimen developed a large number of small cracks, the reference specimen completely failed due to corrosion. The SHCC specimen showed superior performance compared to the reference specimen due to its multiple microcracking ability.

After the accelerated corrosion experiment, both specimens were cut, polished, and the mechanical properties of the rust layer were determined using nanoindentation [2, 3]. The nanoindentation study showed that the Young modulus of rust is highly dependent on the level of confinement provided to the rust layer by the surrounding cementitious material.

SHCC proved to be an excellent alternative to brittle cementitious materials when corrosion induced cracking of the cover is a concern.

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# A New Stress-field Based Model to Simulate the Multiple Cracking Development in Strain-hardening Cementitious Composites (SHCC)

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## ABSTRACT

Strain-hardening cementitious composites (SHCC) are materials exhibiting strain-hardening behavior up to several percent tensile strain with the formation of multiple cracks. The conditions for achieving multiple cracking have been investigated in the literature [1, 2], but few studies have been conducted on the development of sequential multiple cracks in a SHCC member. Issues such as the number of cracks formed at a particular stress level (which governs material ductility) and the crack opening at a particular strain (which affects durability) are seldom addressed.

In this paper, a new model to simulate the overall stress-strain relation for an SHCC member will be developed. After the first crack is formed in a fiber composite, if the fibers crossing the cracked section are strong enough to carry additional loading, multiple cracking will occur [1]. Over a distance from the cracked plane, the bridging fibers under high tension will transfer stress back to the surrounding matrix through the interaction at the fiber/matrix interface, thus enabling the matrix to reach its fracture strength and crack at other sections [3]. In this study, the matrix strength is assumed to be non-uniform along the member and follows the Weibull distribution [4]. Then, for a bridging fiber at a certain inclination angle, the fiber stress and the stress transferred to the matrix at various distances from the crack will be derived, with consideration of the chemical bond and snubbing effect at the fibre/matrix interface [5]. Then, the matrix stress at any distance from the crack is obtained by summing up the stress transfer from all the acting fibers. The stress field in the matrix will be examined against the distributed matrix strength to determine the positions of new cracks. With the model, the strain at a particular stress level, as well as the corresponding number and openings of cracks, can be obtained.

Using this model, the effects of various micro parameters on the ductility and strength of SHCC member can be simulated. This will provide guidelines for the design of SHCC to achieve better mechanical performance.

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# Fracture mechanics based design of an SHCC overlay retrofitting strategy for unreinforced load bearing masonry

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## ABSTRACT

In the Western Cape Province of South Africa, multi-storey buildings of unreinforced load bearing masonry (ULM) were constructed before seismic resistance became a standardized requirement. The region lies in a light to moderate seismic zone in South Africa [1]. It is foreseen that these buildings might perform poorly during seismic activities due to their brittle in-plane shear failure mode. In response, Stellenbosch University (SUN) has launched a research project to develop an overlay retrofitting strategy, to enhance seismic resistance of unreinforced, load bearing masonry (ULM). As overlay material, strain-hardening cement-based composites (SHCC) is used [2]. For practical application of the overlay, material development was done to produce a shotcrete version, optimized for sprayability and adhesion to the masonry.

Empirical testing has been performed recently [3] to study various parameters of such a retrofitting strategy, including the number of ULM wall leafs and overlay thickness. Recent research on SHCC overlay bond [4] showed that the bond characteristics and interaction with multiple crack formation in the SHCC overlay are sensitive to substrate surface preparation. In a strategy to increase seismic resistance, multiple crack formation in the overlay is preferred, as this mobilizes significant ductility of the structural system. In order to determine an appropriate balance between the ULM-SHCC interface properties, the overlay SHCC mechanical properties and overlay thickness, a fracture mechanics approach is followed here. This is verified by computational analysis, combining a plane interface material model incorporating multi-surface adhesive (tensile cut-off) and Coulomb friction limit criteria with a plane stress, multi-surface Rankine-Rankine model for the SHCC overlay. A meso-modelling approach is followed for the ULM, in order to incorporate the head and bed joint heterogeneities. Finally, physical laboratory tests are performed to validate the finite element modeling, and the fracture mechanics based design approach.

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# Characterizing the crack development in strain-hardening cement-based composites (SHCC) by means of acoustic emission (AE)

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## ABSTRACT

The article at hand presents an investigation on crack development in strain-hardening cement-based composites (SHCC) subject to uniaxial tensile loading. Two different types of SHCC were tested, one normal-strength made with polyvinyl alcohol fiber and one high-strength SHCC made with polyethylene fiber. The aim of the work was to evaluate the applicability of acoustic emission (AE) measurements for determining the progressive damage within the material, as well as for differentiating the individual damage events by their origin and decisive mechanism, such as matrix cracking, fiber pull-out or fiber rupture. The acoustic emission method proved to be fully appropriate for recording and evaluating the fracture related processes in different types of SHCC as well as identifying the location of such damage within SHCC specimens. Valuable information on the various mechanisms and quantitative description of damage depending on SHCC composition was obtained and evaluated with respect to the measured stress-strain curves. Furthermore, the discussion of the obtained results was extended under consideration of crack patterns observed on the specimens' surfaces and the appearance of the fracture surfaces as observed in environmental scanning electron microscope.

# Bioinspired Design of Cement Polymer Composites

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## ABSTRACT

The structure of abalone nacre was adopted to develop a new paradigm in the design of structural composites with the goal of high tensile strength, ductility, and toughness. A bio-inspired multilayered structural composite was created using a cement mortar and a variety of polymeric fiber blends, cast into the cells of a 3D printed matrix. The impact of this microstructure on the strength and fracture toughness of multilayered composites was studied as a function of the cell's geometry and scale in a parametric study, using various methods of integrating the nacre cell structure into a system composite with concrete. Flexural strength and fracture toughness of the composite beam specimens were found to be greater than the control specimens. Compressive strength and splitting tensile strength of the cement mortar and polypropylene-fiber blend was also tested, respectively. The control beams reinforced with 1% PP fibers displayed a more gradual break and increased strain versus the beams without fibers. The composite beams proved to be outperforming the control specimen, due to the overall distribution of cracks throughout the beam that results in a higher strain at the beam failure. The composite beams showed more layer shear sliding during the break, whereas the control beams showed more diagonal shearing failure. After an initial first break early on, the composite beams gradually deformed plastically due to interlocking elements, and overall achieved a higher stress before failure.

# Pull-out Response of Single Steel Fiber Embedded in PVA Fiber Reinforced Cementitious Matrix

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## ABSTRACT

Comparing to Strain Hardening Cementitious Composites (SHCC) with polyvinyl alcohol (PVA) fibers or steel fibers alone, recent test results show that the hybridization of these two fibers can improve the crack control ability and shear behavior of SHCC, indicating a possible synergistic effect between the two kinds of fibers. The objective of this paper is to investigate the physical basis behind the synergy between PVA and steel fibers. As steel fibers are much larger in diameter than the PVA fibers, one can consider them to be embedded inside a PVA fiber reinforced matrix. With a specially designed testing set-up, fiber pull-out test is performed on a single steel fiber embedded inside a cementitious block with different contents of PVA fibers. In the test, the load vs displacement relationship during fiber debonding and pull-out is measured. The parameters investigated include the diameter of steel fibers, the fiber inclination angle (0°, 30° and 60°), the PVA fiber volume fraction (0% as control, 0.5%, 1.0% and 1.5%) as well as the effect of combined opening/shear displacements. With the test results, it is possible to quantify the synergistic effect between PVA and steel fibers, which can be used for the optimal design of hybrid PVA/steel fiber SHCC in the future.

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# Nonlocal Representation of Fiber Bridging Forces in Strain-Hardening Cementitious Composites

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**ABSTRACT**

This work involves the development of lattice models of strain-hardening cement composites (SHCC), in which the individual fibers are explicitly represented. The pullout forces of fibers are derived from micromechanical bases and distributed along the fiber embedment lengths. This non-local representation of the fiber bridging forces provides realistic representations of stress transfer between the fiber and matrix, which is essential for simulating crack openings and crack spacing in SHCC. Fibers are placed in the material domain using spatially correlated random techniques and the influence of nonuniformity of the fiber distribution is investigated. Regions with fewer fibers act as potential sites for fracture localization, limiting the strain capacity of the composite material. Multiple cracking produces islands of material interconnected by fiber bridges, which places demands on solution convergence. A special event-by-event solution strategy is adopted for this reason.

# Debilities and Strengths of FEM-Based Constitutive Models for the Material Nonlinear Analysis of Steel Fibre Reinforced Concrete Structures

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## ABSTRACT

During the last decades several improvements have been made on the numerical simulation of concrete type structures by modeling the relevant nonlinearities presented by concrete and reinforcements, as well as their interactions. With the advent of new cement based materials, such is the case of fibre reinforced concrete (FRC), new challenges and difficulties are placed to the computational mechanics community. This work discusses debilities and strengths of constitutive models implemented under the framework of the finite element method (FEM) for the simulation of FRC structures under serviceability and ultimate limit state conditions, and point out areas deserving further specific research for more reliable modeling strategies.

# A procedure for determining the representative tensile strength of UHPFRC using non-destructive methods for assessing the fibre content and orientation

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## ABSTRACT

A procedure is developed for estimating the representative tensile strength along selected orientations of existing thin Ultra High Performance Fibre Reinforced cement Composite (UHPFRC) layers. The procedure relies on measurements acquired using a non-destructive (NDT) method and an on a previous characterization campaign of the composite material, thereby avoiding the extraction of samples from the real structure.

The tensile strength of the composite is assumed to be given by eq.(1), which is based on the assumption that the tensile strength is governed by fibre debonding and pull-out:

$$f_{Ut,u} = \alpha_0 \alpha_1 \tau_f V_f \frac{l_f}{d_f} \tag{1}$$

In the equation above $l_f$ and $d_f$ are the fibre length and diameter, respectively, $V_f$ is the volume fraction of fibres, $\tau_f$ is the equivalent (rigid-plastic) bond strength at the fibre-to-matrix interface, $\alpha_0$ is the orientation factor and $\alpha_1$ is the efficiency factor. Considering that $l_f$ and $d_f$ are known, it is shown that the fibre content $V_f$ and the orientation factor $\alpha_0$ can be estimated from NDT measurements of the relative magnetic permeability of the UHPFRC layer along two orthogonal directions [1]. For a given fibre mix, this requires a previous calibration stage using the results obtained through image analysis of selected specimens. The efficiency factor $\alpha_1$ is assumed to depend on the fibre orientation distribution and is shown to be correlated with $\alpha_0$. The equivalent bond strength $\tau_f$ corresponding to the selected fibre mix and cementitious matrix can be determined from laboratory tests on UHPFRC specimens with varying fibre contents and fibre orientations. It is noted that, being $\tau_f$ the remaining unknown, eq. (1) represents a line passing through the origin ($y=a\cdot x$). Therefore, the estimate of $\tau_f$ is improved if the range of fibre content and fibre orientations of the test specimens is sufficiently large.

An experimental campaign was developed for illustrating the proposed procedure involving the production of 25mm thick UHPFRC plates with fibre contents of 1.5 and 3%, with or without pronounced fibre orientation. This was achieved using a new strategy to align the fibres in UHPFRC which relies on the application of an external magnetic field during casting. The tensile response of the specimens was obtained using the DEWS test [2]. The methodology is applied for predicting the behaviour of a slab strip reinforced with an UHPFRC layer.

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# Strain Localization Analysis of an Elastic-Plastic Model for High Performance Fiber Reinforced Cementitious Composite

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## ABSTRACT

Concrete is presently the most widely used construction material in civil engineering. Although it is a very appealing material, primarily due to its low cost to strength ratio, it also exhibits a limited tensile strain capacity. Short discontinuous fibers have been added to concrete, thus forming a fiber reinforced concrete (FRC), with the aim of improving its performance under tensile stress. Furthermore, when proper fiber geometry and enhanced bond properties between the fibers and matrix are combined within a specifically tailored cementitious matrix, a strain hardening behavior that turns traditionally brittle into a very ductile material can be achieved. This type of material is known as High Performance Fiber Reinforced Cementitious Composite (HPFRCC).

In spite of an upsurge in the related research activities in the past 15 years, most of which has been of an experimental nature, HPFRCC has not yet found its way into the engineering practice. One of the main reasons for this is a lack of adequate numerical models, which would allow engineers to incorporate HPFRCC structural elements into their design. To this end, the main goal of this study was to develop and implement a combined analytical-numerical algorithm that can capture a stress-strain response and onset of strain localization in elastic-plastic fiber-reinforced pressure sensitive materials. This enables the capture of the inception of strain localization. Multi-directional fibers are embedded into a matrix and modeled as a linear elastic material, while the matrix is described by Drucker-Prager hardening plasticity model. The corresponding macroscopic tangent stiffness moduli tensor of the fiber reinforced composite is derived by consistently homogenizing the contribution of fibers in a representative volume element (RVE). Furthermore, a diagnostic strain localization analysis was conducted. Several actual uniaxial tension tests on non-reinforced cementitious composite as well as on the high performance fiber reinforced cementitious composite (HPFRCC) were modelled. It was found that the presence of fibers delayed the inception of strain localization in all uniaxial tension tests on the HPFRCC, thus increasing its ductility and tensile strain capacity. On the other hand, the inception of strain localization coincided with the onset of yielding in the non-reinforced cementitious composite, thus resulting in the extremely brittle response. Both findings correspond closely to the experimentally observed response, which exhibits much more ductile behavior in the presence of fibers.

# Influence of Field-Cast Tensile and Test Methods on Simulated Reinforced HPFRCC Component Behavior

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## ABSTRACT

Research efforts have recently been made to simulate the performance of reinforced high-performance fiber-reinforced cement composites (HPFRCCs) at high levels of deformation. Although constitutive models for HPFRCCs have been developed, selecting appropriate mechanical properties of HPFRCCs in simulations remains a critical aspect to predicting component response in large-scale structures. Additionally, fiber orientation and specimen size are known to significantly impact the tensile and flexural response of HPFRCCs. This paper investigates the simulated performance of reinforced HPFRCC components using tensile properties obtained through various testing and casting methods which result in different fiber orientation. An emphasis is placed on predicting reinforced HPFRCC performance at high levels of deformation, and specifically reinforcement fracture, using total-strain based material models. Recommendations are made for selecting appropriate test-methods and casting-methods for characterization specimens that can improve simulated performance of reinforced HPFRCC components.

# Multi-physics Corrosion Modeling and Sustainability Assessment of Steel Reinforced High Performance Fiber Reinforced Cementitious Composites

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## ABSTRACT

High-Performance Fiber-Reinforced Cement Composites (HPFRCCs) have been designed to exhibit superior ductility over traditional concrete materials through the formation of multiple cracks. When reinforced with steel, HPFRCC members have been proposed for enhanced seismic resistance in structural applications and enhanced durability in harsh natural environments.

Numerous researchers have studied the role that fine, closely spaced, multiple cracks have on the initiation and propagation of steel reinforcement corrosion. Recent studies examine, for example, corrosion of steel reinforced HPFRCC bending members [1] or mechanical performance of corroded reinforced concrete members that have repaired using HPFRCC [2]. However, there remains a gap in the ability to fundamentally model the role that HPFRCC crack formation has on regulating corrosion initiation and propagation phenomena.

Using a newly developed multi-physics transport, corrosion, and cracking model, which models these phenomena as a coupled physiochemical processes [3], the role of HPFRCC crack control and formation in regulating steel reinforcement corrosion was investigated. This model describes transport of water and chemical species, the electric potential distribution in the HPFRCC, the electrochemical propagation of steel corrosion, and the formation of microcracks in the HPFRCC material. Numerical results show that the reduction in anode and cathode size on the reinforcing steel surface, due to multiple crack formation and widespread depassivation, closely match experimental results of HPFRCC steel corrosion studies found in the literature. Such results provide a strong indication of the fundamental mechanisms by which steel reinforced HPFRCC materials are more durable than traditional reinforced concrete. Finally, these results are extended to provide greater insight into the assessment and design of more sustainable steel reinforced HPFRCC structures.

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# Experimental Approach to Evaluation of Fiber Contribution in FRC

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## ABSTRACT

Short fibers such as steel, PVA, PP and PE can contributes the increasing of not only tensile capacity but also shear capacity in Fiber Reinforced Concrete (FRC). There are many design guideline for FRC to consider the fiber contribution in the world. At a crack surface in FRC subjected to shear load, short fibers and interlocking of aggregate (sometimes steel reinforcement) resist shear deformation. For reasonable design, exact fiber contribution should be evaluate experimentally. In this paper, fiber contribution was extracted experimentally by using melting method. In the experiment, FRC with PP fiber was used, and bending or shear crack was induced in the specimens. After that, cracked specimens were exposed in high temperature over 500 degree, and only PP fiber bridging a crack was melted. It was clarified that the evaluated fiber contribution through this manner was much higher than that of ordinary design code.

# Fracture and Size Effect on Fibre Reinforced Self Compacting Concrete Using Digital Image Correlation

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**ABSTRACT**

The size effect and fracture behavior of plain and fiber-reinforced concrete was investigated. Geometrically similar beam specimens of different sizes with (steel fibers and glass fibers) and without fibers were tested under three-point bending in a closed loop servo-controlled machine with crack mouth opening displacement control with a rate of opening of 0.0005 mm/sec. The fracture properties such as, fracture energy (Gf) and brittleness number were determined. Digital images were captured before loading (unreformed state) and at different instances of loading and were analyzed using correlation techniques to compute the load-point displacement, crack length, crack opening and crack tip location. It was seen that the crack mouth opening displacement (CMOD) and vertical load-point displacement computed using DIC analysis matches well with those measured experimentally. It also concluded that addition of fibers in specimens, increased energy absorption capacity tremendously in all size of specimens. It was observed that addition of fibers in concrete, brittleness number is decreased, hence the concrete becomes ductile. It was observed that the specimens follow the Bazant's size effect law which shows that the structure becomes brittle with increase in size.

# Numerical Modelling of a complex UHPFRC Structure by a Micromechanics FEM Model taking into Account two Different Casting Methods

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**ABSTRACT**

Ultra High Performance Fibre Reinforced Concrete (UHPFRC) structures are emerging in several engineering applications as their outstanding tensile strength and ductility allow engineers to develop new structural concepts and overcome construction limits. This paper focuses on the structural modelling of a triangular UHPFRC thin slab reinforced with a steel bar into two external ribs by the means of a new fracture micromechanics Finite Element model.

According to the UHPFRC fibres ratio ($v_f$ =1% or 2%), the specimens are cast by two procedures orienting fibres in 1D or 2D direction. The consequences on the structural behaviour are simulated by taking into account the real orientation of fibres. The numerical model was developed to describe the fibre pullout and the matrix cracking mechanism within a smeared rotating crack framework. We statistically average the orientation of fibres by calibrating the model parameters on the stress-strain relationship extracted from four points bending tests themselves extracted from the specimens. The numerical model has shown the capacity to grasp the specimens' behaviour under central and four point bending loads.

# A Comparison of Reinforced Concrete and Reinforced HPFRCC Beam Response to Various Cyclic Deformation Histories

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## ABSTRACT

High-Performance Fiber-Reinforced Cement Composites (HPFRCCs) have been designed to exhibit superior tensile strength and ductility over traditional concrete. HPFRCCs have also shown improved damage tolerance in compression. When reinforced with steel, HPFRCC components have been proposed for enhanced seismic resistance in structural applications.

Because of the uncertainty associated with ground motions, determining an appropriate cyclic deformation history for seismic design is a challenge. Different cyclic deformation histories have resulted in different cracking patterns in previous HPFRCC component tests. Several different cyclic loading protocols have been used in previous studies, but the deformation history itself has not been treated as a test variable when comparing the behavior of reinforced concrete to reinforced HPFRCC components.

A series consisting of both reinforced concrete and reinforced HPFRCC beams are being tested under several different cyclic loading protocols. Cracking patterns, hysteresis behavior, and strain in the steel reinforcement are monitored through failure. The reinforced HPFRCC beams have responded differently to varying deformation histories than the reinforced concrete beams. To date, the reinforced HPFRCC specimens have shown equal or greater ultimate drift capacity than the nominally identical reinforced concrete specimen subjected to the same deformation history. Results from this study will contribute to a better understanding of reinforced HPFRCC component behavior under various cyclic deformation histories.

# Effect of Cracking and Fracture on the Electromechanical Response of HPFRCC

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## ABSTRACT

High-performance fiber-reinforced cement-based composites (HPFRCC) feature multiple steady-state cracking before localized fracture occurs. This process depends on a variety of factors, such as the flaw distribution in the material, matrix toughness, crack bridging spring law and fiber/matrix interfacial properties. The cracking and fracture process in HPFRCC not only dictates its mechanical behaviour, but also strongly affects its electrical response [1,2]. Understanding such effect on the electromechanical response of HPFRCC will offer fundamental tools to design new multifunctional HPFRCC intentionally encoded with strain and damage self-sensing functionalities.

This paper studies how the complex impedance and piezoresistive behaviour of HPFRCC can be influenced by crack type (i.e. Griffith crack vs. steady-state crack), crack width, and crack pattern (i.e multiple cracking process). This is achieved through coupling mechanical characterization with four-probe electrical impedance spectroscopy. The experimental results lead to the development of a new equivalent electrical circuit model for simulating changes in the electrical properties of the HPFRCC material system due to cracking and fracture. New design concepts to enhance the electromechanical response of HPFRCC for damage self-sensing are also presented.

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# Session MS08: Fracture Mechanics and Earthquake Engineering

# 9th International Conference on Fracture Mechanics of Concrete and Concrete Structures – FraMCoS-9

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## ABSTRACT

In this paper is presented the PARC_CL fixed crack model (implemented in the user subroutine UMAT.for in Abaqus Code), applied to the non-linear finite element analyses (NLFEA) of reinforced concrete (RC) shear wall panels tested, by means of pseudo dynamic test (PSD), at the European Laboratory for Structural Assessment (ELSA, Joint Research Centre) within the project SAFE [1[4]. These experimental tests are included as part of CASH, which is an international benchmarking program organised under an initiative of the OEDC-NEA (Nuclear Energy Agency). The main objective of CASH is to evaluate the reliability of predictive analysis tools and methods as well engineering practice know how to assess the seismic capacity of reinforced concrete shear walls to withstand strong earthquakes considered for beyond design situation.

The PARC_CL crack model is the extension to cyclic load of the previous PARC model [5], which could be applied only to monotonic load. The PARC_CL model is based on a total strain fixed crack approach, in which at each integration point two reference systems are defined: the local x,y coordinate system and the 1,2 coordinate system along the principal stress axes. The concrete and steel behaviors as well as their interaction effects are modeled with constitutive relationships for loading-unloading-reloading conditions.

The shear walls tested at the ELSA have been used to validate the proposed PARC_CL crack model; the shear walls have been modeled using multi-layered shell elements and NLFEA have been carried out considering several loading condition (static pushover, cyclic and dynamic). Furthermore, in order to evaluate the sensitivity of results to mesh discretization several analyses have been carried out adopting different element size.

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# Evaluation of Shear Strength Degradation of RC Column Subjected to Cyclic Loading

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## ABSTRACT

When subjected to cyclic loading, a reinforced concrete (RC) member often suffers shear failure after flexural yielding of tension reinforcing bars (called as shear failure after flexural yielding in this study) at a small deformation ductility, although it ordinarily suffers flexural failure and shows good deformation ability under monotonic loading. The reason of shear failure after flexural yielding is usually explained as that the shear strength degrades with increasing number of load cycles until it is reduced to less than the flexural strength [1]. Hence, it is of significance to quantitatively evaluate degraded shear strengths after each load cycle for seismic deformation-based design.

However, the degraded shear strengths of a RC member, which are ordinarily larger than the flexural strength in initial loading stage, cannot be investigated by test load hysteresis loop as it can only relect the flexural strength.

Thus, the purpose of this study is to propose a numerical method to quantitatively evaluate shear strength degradation of RC member utilizing three dimensional rigid-body-spring-model (3-D RBSM). We simulated the behaviors of a RC column subjected to cyclic loading and repeated loading on one side by 3-D RBSM, and further proposed the numerical method to quantitatively evaluate the behaviors of shear strength degradations [4].

As a consequence, the different degradation rate of shear strength between cyclic loading and repeated loading on one side was clarified, and the reasonability of the numerical method was proved by comparing numerical shear strength degradation curve with previously proposed degradation curves for seismic design concluded by test results [1, 2, 3].

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# New Double-K Criterion for Crack Propagation in Quasi-Brittle Fracture under Moderate Dynamic Loading: Theoretical Investigations

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**ABSTRACT**

The fracture mechanical properties under moderate dynamic loading are essential to the seismic behaviour of quasi-brittle materials like concrete. In order to predict and evaluate the crack propagation in the seismic loading range, a new double-K criterion taking account the strain-rate influences is proposed. Based on the linear asymptotic superposition assumption and dynamic fracture mechanics, a relationship between the nonlinear P-CMOD curve and the critical effective crack length is analytically established. By adopting the Hordijk-Reinhart expression as the softening traction-separation law, an analytical solution of the moderate dynamic cohesive force is obtained. Finally, formulae of dynamic fracture mechanics and asymptotic superposition are employed to determine the dynamic double-K fracture parameters such as the dynamic initial cracking toughness $K_{\mathrm{Id}}^{\mathrm{ini}}$ and the dynamic unstable fracture toughness $K_{\mathrm{Id}}^{\mathrm{un}}$. It's worth noting that the new double-K criterion reduces to the conventional double-K criterion when the loading rate approaches to static condition. The new double-K criterion is available for cracks propagating at either a constant velocity or an arbitrary velocity.

# Fracture Energy-based Full-Process Crack Width Prediction in Nonlinear Numerical Analysis of RC Structural members

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## ABSTRACT

It is challenging to give a full-process crack width prediction of an entire reinforced concrete (RC) structure subjected to time-history loading, despite a considerable number of formulas for predicting the crack width in a single RC member at a specific service limit state.

The cracking of the concrete in reinforced concrete (RC) members under tension is different from the cracking of the plain concrete because the RC member has a series of distributed cracks whereas the plain concrete has only one crack. This difference is caused by the well-known *tension-stiffening effect*. But the fracture of the concrete in RC members at each crack is close to the fracture of the plain concrete. This similarity is due to the *tension-softening effect*. Meanwhile, the slip and splitting failure between rebar and concrete in RC members are rarely taken account of in previous studies on RC crack width predictions. Therefore, thoroughly addressing the tension-stiffening effect, tension-softening effect, and slip & splitting failure of RC members is essential to give a reliable full-process crack width prediction of RC structures.

This paper focuses on the full-process crack width prediction in nonlinear numerical analysis of RC structural members, serving as a fundament of the full-process crack width prediction of an entire RC structure. A fracture energy-based $\beta$-ellipse model is introduced. In the $\beta$-ellipse model, an average stress-strain formulation is utilized to account for the tension-stiffening effect, an ellipse profile is used to mimic the tension-softening effect based on the fracture energy, a spatially local average parameter b is geared for modelling the slip & splitting failure. A specific fiber beam-column element is developed base on the $\beta$-ellipse model, realizing the full-process crack width prediction in nonlinear numerical analysis of RC structural members. The developed fiber beam-column element is extensively verified against various tests in the literature. It is shown that the developed fiber beam-column element offers a reliable and efficient approach for the full-process crack width prediction in nonlinear FEA of RC structural members.

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# Prediction of cracking in RC walls under cyclic loadings by means of a new homogenized global constitutive model

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## ABSTRACT

In Reinforced Concrete (RC) structures, cracking is often a critical design parameter since engineering design codes limit the maximum crack opening to preserve the durability, tightness and aesthetics of RC buildings; robust and reliable crack opening computation methods are therefore necessary. For the case of large RC buildings (in particular for nuclear power plants), and especially for the case of cyclic (seismic) loadings, computational demanding Finite Element (FE) calculations are needed and so overall modeling is used.

In this article, we propose to calculate the crack opening by means of a novel global (stress-resultant) nonlinear constitutive model for RC plates that incorporates crack opening as an internal variable. By means of an analytical homogenization and suitable physical hypotheses, four different local nonlinear phenomena are taken into account in the global model formulation [1]: (i) concrete cracking in two different crack directions and permitting both normal and tangential relative crack displacements; (ii) concrete stiffness reduction modeled by a scalar damage variable; (iii) steel-concrete slip and interface bond stresses, which are at the origin of the tension stiffening effect; and (iv) steel yielding localized at the cracks. The model is able to reproduce the behavior of RC plates submitted to in and out plane cyclic solicitations.

Validation is provided by comparison with several experimental tests on RC structural elements, accounting for a large range of solicitations. Results show a good agreement both at global (force-displacement curves) and local (crack opening) levels.

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# Effect of Loading Rate on the Fracture Behaviour of Steel and Polymer Fibre Reinforced Concrete

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## ABSTRACT

The behaviour of construction materials is greatly influenced by the effect of loading rate. Fibre reinforced concrete (FRC) is used in applications such as tunnel lining, pavements, bridge deck overlays and floor slabs, where the loads are sustained as well as applied over short durations (Abd el Aty, 2013). In this context, effect of loading rate, in the quasi-static range, on the flexural properties of FRC are discussed. The three-point bending test of a notched beam is used to determine the post-peak flexural response of the material at loading rates covering 4 orders of magnitude (Bernad et al., 2002). Two types of fibres are investigated namely, hooked ended steel fibres and polypropylene fibres. The experimental results reveal that the flexural toughness decreases with a decrease in loading rate, as expected (Naaman and Gopalaratnam, 1983; Bazant and Gettu, 1992; Zhang et al., 2014). Stress-crack opening relations are obtained from inverse analysis using the experimental load-crack mouth opening displacement curves (following Sousa and Gettu, 2006) and using the optimization algorithm of Raphael & Smith (2003). The variation in the σ-w curves with loading rate and fibre type are discussed. Finally, the implications of the results for applications such as floors, pavements and tunnel linings are presented.

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# Session MS09: Fracture and Self Healing

# Effect of different types of polymeric microcapsules on the self-healing efficiency of cement based composites

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**ABSTRACT**

Several different healing agents and mechanisms have been put forward for use in autonomous healing of small cracks in cementitious composites. While the existing research on this topic focuses mainly on the use of polymeric materials as encapsulated healing agents, this study aims at assessing the efficiency of inorganic silica precursors as potential healing materials. This work investigates the effect on self-healing of different types of polymeric microcapsules containing silica precursors.

For this purpose the microcapsules investigated had three different types of polymeric shells: crosslinked gelatin, poly-urea and polyurethane. In addition, two different types of cargo materials were investigated: sodium silicate (in liquid and powder form) and colloidal silica (in liquid form). The microcapsules were used in mortar mixes as moderate volume fraction addition, 4% and 8%, with respect to cement. The effect of the addition of the microcapsules on the compressive strength was obtained by performing test on standard cube specimens. To study self-healing three-point loading tests were performed on cracked, healed specimens, coupled with acquisition of microscopic images and capillary absorption tests. The healing products were isolated and characterised through SEM, FTIR and XRD.

The results show that polymeric microcapsules containing inorganic silica precursors can be a very promising solution for the development of self-healing cement based materials. Their incorporation in the mix reduces somewhat the compressive strength of the material but this is being compensated by the observed healing of the formed cracks.

# Investigation of Self-healing by Using Ethyl Cellulose Encapsulated Bacterium in Cementitious Materials

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## ABSTRACT

A new approach to microcapsule based microbial self-healing system is presented that aims to heal the crack in cementitious materials. In this work, ethyl cellulose (EC) was designed to fabricate microcapsule as a protection strategy to encapsulate an alkaliphilic spore-forming bacterium. The technical feasibility of encapsulated spores and the influence factors were studied by calcium precipitation activity (CPA) of the bacterium. The CPA of broken/unbroken microcapsules was evaluated. The micro-morphology of the precipitation produced by the bacterium was investigated through Environmental Scanning Electron Microscopy (ESEM), X-ray Diffraction (XRD) and X-ray energy dispersive spectroscopy (EDS). X-ray Computed Tomography (XCT) was applied to trace the crack development and self-healing behavior of encapsulated mineralization bacterium in cement paste specimens in three dimensions.

The experimental results showed that compared with unbroken microcapsules, higher CPA was achieved by breaking the microcapsule to release the bacterium, suggesting good protection for the encapsulated spores. Subsequent production of calcium carbonate confirmed by ESEM and EDS indicated activation of encapsulated mineralization bacterium. The XCT results showed that formation of crack successfully triggered the breakage of embedded microcapsules. Compared with the specimens without embedded bacterium, the healed crack area of specimens embedded with bacterial microcapsules was monitored, suggesting effective self healing of concrete crack can be achieved by introducing encapsulated mineralization microorganisms into concrete structures.

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# Requirements to Ensure the Crack Sealing Performance of Bacteria-Based Self-Healing Concrete

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**ABSTRACT**

Self-healing concrete has been the subject of great scientific interest over the last ten years. Various research groups worldwide have been working on different healing agent concepts, with bacteria-based healing agents being one of the most popular.

Bacteria spores together with organic mineral compounds are immobilized and protected in capsules, in order to survive the mixing process and be released upon cracking. Once a crack is created the bacterial spores turn from a dormant to an active state and start to metabolize the organic compounds found in the capsules. For the current study, porous expanded clay particles were used as protecting capsules and calcium lactate as organic mineral compound. The bacterial metabolic activity results in the production of calcium carbonate crystals. These formations are able to bridge the open crack and protect the concrete from the ingress of harmful gasses and liquids.

Many studies have proven the enhanced healing performance of bacteria-based self-healing cementitious materials in comparison to the ordinary ones. However, they do not explicitly designate which conditions should be satisfied in order to verify the functionality of an embedded healing agent. This study presents three requirements needed to ensure the performance of a bacteria-based healing agent, namely the reduced crack permeability, the presence of mineral formation and the evidence of bacterial activity. The requirements are studied on mortar prismatic specimens through: i) crack permeability tests via water flow on cracked samples, ii) oxygen concentration measurements on samples immersed in water and iii) microscopic observations on crystals found inside the cracks.

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# INFLUENCE OF SUPERABSORBENT POLYMER PARTICLES ON THE SELF-HEALING BEHAVIOR OF ENGINEERED CEMENTITIOUS COMPOSITES

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**Keywords:** Engineered Cementitious Composites; PVA fiber; Self-healing; Superabsorbent polymer; Mechanical properties

**Abstract:** Self-healing behavior of engineered cementitious composites (ECC) with superabsorbent polymers (SAPs) was investigated in this paper. Four point bending tests were used to precrack ECC specimens at the age of 7 and 28 days, respectively. The precracked samples were then cured in 99%RH curing and 99%RH/room air cycle curing to promote the occurrence of self-healing behavior and in room air curing for control. The addition of SAPs help tighten the crack width, resulting in enhanced flexural stiffness for the 99%RH cured and 99%RH/room air cycle cured samples. Furthermore, the effect of SAPs also promotes a larger degree recovery of deformation capacity, despite of much lower the initial deformation capacity for ECC2. The self-healed samples were observed by environment scanning electron microscope (ESEM) to reveal the products of self-healing behavior.

# Influence of fly ash type on mechanical properties and self-healing behavior of Engineered Cementitious Composite (ECC)

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## ABSTRACT

This paper aims to clarify the influence of different types of fly ash on the mechanical properties and self-healing behavior of Engineered Cementitious Composite (ECC). Five types of fly ash with different chemical and physical properties were used to produce ECC mixtures. The fly ash to cement ratio was fixed at 3.0. The compressive and uniaxial tensile tests were conducted to evaluate the influence of fly ash type on mechanical properties. The permeability test was used to assess self-healing behavior of ECC with different types of fly ash. Chemical characteristics of the self-healing products in the cracks were examined by environment scanning electron microscope (ESEM) and energy dispersive X-ray spectroscopy (EDS). The fly ash with relatively higher calcium content and smaller particle size were found conducive to a higher first cracking strength. The lower combined $Al_2O_3$ and CaO content of this fly ash, however, was found to enhance the tensile strain capacity. Furthermore, high calcium fly ash accelerates the self-healing process of ECC for the same pre-damaged level. The self-healing product was a mixed C-S-H/$CaCO_3$ system with the $CaCO_3$ as the main ingredient.

# Feasibility Study on ECC Fatigue Life Extension through Self-Healing

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## ABSTRACT

The failure of concrete infrastructures subject to repeated loading, such as bridge deck, road surface, and railway sleepers, is a result of fatigue-induced material degradation. For these infrastructures, the progressive crack propagation of concrete under fatigue loading defines the service life. The self-healing of cracks has been engaged in engineered cementitious composites (ECC), a unique group of fiber-reinforced cement-based composites that emerges to replace conventional concrete. Current study investigated the feasibility of decelerating the fatigue-induced crack propagation and extending the fatigue life of ECC by taking the advantage of self-healing. ECC prism specimens made of locally available ingredients were pre-cracked by flexural fatigue loading of different load cycles; the specimens were conditioned under wet-dry cycles for self-healing; the self-healing efficiency was evaluated by the crack width reduction and fatigue life extension, compared to the control group without self-healing. The results indicate that self-healing can extend ECC fatigue life. The degree of crack width reduction and fatigue life extension decreased with the increasing material damage level, or the number of fatigue load cycles experienced before healing.

# Self Healing of Cement Based Materials: Fiver Years of Experience at Politecnico di Milano

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## ABSTRACT

Worldwide increasing consciousness for sustainable use of natural resources has made “overcoming the apparent contradictory requirements of low cost and high performance a challenging task” as well as a major concern. The importance of sustainability as a requisite which has to inform structure concept and design has been also recently highlighted in Model Code 2010. In this context, the availability of self-healing technologies, by controlling and repairing “early-stage cracks in concrete structures, where possible”, could, on the one, hand prevent “permeation of driving factors for deterioration”, thus extending the structure service life, and, on the other hand, even provide partial recovery of engineering properties relevant to the application

The author’s research group has undertaken a comprehensive research project, focusing on both experimental characterization and numerical predictive modelling of the self healing capacity of a broad category of cementitious composites, ranging from normal strength concrete to high performance cementitious composites reinforced with different kinds of industrial (steel) and natural fibres. Both autogenous healing capacity has been considered and self-healing engineered techniques, including the use of presaturated natural fibres as well as of tailored admixtures.

Tailored methodologies have been employed to characterize the healing capacity of the different investigated cement based materials. These methodologies are based on comparative evaluation of the mechanical performance measured through 3- or 4- point bending tests. Tests have been performed to pre-crack the specimens to target values of crack opening, and after scheduled conditioning times to selected exposure conditions, ranging from water immersion to wet and dry cycles to exposure to humid and dry climates.

The healing capacity has been quantified by means of the definition and calculation of suitably defined “healing indices”, based on the recovery of the load bearing capacity, stiffness, ductility, toughness etc. and correlated to the amount of crack closure, measured by means of optical microscopy and also “estimated” through suitable indirect methodology. As a further step a predictive modelling approach, based on modified microplane model, has been formulated. The approach incorporates the self-healing effects, in particular, the delayed cement hydration, as well as the effects of cracking on the diffusivity and the opposite repairing effect of the self-healing on the microplane model constitutive laws.

The whole experimental and numerical investigation represents a comprehensive and solid step towards the reliable and consistent incorpoation of self healing concepts and effects into a durability-based design framework for engineering applications made of or retrofitted with self healing concrete and cementitious composites.

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# Effect of Post-Fire Curing on the Residual Mechanical Properties of Fire-Damaged Self-Compacting Concrete

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## ABSTRACT

Concrete is recognized for being a fire-resistant construction material. At elevated temperatures concrete can, however, undergo considerable damage such as strength degradation, cracking, and explosive spalling. In recent decades, reuse of fire-damaged concrete structures by means of developing techniques to repair the degraded material has gained interest amongst researchers. Autogenic self-healing methods such as re-curing in water has proven to partly restore the strength of concrete. The extent of restoration is dependent upon various parameters such as concrete type, exposure temperature, and post-fire curing conditions for example.

The use of self-compacting/consolidating concrete (SCC) has become common in the construction industry due to its high workability and low permeability. This paper presents the results of an experimental study aimed at investigating the improved mechanical properties of high temperature exposed SCC concrete by the autogenic self-healing phenomenon resulting from water re-curing. The residual mechanical properties including strength, modulus of elasticity and ultimate strain of the material upon application of different post-fire curing regimes are presented herein with special emphasis on the effect of thermal profile including exposure time, temperature and cooling rate. Moreover, pertinent microstructure alterations and healing of micro-cracks are investigated using X-ray tomography.

The experimental results confirm that the recovery of material properties in fire-damaged SCC concrete is contingent on the post-fire water curing conditions.

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## Challenges of Self-healing Concrete Scale-up and Site Trials.

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### ABSTRACT

The Materials for Life (M4L) project, funded by EPSRC, is a collaboration of three UK universities investigating interdisciplinary techniques for self-healing of cementitious materials. These include encapsulation of healing agents lead by Cambridge University, bacterial healing by Bath University, development of vascular flow networks and shape memory polymer (SMP) based system for crack closure in concrete by Cardiff University [1,2,3,4]. These techniques have been tested in a laboratory environment on relatively small scale specimens, from which it was observed that their combined effect produced a greater strength recovery than any one of the individual self-healing systems alone [5]. The current work of the project is concerned with the scale-up of the techniques and their implementation and evaluation in site trials.

Full-scale concrete structures, comprising wall panels that incorporate different combinations of the developed self-healing systems, have been built by Costain, an industrial partner of the project. These wall panels are loaded to induce cracks and then the recovery of the structural and durability parameters of the concrete are monitored over time. An overview of the M4L site trial setup with a particular focus on the challenges of the scale-up of SMP system in combination with flow networks for applications in concrete structures in site environment is discussed.

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# Micromechanical modelling of self-healing cementitious materials

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## ABSTRACT

A number of numerical models have been developed for simulating self-healing behaviour, these include models based on hydration [1], mechanical damage at the macro-scale [2] and coupling hydro-chemo-mechanical processes [3,4] . This paper describes a new model for simulating self-healing behaviour in cementitious materials by using a 3D two phase micro-mechanical constitutive formulation. The composite is modelled using a Mori-Tanaka homogenisation scheme and the stress concentrations, adjacent to inclusions, are included using an exterior point Eshelby solution. Anisotropic micro-cracking is simulated using arrays of circular cracks [5,6]. This model incorporates self-healing by using a new solidification formulation. Self-healing is measured using the recovery of mechanical properties of the micro-cracked material [8]. The focus of this paper is on how the different model parameters control the predicted response. The initiation and subsequent evolution of micro-cracks in both the original and healed materials are simulated alongside the healing processes. The performance of the 3D micromechanical self-healing model is illustrated using a series of stress-strain paths that involve damage and healing cycles. A series of model validations employ data from a recent test series undertaken at Cardiff University [7] as well as data from tests undertaken by others [3]. The examples and validations show that this micro-mechanical self-healing model is capable of representing the characteristic mechanical response of self-healing cementitious materials.

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# Characterization of a rehydration phenomenon on cement-based materials containing heat-induced cracks: coupled transport properties and X-ray micro-tomography

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ABSTRACT

This article is devoted to investigate the rehydration phenomenon on heat-induced macro/micro cracks of a normalized mortar and cement past, both with a W/C ratio of 0.5. It is testified by means of steady state gas (argon) and ethanol permeability, dedicated by our laboratory, coupled with thermo-gravimetry (ATG) and micro-tomography (CT) analysis. Prior to the above experiments, all samples are undergoing a successively heating-cooling cycle from 105 °C (reference state) up to 400 °C, 500 °C, 600 °C and 700 °C, accordingly. After this, on the macro-scale, transport properties are identified by gas permeability; and subsequent, for the same sample, by the test ethanol permeability (after the saturation in demineralized water and then drying at 105 °C). On the micro-scale, the pore network of heat-treated cement pastes (before and after saturating in demineralized water) are characterized by CT (voxel≈4μm), which assesses the 3D profile of the pore network, including quantitative analysis of the crack size, connected and non-connected pore volume, pore surface, as well as their distributions. In conjunction with the mineralogical composition results by ATG, the self-healing capacity of saturated heat-treated cement-based materials is obvious.

Results show that, gas permeability varies from $10^{-16}$ to $10^{-14}$ $m^2$ for mortars after heat-treated from 400 °C to 700 °C, respectively; while ethanol permeability is on the order of $10^{-16}$-$10^{-17} m^2$, which is nearly close to the value of intact gas permeability in 105 °C ($10^{-17}$ $m^2$) . This is mainly about the self-healing occurring in both the macro and micro heat-induced cracks when saturated in water; simultaneously, in the previous cycle of gas permeability, the increase of confining pressure also contributes to the part of irreversible closure of cracks in some extent. Finally, a good correlation between the results of ATG, CT and permeability (gas, ethanol) is founded, all of

# Session MS11: Dynamic Fracture of Concrete: Validation of Numerical Models

# Dynamic Fracture of Concrete: Mesh Sensitivity Study

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## ABSTRACT

In order to realistically simulate behaviour of concrete structures under dynamic loading, the numerical finite element analysis should account for the influence of high strain-rates on the mechanical properties of concrete. Moreover, the phenomena that are related with the hardening and softening of the material and the crack propagation (inertia effects) should also be properly accounted for. It is well known that without a proper regularisation scheme the local finite element analysis of softening materials leads to mesh dependent response. The results of the analysis should be as less as possible dependent on the choice of the finite element type and on the finite element discretization.

The main objective of the present contribution is to demonstrate that the regularization scheme based on the relatively simple energy approach (crack band method) employed in dynamic finite element fracture analysis is able to realistically predict response and failure mode for different sizes and types of finite elements. In the analysis as a constitutive law a rate sensitive microplane material model is used. In the model the concrete tensile behaviour is described through a bilinear stress-crack opening law [1], which is a function of four parameters: tensile strength ($f_t$), initial and total fracture energies ($G_f$ and $G_F$) and critical crack opening ($w_c$).

The mesh sensitivity using local crack band approach is validated based on the recently conducted experimental tests on concrete tensile specimen CTS [2]. The parametric study is carried out using three different finite element discretizations. For each discretization four and eight nodes 3D solid finite elements are employed. Static and dynamic analyses with different loading rates are carried out. It is demonstrated that the local constitutive low together with the crack band method is able to realistically replicate experimental evidence, i.e. the results are independent of the element size and type. Moreover, it is shown that for high loading (strain) rates the response history as well as branching phenomena is realistically predicted, regardless of the employed mesh size and element type.

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# Modeling dynamic fragmentation of concrete under high-rate loading

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**ABSTRACT**

Extreme high-rate loading conditions in structural materials trigger a complex process of fragmentation involving probabilistic, energetic and mechanical aspects. In this work we discuss a one-dimensional model based on [1] that captures the physics of dynamic fracture and fragmentation in concrete at strain rates from $10^2$ to $10^5$ /s, with particular interest in the higher strain rate values. In particular, the model considers a one-dimensional bar under a uniform tensile initial strain rate, with a stochastically varying strength. Initial results for the relationship between average fragment size and strain rate show good agreement with shock tube experiments on concrete panels. However, the predicted distribution of fragment size exhibits a smaller variance than that observed in the experiments. Future work will evaluate this difference in the results, which could be the result of the one-dimensionality of the model, heterogeneity of strain rate in the shock tube tests, experimental measurement errors, or a combination of all of these. Further investigations to extend the present model to other brittle materials like glass and concrete are also currently under development.

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# Dynamic Fracture of L and CT Concrete Specimens: Numerical and Experimental Studies

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## ABSTRACT

Recent numerical simulations performed on plain concrete specimens showed very interesting and complex fracture behavior of concrete under high loading rates. The simulations performed on compact tension (CT) specimen [1] highlighted the phenomenon of crack branching at high loading speeds, while the simulations on L-specimen [2] brought out the influence of loading rate on direction of crack propagation.

In order to confirm the findings of numerical studies and to obtain the experimental evidence on dynamic fracture of concrete, experiments were performed on both CT-specimen and L-specimen. The experiments confirmed the results of previously performed numerical predictions. The phenomenon of crack branching, as predicted by numerical studies, was reproduced experimentally for CT-specimen. The evaluation of test and numerical results show that for strain rates of approximately above 50/s, crack branching occurs. This phenomenon is related directly to the sudden and progressive increase of resistance and is controlled primarily by inertia.

For L-specimen, the experiments confirm the influence of loading rate on the direction of crack propagation as numerically predicted. For quasi-static load, the crack tends to propagate horizontally (perpendicular to the loading direction), while as the loading rate is increased, the crack propagation tends to get vertical. Similar to the CT specimen, for higher loading rates crack branching is also observed. The comparison between numerical and experimental results proves that relatively simple modeling approach based on continuum mechanics, rate dependent microplane model and standard finite elements is capable to realistically predict complex phenomena related to dynamic fracture of concrete and no special criterion is required to capture crack branching, change in crack propagation or progressive strength increase.

The presented, relatively simple, tests can be used to check whether the numerical model is able to realistically predict complex phenomena related to dynamic fracture of concrete.

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# Strain Rate Dependent Microplane Constitutive Model for Comminution of Concrete under Projectile Impact

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## ABSTRACT

The pulverization, fracturing and crushing of materials, briefly called comminution, creates numerous cracks which dissipate a large amount of kinetic energy during projectile impact. At high shear strain rates (10/s—$10^6$/s), this causes an apparent large increase of strength, called `dynamic overstress'. This long debated phenomenon has recently been explained by the theory of release of local kinetic energy of shear strain rate in finite size particles that are about to form [1-4]. The theory yields the particle size and the additional kinetic energy density that must be dissipated in finite element codes. In previous research, it was dissipated by additional viscosity, in a model partly analogous to turbulence theory. Here it is dissipated by scaling up the material strength [5]. Microplane model M7 is used and its stress-strain boundaries are scaled up by factors proportional to the - 4/3rd power of the effective deviatoric strain rate and to its time derivative. The crack band model with a random tetrahedral mesh is used and all the artificial damping is eliminated from the finite element program. The scaled model M7 is seen to predict the crater shapes and exit velocities of projectiles penetrating concrete walls as closely as the previous models. The choice of the finite strain threshold for element deletion, which can have a big effect, is also studied. It is proposed to use the highest threshold above which a further increase has a negligible effect.

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# SIMULATION OF DYNAMIC BEHAVIOR OF QUASI-BRITTLE MATERIALS WITH NEW RATE DEPENDENT DAMAGE MODEL

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**ABSTRACT** In concrete often complex fracture and fragmentation patterns develop when subjected to high straining loads. The proper simulation of the dynamic cracking process in concrete is crucial for good predictions of the residual bearing capacity of structures in the risk of being exposed to extraordinary events like explosions, high velocity impacts or earthquakes.

As it is well known, concrete is a highly rate dependent material. Experimental and numerical studies indicate that the evolution of damage is governed by complex phenomena taking place simultaneously at different material scales, i.e. micro, meso and macro-scales. Therefore, the constitutive law, and its rate dependency, must be adjusted to the level of representation. For a proper phenomenological (macroscopic) representation of the reality, the constitutive law has to explicitly describe all phenomena taking place at the lower material scales. Macro-scale inertia effects are implicitly simulated by the equation of motion.

In the current paper, dynamic crack propagation and branching is studied with a new rate-dependent stress-based nonlocal[1] damage model [2]. The definition of rate in the constitutive law is changed to account for the inherent meso-scale structural inertia effects. This is accomplished by a new concept of *effective rate* which governs the dynamic delayed response of the material to variations of the deformation (strain) rate, usually described as micro-inertia effects. The proposed model realistically simulates dynamic crack propagation and crack branching phenomena in concrete. The validation of the model is made against experimental results of a dynamic compact tension test [3].

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# Meshfree modelling of dynamic fracture in high-strength concrete

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## ABSTRACT

The present work is concerned with the meshfree modelling of dynamic fracture in concrete. The OTM (optimal transportation meshfree) approximation scheme[1] is chosen for its numerous advantages such as the exact mass transport, the satisfaction of the continuity equation, exact linear and angular momentum conservation in order to solve different problems as spurious modes, tensile instabilities and unknown convergence or stability properties. Since the deformation and velocity fields are interpolated from nodal values using max-ent shape functions, the Kronecker-delta property at the boundary makes it possible for the direct imposition of essential boundary conditions. Fracture is modelled through material-point erosion, i.e. each material point can be either intact, in which case its behaviour is elastic, or be completely failed—or eroded—and has no load bearing capacity. The crack set is approximated by means of eigen-deformations, which enable the material to develop displacement jumps at no cost of local elastic energy. The feasibility of such methodology has been demonstrated for brittle materials [2] and dynamic fragmentation of metals [3].

We endeavour to apply the aforementioned approach to simulate the dynamic fracture propagation in concrete loaded in a three-point bend configuration through a drop-weight impact device. The experimental campaign [4] was carried out for a high strength concrete loaded at displacement velocities ranged over six orders of magnitude. Both the concrete beam and the drop weight are explicitly modelled. An empirical strain-rate dependent energy release rate is fed to capture the observed peak load increase. Both the reaction and impact forces compare well with the experimental ones.

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# Calibration and Validation of Concrete Model for the Simulation of the Quasi-Static and Dynamic Response of Concrete Structures

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## Abstract

This research deals with the calibration and validation of the Lattice Discrete Particle Model (LDPM)[1] for the simulation of concrete failure behavior under quasi-static and dynamic loading conditions. LDPM is a mesoscale discrete model, which simulates concrete at the level of coarse aggregate pieces using realistic aggregate size distribution function. Vectorial constitutive equations simulating tensile fracturing with strain softening, cohesive and frictional shearing, and nonlinear compressive behavior with strain hardening are defined at the mesoscale to serve as the interaction between aggregate pieces through the embedding mortar. LDPM has shown strong abilities in reproducing concrete response in different experiments, such as tensile fracturing, confined and unconfined compression, torsion, and shear tests[2].

Different quasi-static experiments, such as three point bending, unconfined compression and confined compression tests, were performed at Politecnico di Milano. In addition, the HOPLAB in Ispra (Italy), facility recently developed some innovative equipment based on Hopkinson bar technique to carry out dynamic experiments on large-scale concrete samples. Different type of dynamic tests, such as unconfined compression, tensile splitting, three point bending test, and single notch specimen under tension, are performed. Both quasi-static and dynamic experiments are carried out on standard and dam concrete, which are essentially distinguished by the maximum aggregate size. Having access to broader range of experimental data leads to an efficient and accurate calibration of LDPM parameters. Size effect is also examined in the experiments through considering different sample sizes for each test.

In the current project, LDPM is calibrated and validated with reference to the provided experimental data. The LDPM set of parameters governing the mesoscale mechanical constitutive law as well as the rate dependence of concrete behavior are first calibrated by precisely fitting the results of the numerical simulations with the experimental data. Validation procedure is then carried out by illustrating an accurate match of the numerical results and the experimental data that are not utilized in the calibration process.

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# Simulation of Dynamic Fracture of Concrete with Damaged Viscoelasticity and Retarded Damage

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## ABSTRACT

Stress-strain relations and strength of concrete may be strongly affected by the strain-rate as is shown by many experiments. According to the current state of knowledge this is mainly caused by two physical mechanisms: (1) The movement of water in the different capillary systems of concrete leads to increased material resistance in case of high strain-rates due to viscous-like effects [1]. (2) Damage of concrete is connected to micro-cracking which cannot spread arbitrarily fast due to limited speed of wave propagation which occurs on macroscopic as well as on microscopic levels [2]. The contribution develops an extension of a standard isotropic damage material law with damaged viscoelasticity on one hand and retarded damage on the other hand to cover both effects [3]. The approach is fully triaxial and implemented as user-subroutine with the explicit LS-Dyna code.

It basically introduces two material parameters for viscosity and two further parameters for retarded damage in addition to the material parameters for quasi-static behaviour. These parameters are calibrated from dynamic strength increase factors for uniaxial behaviour as they are available from a number of experiments. A simulation of different types of Hopkinson-Bar experiments is performed using the material law and LS-Dyna. This includes the Split-Hopkinson-Pressure-Bar, the Hopkinson-Bar in a spallation configuration and a biaxial Split-Hopkinson bar. Simulation results are validated with the experimental data available from these set-ups.

It can be shown that the strain-rate effect as it is evident within these experiments cannot be explained with structural inertia and using the quasi-static damage law alone. It has to be completed with both damaged viscoelasticity and retarded damage in order to reproduce the experimental data in a satisfactory way. In contrast to experimental set-ups the numerical simulations yield complete fields of stress and strain depending on time. The computed results show, e.g., stresses, strains and strain rates highly varying in space and time. Computed stresses exceed the quasi-static strength to a large extent, but are maintained only for short periods. Such periods are generally followed by material failure of specimen. Furthermore, the material model allows for a computation of the internal energy dissipated during dynamic fracture. Corresponding computed values by far exceed the quasi-static crack energy.

First results regarding drop tests with hard impact of projectiles on plain concrete slabs shall be demonstrated and compared to experimental data.

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# Loading Rate Effect on the Fracture Behaviour of Three Different Steel Fibre-Reinforced Concretes

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## ABSTRACT

Three-point bending tests on notched beams of three types of steel fiber-reinforced concretes (SFRC) have been conducted using both a servo-hydraulic machine and a drop-weight impact instrument. These three different concretes had the same matrix, while various fiber contents and softening behaviours, i.e., 40 kg/m$^3$ Bekaert OL 13/0.20 (low fiber content), 40 kg/m$^3$ Bekaert OL 13/0.20 + 20 kg/m$^3$ Bekaert RC 80/30 BP (intermediate fiber content) and 40 kg/m$^3$ Bekaert OL 13/0.20 + 60 kg/m$^3$ Bekaert RC 80/30 BP (high fiber content), respectively. The shape and geometry of the specimen followed the RILEM recommendation but with a reducing factor 1.5. Namely, 100 mm × 100 mm in cross section, 450 mm in length, notch-depth ratio was around 1/6 and span was kept constant 333 mm.

The peak load and the fracture energy were measured over a wide range of loading rates (displacement rates), spanning six orders of magnitude. Under low loading rates, $2.2 \times 10^{-3}$ mm/s (Quasi-static) and $2.2 \times 10^{1}$ mm/s, the tests were performed with the servo-hydraulic machine; under high loading rates, $1.8 \times 10^{3}$ mm/s and $2.7 \times 10^{3}$ mm/s, the drop-weight impact machine was used instead.

The results show that the fracture energy and the peak load increase as the loading rate increases for these three materials. Besides, such a trend is relatively mild under low rates. The gain of the fracture energy and peak load is around 30% compared with its quasi-static values. However, under high rates the increases in the fracture energy and the peak load are pronounced due to more microcracking, the additional resistance to the micro cracks initiation and growth, and higher pull out energy absorbed between the fibers and the matrix. For the concrete with low fiber content, the dynamic increase factors of the peak load and the fracture energy are approximately 5 and 3, while for the concrete with high fiber content, they are around 3 and 2 respectively. That is, the higher the fiber content is, the less rate sensitivity gets.

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# Failure Behaviour of RC structures under Dynamic Loads with Intermediate and High Strain Rates

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## ABSTRACT

In this study, dynamic behaviour of reinforced concrete is simulated to account for the rate dependent features of concrete on mechanical properties and failure mode. The mechanical properties (strength, elasticity, and fracture energy) of concrete are increased with faster loading rate conditions. This characteristic is usually depicted as Dynamic Increase Factor (DIF) curve – the ratio of dynamic properties to static properties as a function of strain rate. Generally, The DIF curve has two regimes, and at the first regime, the DIF value is gradually increased as strain rate increased but, at the second regime, its value is rapidly increased near at the strain rate, 1 $s^{-1}$. This phenomena can be hypothetically explained by the Stefan effect for slower rates, related with the viscosity of free water within the nano-/micro-structures of concrete and the inertia effect for faster rates. And these explanations have been confirmed with related experimental results.

Herein, the three-dimensional dynamic Rigid-Body-Spring Network (RBSN) framework, based on the random lattice model, is simulated to understand the dynamic behaviour of reinforced concrete structures with different loading rates. For reinforcement, it is adopted the semi-discrete method, constructing reinforcement mesh independent of concrete mesh background, and the strengthening effect of reinforcement is represented by adjusting the spring stiffness of corresponding RBSN element by simple transformation rule.

The failure mode changes under different loading rate is studied through the beam-column joint types of structures by simulation. At the free end of the beam, the cyclic loadings with two different loading rates are loaded, and at the faster loading rate, the fewer and localized cracks are produced compared to the slower rate condition. From the simulation results, it is examined that the trend of failure mode changes under different loading rates can be described, and it is anticipated to use for understanding the various RC structures subjected to dynamic loadings such as earthquakes.

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# Session MS12: Probabilistic Aspects of Concrete Fracture

# Probabilistic aspects of high-dynamic compressive failure of cementitious materials

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## ABSTRACT

When subjecting cementitious materials to high-dynamic uniaxial compression, the ultimate load carrying capacity of tested specimens increases significantly with increasing loading rate. We here report on an engineering mechanics model which explains high-dynamic strengthening of cement pastes, mortars, and concretes under uniaxial compression [1,2]. The model explains that high dynamic strengthening is probabilistic in the sense that the first crack may nucleate at any position within the volume of the tested specimen, and that the actual position of crack nucleation is relevant for the achievable compressive strength of the specimen. In more detail, the model envisions that the total duration of a compression experiment consists of two characteristic parts: (i) the period of time required for load increase up to the level at which the first crack nucleates, and (ii) the period of time required for the first crack to propagate through the specimen. Crack nucleation is modeled by an elastic limit criterion. Crack propagation is considered to happen under mode I, in direction of uniaxial loading, at the speed of Rayleigh waves. The ultimate load is equal to the product of the elastic stress rate and the total test duration. The model does not include any fitting parameters. Still, model predictions agree qualitatively and quantitatively very satisfactorily with measured dynamic strength increase factors. This suggests that high-dynamic strengthening is a purely structural effect, depending on geometric properties of the tested specimen.

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# FE analyses of a coupled energetic-statistical size effect in plain concrete beams with varying material properties

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## ABSTRACT

A size effect in quasi-brittle materials such as concrete causes that both the nominal structural strength (the measure of the ultimate load expressed in stress units) and material brittleness decrease with increasing characteristic specimen size *D*. Thus, concrete becomes ductile on a small scale and perfectly brittle on a sufficiently large scale. This behaviour can be explained on the one hand by energetic (deterministic) phenomena caused by strain localization of a finite volume, depending on a characteristic length of microstructure $l_c$ [1]. On the other hand, a statistical effect may be found in a heterogeneous nature of concrete with randomly distributed material properties [2]. The first statistical theory of size effect has been introduced by Weibull [2] and assumes that a structure is as strong as its weakest component. However, the statistical size effect by Weibull ignores a spatial correlation between local material properties and an energetic (deterministic) size effect. As a result, the pure statistical theory of size effect by Weibull provides the unrealistically low nominal strength of small and medium specimens. The coupled energetic-statistical size effect theory has been given by Bazant [1] and describes the concrete nominal strength depending on *D* as a non-linear function approaching a plasticity limit for small sizes and Weibull asymptote for large sizes.

Our extensive numerical FE analyses of a coupled energetic-statistical size effect in unnotched concrete beams was focused on the effect of the simultaneously varying local uniaxial tensile strength $f_t$, fracture energy $G_f$ and elastic modulus *E*. The beams subjected to three-point bending were geometrically similar in 2 dimensions i.e. height and length. Four beams sizes were taken into account with the height varying from 80 mm up to 1920 mm. The fluctuation of local material parameters was defined by random fields described with a square exponential autocorrelation function and Gauss probability distribution function [3]. First, the FE calculations were performed with the spatially varying $f_t$ and uniformly distributed constant fracture energy $G_f$ and elastic modulus *E*. Thus the Irwin's characteristic length $l_{ch}=G_f{\times}E/f_t^2$ was random. Next, the tensile strength $f_t$ and fracture energy $G_f$ were assumed to be random. Finally, all three material parameters $f_t$, $G_f$ and *E* spatially varied. A positive and strong cross-correlation between $f_t$, $G_f$ and *E* was taken into account, i.e. all parameter increased simultaneously ($l_{ch}$ was constant). The numerical outcomes showed a strong coupled energetic-statistical size effect in concrete beams [3]. The uniaxial tensile strength $f_t$ turned out to be a crucial material parameter for the mean stochastic nominal strength. The effect of the spatially varying fracture energy $G_f$ and elastic modulus *E* was weaker on the mean nominal strength.

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# Implications of Spatial Variability Characterization in Discrete Particle Models

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**ABSTRACT**

Characterization of the inherent spatial variability of the mechanical properties of advanced composite materials as well as of standard concretes is among the primary concerns of the presented paper. In the context of discrete particle models the random field concept is frequently adopted in order to account for the fluctuations of material characteristics on scales independent of the geometrical characterization of the mesostructure as represented by particular particle configurations mimicking the aggregate placement. The specific goal of this paper is to introduce spatial variability into structural reliability by providing a sample reduction strategy for the discrete framework. Presented simulations of a classical experiment utilize the well-established Lattice Discrete Particle Model (LDPM) and demonstrate the general potential of the proposed strategy towards current state-of-the-art in stochastic mechanics and some relating open problems.

# Interplay of probabilistic and deterministic internal length in simulations of concrete fracture

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## ABSTRACT

Concrete is recognized as highly heterogeneous material. The macroscopic material response is influenced by the internal structure which can be reflected by an internal length scale. The internal length scale is dictated by the size of the mineral grains. Modelling of its fracture must include some information about this *characteristic length*. A convenient way is to use meso-scale models that contain information about the concrete internal structure directly. Despite the rich information about material mesostructure, the meso-scale models are incomplete unless they include also spatial variability in material properties that arise during the production process (mixing, drying, etc.) and service life. These spatial fluctuations are usually modelled via random fields. Though there are several sources of random fluctuations, it is considered here that all of them can be approximately described by a single random field. This random field has its own characteristic length referred to as the *correlation length*.

The interplay of these two characteristic lengths is studied. Simulations of three-point-bending beams (with and without notch) are calculated using discrete meso-scale model [1]. The simulations are performed repeatedly with randomly generated aggregate structure. Next, the simulations are further repeated several times with material parameters (related to local strength) fluctuating according to samples of a random field. The influence of additional variability due to the random field is studied with focus on the dependence of the peak load on the correlation length. Strong dependence of the mean value and standard deviation of the peak load on correlation length of the random field is reported.

In notched simulation, the average peak load is found to be independent of the correlation length. The reason for such insensitivity is that the crack is forced to propagate from one specific location (notch tip). However, the standard deviation decreases as the correlation length decreases. This is caused by averaging of the fluctuations within the fracture process zone. The shorter the correlation length, the more fluctuation is contained within the fracture process zone. These fluctuations get averaged which leads to lower dispersion of the peak load. Random fields with large correlation length can be seen as an additional source of variability that can be superposed onto variability due to the random meso-structure.

In unnotched models, the standard deviation follows the same trend. The mean value of strength in models with both, very low and very high correlation lengths of random field, is approximately equal to the one obtained with models without random field. However, there is a certain range of correlation lengths for which the mean value of the peak load exhibits a clear downtrend. The minimum of the mean value occurs when the correlation length equals approximately the internal material length. Such a correlation length enables the structure to sample the position of fracture process zone inside the weakest spot that has the size of the characteristic length. Decrease below such a correlation length leads to more averaging within the fracture process zone which homogenizes the response. Increase in correlation length leads to smoothing of the local strength and prohibits the weakest spots to appear. Such a source of variability just increases the overall variability in the peak load but does not influence its mean value.

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# Investigation on Mesh Dependency of Stochastic Simulations of Quasibrittle Fracture

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## ABSTRACT

This paper presents a new crack band model for stochastic finite element simulations of quasibrittle fracture. The model is anchored by a probabilistic treatment of damage initiation, localization and propagation. This study focuses on the case in which the finite element size is larger than the crack band width. A weakest link model is used to describe the probabilistic onset of damage localization inside the element, where the randomness of the location of the localization band is related to the random material strength. Meanwhile, the model also includes the regularization of fracture energy for the transition from damage initiation to localization based on the overall localization level. The proposed model is applied to analyze the probability distributions of nominal strength of quasibrittle structures of different geometries. The results show that, without a proper treatment of probability distributions of constitutive parameters, the direct application of the conventional crack band model for stochastic simulations would lead to mesh-sensitive results. The proposed model is able to effectively mitigate this issue of spurious mesh sensitivity.

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# Mechanistic Modeling of Strength Distribution of Quasibrittle Structures and Its Implication on Structural Reliability

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## ABSTRACT

This paper reviews a recently developed finite weakest link model of strength of quasibrittle structures, which fail under controlled load at macro-crack initiation from one representative volume element (RVE). The probability distribution of RVE strength is derived from the transition rate theory and a hierarchical multi-scale transition model. The model predicts that the strength distribution of quasibrittle structures depends on the structure size and geometry, transiting from a predominantly Gaussian distribution to a Weibull distribution as the structure size increases. The predicted size effect on the strength distribution is validated by a series of size effect experiments on the strength histograms of asphalt mixtures at low temperature. By further considering the load randomness, it is shown that the size dependence of the strength distribution directly leads to a strong size effect on the Cornell and Hasofer-Lind reliability indices. Through asymptotic matching, approximate size effect equations can be constructed for both the nominal and central safety factors. The important role of size effect in the reliability analysis of large-size structures is clearly demonstrated through the analysis of the failure of the Malpasset Dam.

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## Probabilistic Fragility Analysis of the Cohesive Crack Model

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### ABSTRACT

The zero thickness, fracture mechanics inspired cohesive crack model has been widely used in its various formulations. The constitutive model being formulated in terms of about fourteen parameters, yet only few can be measured experimentally, and other must be estimated [1].

This paper performs a sensitivity analysis to assess the relative importance of each of the parameters resulting in the model tornado diagram. For the most sensitive parameters, uncertainty analysis is performed through Latin Hypercube Sampling to determine capacity and fragility curves. Finally, impact of correlations among the parameters is assessed [2].

The study is conducted by performing pushover analysis of a simple interface element under mode I and II, and dynamic analysis of a model subjected to mixed-mode fracture. This investigation leads to a probabilistic-based safety assessment of structures which responses is primarily governed by cohesive cracking.

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# Bayesian System Identification of Fatigue Crack Growth in Concrete

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## ABSTRACT

Quantification of uncertainty in the response of structural elements subjected to fatigue loading is less explored especially for the case of structures made of quasi-brittle materials like concrete. The micro-structure of such structural materials is highly random that a deterministic study has very less to do in understanding their behaviour.

In this work, a model has been proposed to capture the behaviour of crack propagation in concrete beams upon the application of fatigue load, using the concepts of dimensional analysis and self-similarity. The important parameters chosen for determining crack growth in concrete are stress range, fracture energy, modulus of elasticity, stress ratio, crack length and the depth of the specimen. The posterior stochastic model of system parameter uncertainties along with measurement noise uncertainty are identified using Bayesian analysis. The results of this study would help in predicting the number of fatigue cycles that can be applied to beams with an existing crack in it, for a specified reliability value. This proposed model does not take into account the effect of variable amplitude loading and multiple cracks.

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# MONTE CARLO SIMULATIONS OF MESO-SCALE DYNAMIC FRACTURE OF CONCRETE BASED ON IN-SITU X-RAY COMPUTED TOMOGRAPHY IMAGES

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**Key words:** Dynamic fracture, Meso-scale modelling of concrete, In-situ X-ray computed tomography, 2D Image based modelling, Damaged plasticity model

**Abstract:** Meso-scale two-dimensional (2D) finite element models are developed for fracture modelling in concrete based on images from an in-situ micro-scale X-ray Computed Tomography test. The concrete damaged plasticity model is employed to capture the dynamic fracture mechanical behaviour of concrete under uniaxial compression. By Monte Carlo simulations, the present study statistically focuses on the effects of loading rate as well as heterogeneity of meso-structure on the macroscopic mechanical properties and the failure patterns of concrete. The calculated dynamic increase factors are in good agreement with experimental results and empirical predictions. Cracks in high strain rate case are more likely to connect voids and form dense damage network within the whole specimen. It is also suggested that the internal defects should be minimized for optimal material design especially when structures are exposed to high strain rate.

## Session MS13: Nondestructive Testing and Monitoring of Fracture

# Delamination Detection for CFRP Laminated Concrete Structures using Pulsed Laser Scanning-based NDE Technique

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## ABSTRACT

One of the most critical characteristics of concrete structures is brittleness and hence the concrete is vulnerable to tension force. To overcome this drawback, CFRP sheets and/or plates have been increasingly laminated on the surface of the concrete structures.

However, the efficiency of the CFRP reinforcement to endure the tension force becomes lower when the CFRP sheets and/or plates are delaminated from the concrete structures due to external loads and impacts during service.

This study prensents the application of a pulsed laser scanned ultrasonic wave propagation imaging technique for detecting delamination damage of the CFRP laminated concrete structures. As for the experimental studies, the delamination was artificially formed when the CFRP sheets were attached on the concrete structures and scanned using the Nd: YAG pulsed laser canning system.

By utilizing a frequency-wave number filtering algorithm to the wave responses measured from the Nd: YAG pulsed laser scannig system, the flaw images with delamination of the CFRP sheets were succesfully obtained.

This result proved the feasibility of the pulsed laser scanned ultrasonic wave propagation imaging technique to serve as an effective structural health management system for real-world CFRP laminated concrete structures.

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# Combination of inspection and monitoring techniques for the detection of fractures in concrete with self-healing properties

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## ABSTRACT

For applications studying fracture mechanical properties of concrete or the in-situ performance of cementitious materials non-destructive inspection (NDT) and monitoring techniques (structural health monitoring, SHM) are beneficial. This will be demonstrated for a special application developing concrete exhibiting properties to heal or seal cracks (Jonkers 2011, Van Tittelboom et al. 2011). A development of a new material is typically done starting on a laboratory scale and ending up with demonstrating the techniques at real constructions. For the particular development – self-healing concrete – it was found that a combination of inspection and monitoring techniques is most useful. This includes ultrasonic (UT), vibrational testing and acoustic emission techniques (AET). With AET (Grosse & Ohtsu 2008) can the activation of healing agents be monitored as well as the opening of cracks under load. Since this technique is time consuming and laborious more efficient NDT techniques are required to help proving the performance of the new material to the stakeholder on the construction site. This could be ultrasonic or vibration testing.

The development and application of NDT inspection and monitoring techniques will be described as well as the combination of these techniques with simulations and material developments.

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# Fracture Monitoring by Acoustic Emission: Recent Applications of Parameter-Based Characterization

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## ABSTRACT

The present paper describes a collection of fracture monitoring cases in different materials. The cases examined include bending of textile reinforced cement (TRC), hybrid concrete-TRC lightweight beams, granite, additive manufacturing metal components, combined loading of human femur bone and pull-out in reinforced concrete. In all cases the basic role is played by acoustic emission (AE). It is shown that certain waveform parameters exhibit strong sensitivity to the rate of fracture as well as the dominant fracture mode. Parameters like frequency content and the duration of the signals supply real time trends that in the present cases are verified by optical techniques. It is concluded that AE supplies important information and allows the prediction of how the material will behave based on the initial AE recordings and before serious damage is inflicted. AE shows a very broad application range; however, the contribution of combination with other techniques is highlighted in order to increase the reliability of the interpretation of AE results.

# Measurements of Energy Dissipation in Fiber Reinforced UHPC Using Acoustic Emission and X-ray Tomography

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## ABSTRACT

The overall role of fiber reinforcements in cement-based composites is well known and well documented. Fibers introduce a variety of mechanisms that vastly improve the toughness of an otherwise quasi-brittle material. These well known toughening mechanisms include fiber bridging, pullout, and facilitation of crack branching and a vast matrix cracking network. What is less well documented is a detailed quantification of the relative contributions of these mechanisms to the increases in fracture toughness.

In this work, we are employing complementary techniques to measure internal energy dissipation mechanisms in a steel fiber reinforced ultra high performance concrete (UHPC) matrix. 50 mm diameter by 50 mm long cylinders with a nominal 3.5% volume fraction of 13 mm long by 0.2 mm diameter brass coated steel fibers were subjected to split cylinder loading. Specimens were scanned using x-ray computed tomography (CT) before and after loading. During loading, specimens were monitored with a 6 channel full waveform acoustic emission (AE) system. 3D analysis of CT images made before and after tests allow us to make detailed measurements of complex crack networks and fiber pullout. From calibration tests (specific fracture energy of unreinforced specimens, and individual fiber pullout tests), we are in a position to make high quality estimates of energy dissipated by these different mechanisms.

The limitation of the CT data is that it consists of (in this case) two discrete snapshots of the specimen at to points in its loading history. Through an analysis of the AE data taken during the test, we can establish (to a limited extent) matrix cracking, fiber debonding, and fiber pullout events. When this data is aligned with the CT data, we can not only quantify the relative contributions of the toughening mechanisms, but we can also establish when these they manifest themselves.

# 3D Crack Detection Using an XFEM Variant and Global Optimization Algorithms

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## ABSTRACT

In the present work, a scheme is presented for the detection of cracks in three dimensional (3D) structures. The scheme is based on the combination of a newly introduced variation of the extended finite element method (XFEM) [1] to global optimization algorithms.

As with existing crack detection schemes [2], optimization algorithms are employed to minimize the norm of the difference between measured response of the structure, typically strains in some specific points along the boundary, and the response predicted numerically by XFEM. During the optimization procedure the crack geometry is parameterized and the parameters serve as design variables. The whole procedure involves the solution of a very large number of forward problems, which constitute the main computational effort. Therefore, emphasis is given in the reduction of the computational cost associated with the solution of each individual forward problem since it can directly affect the total computational time.

The employed XFEM variant [1] can provide increased accuracy for the forward problems at a reduced computational toll, thus decreasing the overall analysis time associated with the crack detection scheme. This reduction is a result of the improved conditioning of the system matrices which leads to a decrease in the time needed to solve the corresponding systems which ranges from 40% up to a few orders of magnitude depending on the enrichment strategy used.

Since during the optimization procedure cracks are randomly generated, cracks that lie beyond the boundaries of the structure can occur. In order to exclude those cracks, implicit functions are defined in order to localize the cracks within the structure. In some cases those functions are modified so as to exclude also cracks lying in further invalid locations within the search space.

The potential of the proposed scheme is demonstrated through numerical examples involving the detection of cracks in 3D structures.

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# Moment Tensor Inversion Applied to Acoustic Emission Data fro Large-Scale Laboratory Concrete Beams

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**ABSTRACT**

Acoustic emission (AE) techniques have been used for a number of years to monitor fracture processes in concrete. AE monitoring is a particularly well-suited technique as the measurements are directly related to the energy released from fracture processes. In this research, we are evaluating the moment tensor inversion (MTI) technique, which produces quantitative estimates of the AE source properties such as strength and fracture type, which give insight into the physics of an AE source. Specifically, we used a code that was developed for mining-induced seismicity and has a number of built-in algorithms to perform absolute, relative, and hybrid MTI. In this presentation, we discuss the MTI code, underline its main features as well as its strengths and limitations for the use in fracture monitoring of concrete. Finally, we present and discuss a set of experiments conducted on two large-scale reinforced concrete beams, one designed to fail in flexure and the other one in shear. The objective was to establish whether MTI is capable of distinguishing between vertical flexural and inclined-shear cracks. We show that it is indeed possible to distinguish between the two crack types and discuss further work.

# Experimental investigation of damage evolution in concrete under high-cycle fatigue

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## ABSTRACT

The current knowledge about fatigue behaviour of concrete is still incomplete. This concerns especially the process of fatigue which is preceding the fatigue failure, e.g. [1] – [5]. Therefore, a systematic and comprehensive investigation of the process of fatigue itself under cyclic compressive loading was done. The aim of this investigation was to get a deeper insight and to provide a better understanding of the damage process occurring within the material during fatigue loading (to enlarge the existing findings e.g. from [1], [2] and [4]).

Around 65 concrete cylinders with 10cm/30cm were tested with numbers of cycles to failure between $10^6$ and $10^7$ as well as $10^3$ and $10^4$. To investigate macroscopic and microscopic changes within the material, different kinds of non-destructive and destructive testing methods were used like strain measurement, deformation of surface, ultrasonic signals, acoustic emissions, optical microscopy and also scattering electron microscopy. One main finding was, that in contrast to other authors (e.g. [1], [4]), it could not be determined that the investigated changes in macroscopic material behaviour are caused by a development of micro cracks. Rather the results indicated that the fatigue related changes are mainly a result of viscous processes in cement stone, similar to processes of creep.

Based on the experimental findings the author was able to derive a detailed description about the possible processes which take place within the material structure (at meso-scale) during the fatigue loading and also leads to the observed macroscopic changes in material behaviour. In this context, the results have shown that relating to stiffness reduction a scalar value could not capture the damage effect on stress-strain-relationship caused by fatigue.

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# Source Localization of Pencil-lead Breaks in a Notched Concrete Specimen Using Multi-Segment Path Analysis

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## ABSTRACT

*FastWay* is a novel method for source localization of acoustic emissions (AE) in complex solid media. It uses the fastest, rather than the shortest, wave travel path between the sensors and the AE source. In order to consider the influence of air inclusions such as air voids and cracks and the heterogeneous material properties of concrete on the wave propagation behavior, a multi-segment path analysis based on a heterogeneous velocity model is employed. The method was first validated using numerical simulations of elastic wave propagation. A feasibility study was performed using artificial sources with full control of the source material characteristics of the specimen. The artificial sources were successfully localized using *FastWay* within a strict error estimation criterion. It could be demonstrated that *FastWay*, compared to commonly used localization methods such as the homogeneous and heterogeneous Geiger methods [1], shows superior performance with significantly higher source localization accuracy [2, 3]. After the successful numerical validation, physical experiments with pencil-lead breaks (Hsu-Nielson source) were carried out on a notched concrete specimen of dimensions 152 mm x 152 mm x 533 mm. Pencil-lead breaks were applied on a 25 x 25 mm grid on the specimen surface. Piezoelectric sensors were mounted to the concrete surface to record the signals from the pencil-lead breaks. To evaluate the performance of *FastWay*, a number of randomly selected localization results were compared to those obtained with the traditional Geiger method. It could be demonstrated that *FastWay* performs reliably and accurately in the presence of air inclusions and cracks using experimental data. It was also shown that the sensor arrangement has a considerably small impact on the accuracy of the estimated source location. The influence considered most crucial is the velocity model, which represents the internal material structure of the investigated specimen. Future work includes localization of AE from concrete cracking caused by an applied external load.

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# Transition from energy dissipative processes to displacement discontinuities during concrete failure

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## ABSTRACT

The description of failure process is one of the key factors to improve the durability and life time. Failure of concrete is usually assessed by the loss of stiffness and material strength due to damage growth associated with microcracks. The failure process is generally described by plotting macroscopic response of the structure under mechanical forces. Such analysis provides a reasonable understanding of material failure process at the structural scale.

The failure process as observed on the macroscopic scale is the result of local fracture process occurring at the material level. In recent years a large amount of experimental studies have been published where efforts are made to identify the fracture mechanisms and identify the fracture parameters [1]. The objective of this paper is to provide the relation between the global failure process and the local fracturing mechanisms (thanks to the real time monitoring techniques). Digital image correlation (DIC) and acoustic emission (AE) techniques are applied to investigate the fracturing process.

Three point bending tests are performed on notched concrete beams of multiple sizes. The simultaneous observation using DIC and AE technique makes it possible to monitor at the same time the energy dissipation process and displacement discontinuities. The energy dissipation process is examined by determining energy release rate of AE signals. As the loading increases energy release rate also increases. At peak load, a sharp increase is observed. The peak load, however, does not define the maximum energy release rate which keeps on increasing during the initial post-peak loadings and then starts decreasing.

Displacement discontinuities are measured on the surface of specimen using a novel approach with takes into account only the inelastic strains and exclude the elastic strains. It is observed that the increase in the AE energy release rate is not accompanied with the similar increase in crack openings. During the pre-peak loadings when energy release rate increases, very small crack openings were noticed. No sharp increase in crack openings was observed at peak load. The behaviour of crack openings was further analysed by analysing crack opening rate at different locations on the crack. The crack opening rate relationship with loading steps indicates a transitory phase i.e. when behaviour is not clear. This transitory phase ranges just up to about peak load. The crack opening rate then becomes stable and almost constant. During this phase it is observed that crack openings (at different locations on the crack) increases linearly with CMOD.

The analysis of local failure processes thus indicates three domains which describes overall failure mechanism: (1) high energy dissipation domain during which energy release rate increases. (2) The shift phase, very short phase near peak load where energy dissipation rate arrives at its maximum value, and (3) discontinuity phase where energy dissipation rate drops and displacement discontinuities becomes more important.

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# Interpretation of Fatigue Damage Evolution in RC Slabs by Means of Innovative 3D AE Tomography

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## ABSTRACT

Damage evolution of RC slabs in road bridges is regarded as the most difficult problem to solve for the rational maintenance. As the resultant investment from this fatigue damage shares a large portion in road budget, such measures have been conducted for this issue as from the basis of materials: improvement for the durability of concrete materials to resist the fatigue damage as well as to avoid cracking; and from the total cost for the life span: early damage detection with non-destructive testing and corresponding reasonable repair works which enable reduction of life cycle cost.

As for the latter measure, the authors have been studying NDT based visualization techniques that have potential to exhibit damage not only qualitatively but quantitatively. In the paper, two major aspects contributing to the fatigue damage have been introduced: prospective damage indices representing real internal condition; and damage visualization techniques with an acoustic approach, namely Acoustic Emission tomography. For a prospective damage index, Q-value, an attenuation feature of stress wave and can be treated as an irrespective parameter of frequency is demonstrated using several types of specimens changing the volume of artificial damage. And as for an innovative and latest NDT technology, 3D AE tomography, which can visualize the internal 3D damage evolution, only from one side access situation, is introduced, followed by experimental verification using RC slabs subjected to cyclic mobile loads. For the advanced technology of this AE tomography, C (composite)-AE tomography for planar structures having dispersion as well as velocity anisotropy is shown, and the applicability to the innovative materials/ structures is discussed.

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# Importance of acoustic emission based *b*-value in the study of fracture process of reinforced concrete structures

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## ABSTRACT

This article reports on importance of acoustic emission (AE) based *b*-value in the study of fracture process of reinforced concrete (RC) structures. The significance of amplitude-distribution and *b*-value (slope of the log-linear frequency-amplitude relation) of acoustic emissions released ahead of the failure of reinforced concrete beams of 3.2 m span are presented. The experiments were conducted in incremental cyclic loading under load control and simultaneously the released AE, strain in tensile steel, displacement at midspan were recorded. The effect of loading rate, compressive strength of concrete, percentage of steel in RC specimens on variation in AE based *b*-values with the development of cracks in RC structures were studied. The average *b*-values are lower as a few but larger amplitudes of AE events occurred in contrast to more number of low amplitude AE events observed at low loading rates (or at low strain rates). Moreover, the *b*-values are compared to the strain in steel and the evolution of cracks on the specimen to assess the damage state. It is observed that when the loading rate is higher, quick cracking development lead to rapid fluctuations and drops in the *b*-values.

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## Session RS01: Theoretical Considerations

# Fatigue Damage Evaluation in Plain Concrete using Concepts of Entropy and Disorder

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## ABSTRACT

Fatigue in concrete is a complex process starting from microcracking, coalescence of microcracks to the formation of a major crack which propagates leading to ultimate failure of the structural member. It is important to identify a damage index in order to assess the extent of damage occurred to a structural member when subjected to fatigue loading. An energy approach is adopted in this work within the framework of thermodynamics to quantify damage in a concrete member subjected to fatigue. According to the second law of thermodynamics, every irreversible process is associated with an entropy gain. Fatigue is an irreversible process, hence entropy production serves as a damage indicator during fatigue.

Damage in concrete can be considered as a change in the material structure. The response of a material depends on its current state of microstructural arrangement. The reorganization that takes place in the microstructural configuration of a material during the damage process is irreversible. During the self-organization process, the entropy that is a measure of disorder in the system, increases in accordance with the second law of thermodynamics [1]. In classical thermodynamics, entropy is related to energy dissipation and includes all the energy lost either in crack formation or propagation or by any other dissipative mechanism. In this work, a concrete member subjected to fatigue is considered as a thermodynamic system and a damage index is proposed by combining the concepts of statistical mechanics and classical thermodynamics.

Entropy generated during fatigue crack propagation is derived in terms of energy dissipated using principles of fracture mechanics. A closed form expression for entropy generated derived by the authors [2] using concepts of dimensional analysis and self-similarity is utilized here. This definition of entropy in classical thermodynamics sense is compared to the entropy in statistical mechanics described by the Boltzmann equation, and a fatigue damage index is proposed.

Using experimental data on fatigue of plain concrete, for constant amplitude [3] and variable amplitude loading [4], the proposed damage index is evaluated at various stages of the fatigue life and compared with available damage indices. The proposed damage index is robust and effectively captures size effect in concrete. A framework to evaluate fatigue damage in concrete based on sound physical principles is established in this work.

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# Structural size effect in Paris law for fatigue crack growth in quasibrittle materials

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## ABSTRACT

Quasibrittle materials exhibit a structure size effect on the fatigue crack growth rate, especially on the Paris law coefficient. This size effect can be modelled by a size-adjusted Paris law, which normalizes the Paris law for different sizes to obtain a unified plot. The material characteristic length scale that governs this size effect, called the transitional size for fatigue, is proportional to the size of the cyclic fracture process zone (FPZ). Previous studies aimed at a quantitative determination of this length scale, failed to account for the scatter in experimental data, which is expected to be huge for fatigue. This led to vastly differing estimates of the transitional size, and thereby the cyclic FPZ size. Here, more reliable estimates are obtained by conducting, for concrete, multiple fatigue tests per size and determining the average response for each size. These size parameters are also estimated numerically using the most recent version of the microplane constitutive damage model for quasibrittle fatigue. The numerical estimates reveal a discrepancy in that the transitional size obtained from the existing form of the size-adjusted Paris law is not proportional to the cyclic FPZ size. This discrepancy is resolved by proposing a new form of the size adjusted Paris law based on an updated form of dimensional analysis involving the transitional sizes for both monotonic and cyclic fracture.

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# Studies on the Application of Variable Amplitude Loading to Concrete through Energy Equivalence

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## ABSTRACT

Engineering structures such as Reinforced concrete buildings, bridges, pavements etc. are subjected to variable and non-proportional cyclic loads during their service. These service loads cause failure under high cycle fatigue. Due to non-uniformity in the loads and in the material properties, the computation of damage and the response of the structure subjected to service loads becomes a very tedious process.

Most of the fatigue tests conducted on the structural components to evaluate damage make use of constant amplitude cyclic loading, which reduces the complexity involved in the evaluation procedure. If we could convert the in-service variable amplitude loading data to an equivalent constant amplitude load through an energy equivalence concept it would ease the analysis procedure [1].

An energy equivalence principle works well for a quasi-brittle materials such as concrete. The fatigue phenomenon in general is a localized event; the parameters used in the classical strength theories are not applicable to describe the mechanism of fatigue. The physical mechanism in the concrete is characterized by debonings and micro-decohesions which give rise to micro cracks, and these micro cracks coalescence to produce mesocrack. The microstructural properties of the concrete show a random characteristic and hence a suitable method to evaluate the behavior of the concrete is through statistical approach.

In the present study, a method is devised to convert the variable amplitude loading data to an equivalent constant amplitude one through an energy equivalence which is based on the assumption that the energy accumulated for a fatigue fracture of the material is comparable with the strain energy required for static failure of the material [2]. The accumulated hysteresis energy during cyclic loading is expressed as a probabilistic quantity which takes into account the micro-inhomogeneity of the material [3].

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# State-of-the-Art Analyses for the Fracture Energy of Concrete: Revisited

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## ABSTRACT

Fracture energy of concrete is an essential parameter to characterize the fracture behaviour of concrete. It is a necessary parameter to identify the crack propagation in concrete. In this regard, many researchers have studied experimentally and theoretically on the fracture energy of the concrete during last several decades. Many researchers reported that the fracture energy of concrete depends on the size, shape, and compositions of specimens. The mixture compositions may surely affect the fracture energy of concrete because different mixtures may give different microstructures and thus different strengths and ductility. On the other hand, there are still controversial aspects for the size dependency of fracture energy. This thought comes from the fact that fracture energy is defined as the energy required to open unit area of crack surface and thus it may be a material property that does not depend on size of structure. However, in reality, many experimental results reveal that there exists great size dependency in fracture energy of concrete for same material mixtures.

In this study, through review and analyses of various experimental data for the fracture energy of concrete will be executed. From the analyses of experimental data, the effects of size and shape on the fracture energy are discussed and possible causes of such effects will be discussed and clarified.

Some other researchers also reported on the determination of size-independent fracture energy in concrete. They argued that the size-independent fracture energy can be estimated from the fracture energy data measured on laboratory-size specimens by introducing a local fracture energy distribution.. However, this approach artificially reduces the width of fracture prcess zone at the end parts of the ligament and lacks correct physical interpretation of actual phenomena.

Therefore, realistic physical interpretation of fracture process is proposed in this study to explain fracture energy distribution and size effect of fracture energy. The proposed idea will be validated through comparison of various data. The present study will enable to view correctly the fracture energy behavior of concrete, which have been controversial among the researchers.

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# Effect of Fracture Process Zone on Fatigue Crack Growth in Concrete

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## ABSTRACT

Civil engineering structures such as airport, highway pavements and bridges etc. are subjected to repetitive kind of loading, resulting fatigue failure. The problem of fatigue starts from micro-structural level and upon application of subsequent load cycles reaches to a critical size leading to fracture of the specimen. Fatigue crack initiation and propagation essentially influenced by important parameters evolving at the micro level. An accurate prediction of fatigue life and crack propagation analysis of a concrete specimen requires the consideration of micro-scale parameter in the formulation. In the present work, an attempt has been made to propose an analytical model to predict crack propagation in plain concrete under the action of repetitive loading. The analytical formulation incorporates the influence of fracture process zone, which is considered to be evolved at the micro-scale level together with the other crack growth characterizing parameters. Various crack growth characterizing parameters considered in the proposed model categorized into material, geometrical and loading parameters. Generalized Barenblatt and Botvina dimensional analysis approach for fatigue crack growth problems has been adopted in conjunction with the theory of intermediate asymptotic. Further, a physical interpretation of various non-dimensional terms (derived through dimensional analysis) in the analytical formulation has been made with respect to the fatigue crack propagation. The scaling behavior of various parameters has been explored for the fatigue crack propagation problem in plain concrete specimens. The proposed model has been calibrated and validated with the available experimental results from the literature.

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# Investigation on Fracture Mechanisms and Crack Propagation Process of Natural Rock-Concrete Interface

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**ABSTRACT**

The tests of uniaxial tension and three-point bending are carried out on rock-concrete composite specimens with natural interfaces to investigate the interface mechanics and fracture process so that to establish interface tension-softening constitutive law between concrete and rock. Tensile strength, fracture energy and initial fracture toughness of rock-concrete interface are investigated qualitatively. Based on the load-displacement curves measured in three-point bending test, the energy dissipation at rock-concrete interface is derived using the modified J-integral method. Further, through enforcing balance between energy dissipation and energy caused by fictitious cohesive force acting on fracture process zone, the tension-softening constitutive law of rock-concrete interface is established, which takes into account the effects of fracture energy and tensile strength of interface. For the sake of practical applications, the tension-softening constitutive expression is simplified as a bilinear function. Finally, the crack propagation process of the concrete-rock composite beam is simulated numerically based on nonlinear fracture mechanics theory by introducing a crack propagation criterion. The predicted *P-CMOD* curves show a reasonable agreement with the experimental ones, which verifies the tension-softening constitutive law for rock-concrete interface derived in this study.

# Session RS02: Experimental Methodologies

# Size effect on behavior of critical shear crack in reinforced concrete beams without stirrups using Digital Image Correlation (DIC)

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## ABSTRACT

The shear strength of a reinforced concrete beam remains an issue of great interest in structural engineering. The behavior of reinforced concrete beams under shear load is characterized by a sudden failure. The shear behavior of reinforced concrete members with or without transverses reinforcement is described by five mechanisms: Aggregate interlock (interface shear transfer), Un-cracked concrete zone (compression zone), Dowel action of longitudinal reinforcement, the residual stress tensile of concrete, and the arch action [1]. Several researches have shown that the aggregate interlock Is the most dominant mechanism compared to other ones. These mechanisms depend on several parameters like concrete strength and aggregate size, longitudinal reinforcement ratio, shear span to depth ratio, and depth effect. In addition, it is well know that the mechanical performance of real structure needs to take into account the phenomenon of “Size Effect”. A number of experimental programs were conducted to understand the size effect under shear loading [2]. Previous works are performed to develop models able to define the nonlinear behavior of structures, and also empirical relations for design codes.
In this paper, an experimental study was performed on three reinforced concrete beams without transverse reinforcement to obtain shear failure. The scale effect method was adopted to analyze the behavior of three sizes of beams that are geometrically similar, with a constant width of the cross section, the same longitudinal reinforcement ratio ($\rho$=1.5%) and the same shear-span ratio was retained. Three point bending tests are performed in order to obtain the global mechanical behavior of each beam. During these tests, strains in longitudinal reinforcement bars were recorded using strain gauges embedded on the steel surface. The technique of digital image correlation (DIC) [3] was used to monitor cracking during mechanical loading. In order to measure the intrinsic parameters of cracking (crack opening, crack length…) at different mechanical states. A significant size effect on the mechanisms of initiation and the propagation of the critical shear crack was observed. In the light of these results, discussion is provided, in order to take into account this size effect on the shear strength on members.

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# Experimental database with full-field measurements for mixed-mode crack propagation in concrete: comparison between experimental and numerical results

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## ABSTRACT

The concrete damage and fracture models are continually evolving, increasing in number, in complexity, and most of the existing nonlinear models depend on an important number of parameters that have to be identified [1]. The choice between the different models is not trivial and has to be validated. Therefore, to experimentally validate these numerical models, identify their parameters and better characterize the concrete behavior during mixed-mode crack propagation, multiaxial tests are developed. Inspired by former works of Nooru-Mohamed (1992) [2] we perform rich and discriminating tests by using modern techniques.

A digital image correlation (DIC) [3] algorithm is used to measure the experimental boundary conditions during crack propagation, which will be further used for the numerical simulations. The mechanical solicitations are applied using a 6 degrees of freedom testing machine controlled by a 3D displacement measurement system [4] and the cracking state is analyzed via digital image correlation. The major difficulty when performing this type of tests is given by the important difference between the sample's dimensions (order of magnitude equal to several tens of centimeters) and the applied displacement at fracture (order of magnitude equal to few micrometers).

With the proposed experimental setup several loading histories are analyzed: proportional loading histories and non-proportional ones, with and without crack closure and friction. To obtain a more complex evolution of the crack path, during the tests DIC computations are performed to determine the crack advancement and in certain key positions of the crack tip the loading is changed in order to reorient the crack.

To show the complexity and richness of the tests, the experimental results are further compared with two differnt numerical models frequently used to characterize concrete behavior: a nonlocal damage model [5] and a linear elastic fracture mechanics model [6];. The experimental test is considered challenging not only for the presented models but also for a wide class of damage and fracture models.

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# Effect of temperature and moisture on the instantaneous behaviour of concrete

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## ABSTRACT

In nuclear power plants, a severe accident in the containment building results in an increase in pressure, temperature and relative humidity that can reach respectively 5 bars, 140 °C and the saturation of water vapour [1]. As well as the regulatory calculations, accurate knowledge of the thermal and mechanical behaviour of materials and more specifically of concrete is required to carry out more precise numerical simulations.

Our study aims to investigate the mechanical behaviour of concrete under homogeneous conditions of moisture and temperature. An experimental apparatus was designed in order to assess the evolutions of the fracture energy, modulus of elasticity and tensile strength of concrete. Different temperature levels up to a maximum of 160 °C and at different values of the controlled moisture content were investigated. The equipment was used to perform DCT (Disk-shape Compact Tension) tests [2] at 30, 90, 110, 140 and 160 °C. Five levels of degree of liquid water saturation ($S_w$) were investigated for each temperature level. Finite-element computations with the code Cast3m [3] were carried out to determine the modulus of elasticity and the tensile strength from the results of DCT tests.

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# The influence of moisture on the fracture behaviour of concrete loaded in dynamic tension.

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## ABSTRACT

The fracture behaviour of concrete is represented in the load-deformation relation which shows the response up to maximum strength as well as the post-peak response up to complete failure. Dynamic tests performed by the authors demonstrate an extensive rate effect on the tensile strength as well as the post-peak behaviour beyond loading rates of about 50 GPa/s (strain rates > 1/s).

The causes for the extensive rate effects beyond 50GPa/s are under discussion. Possible explanations for the observed rate effects on the fracture behaviour are (i) the influence of (structural) inertia forces which are generated when the material starts to weaken by micro-cracking in the fracture zone, (ii) inertia at micro-level in the pre-peak phase and also in the softening phase, due to limitations in crack propagation, (iii) additional micro-cracking and (iv) enhanced resistance by moisture in the pores. The authors contributed to the discussion by their instrumented SHB and spalling tests. The authors show that the structural inertia effects in the fracture zone do not contribute to the enhanced maximum strength and only contribute to a small extent to the higher fracture resistance at high loading rates. Also, experimental data on the fracture patterns shows that the increase in micro-cracking is limited. Therefore, the moisture in the pores and the inertia at micro-level are believed to be the main causes for the enhanced strength and failure behaviour. The discussion in this paper focuses on the influence of moisture on the dynamic resistance.

In the experimental programme two types of concrete, Portland cement concrete and Blast Furnace Slag cement concrete, were tested at three moisture levels, i.e dry, normal and saturated. Static, SHB and high rate spalling tests were performed so data on a wide range of loading rates was obtained.

The effect of moisture and the pore structure on the enhanced tensile resistance is believed to be due to the so-called Stefan effect. The experimental data on (i) tensile strength, (ii) the pore structure of the concretes used and (iii) the moisture distribution in the pores, are used to estimate the influence of pore sizes, pore structure and saturation level on the rate dependency of concrete under tensile loading.

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# Experimental and Numerical Analysis of Crack Evolution in Concrete through Acoustic Emission Technique and Mesoscale Modeling

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## ABSTRACT

Fracture of concrete is accompanied by the formation and evolution of an inelastic zone, referred to as the fracture process zone (FPZ), around the propagating crack tip. The existence of the FPZ is responsible of the nonlinear behaviour of concrete and can lead to complex phenomena as size effect.

In this paper, the FPZ was investigated on unnotched and notched beams with different notch depths. Three point bending tests were realized on plain concrete under crack mouth opening displacement (CMOD) control. Crack growth was monitored by applying the acoustic emission (AE) technique. This later allows a continuous and a real time data acquisition of damage evolution in concrete. A comparison with a numerical model was also realised by using a mesoscopic approach which has shown a particular interest in the analysis of interactions between cementitious matrix and aggregate and presents many advantages in the understanding of the fracture process and the corresponding effect of concrete heterogeneities.

The numerical load-CMOD curves show that the mesoscopic modeling reproduces well the notch and size effect in concrete beams. In addition, several AE parameters were studied during the entire loading process and showed that the relative notch depth influenced the AE characteristics, the process of crack propagation and the brittleness of concrete. The number of AE hits increases with the decrease of the relative notch depth and shows a good proportionality with the evolution of the numerical damage. An important energy dissipation was also observed at the crack initiation in unnotched beams. In order to improve our understanding of the FPZ, the length of the crack was followed based on the AE source location maps in parallel with the numerical damage fields. The differences observed indicate a non-uniform stress distribution in the cross section of the beams which could be responsible, in combination with the softening behaviour of concrete, of the size effect in concrete structures.

# Rotational Capacity of Concrete Beams Based on a Crack Process Band

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## ABSTRACT

The rotational capacity of a reinforced concrete structure is a measure of the ability to obtain deformations prior to failure. In many aspects, this makes rotational capacity an important factor of reinforced concrete structures, i.e. redistribution of internal forces, robustness and warning before failure.

The rotational capacity of reinforced concrete beams is determined on the basis of modelled load-deflection curve. The model is based on a method with a crack band developed for plain and lightly reinforced concrete beams [1] combined with virtual work. In order to obtain equilibrium in all cross-sections an iterative procedure is implemented.

The rotational capacity is calculated by two different methods. At first as the total plastic work, obtained as the area beneath the load-deflection curve, divided by the yield moment. Secondly as the plastic mutual rotation of the beam in the plastic hinge.

The modelled load-deflection curves are compared with experimental results from 27 tests of reinforced concrete beams in three-point bending of varying size and reinforcement ratio.

Finally, a parametric analysis is performed to evaluate the influence on the rotational capacity when reinforcement ratio and the beam dimensions are varied. Finally the size of the band is estimated based on a fracture mechanical approach.

# The double-K fracture parameters of steel fiber reinforced concrete

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**ABSTRACT**

Double-K fracture parameters can also describe the crack propagation of steel fiber reinforced concrete(SFRC) well since the crack ,which are similar to plain concrete,goes through three stages: crack arises, expand stage and break stage.A new Double-K fracture parameters which apply to SFRC is derived in this paper.Stress intensity factor cased by bridging stress and the net stress intensity factor are given based on the hypothesis of linear asymptotic superposition.Analytical expression and practical estimation of their values for double-K fracture parameters,as well as the critical effective crack length,is proposed.Based on the formulas obtained in the paper,a novel crack propagation resistance,in which both of the cohesive force and the bridging stress are taken into account,is established.Based on the theory of this article,crack propagation resistance at different stage were put forward.In addition, unstable fracture toughness would nearly for increases in volume ratio ,but it wouldn't occur to the initiation toughness according to analysis. Analyses of the datum got by previous researcher indicates that the new Double-K fracture parameters present in this paper can be directly used to depict SFRC's crack propagation with a satisfactory accuracy.At last, three-point bending experimental studies were carried out and the results verify the validity of theoretical analyses.

# Experimental failure analysis of shear-critical ordinary and steel-fibre prestressed concrete beams using optical measurement techniques

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## ABSTRACT

Despite more than a century of continuous research effort [1], the problem of determining the shear capacity of a structural concrete member is not yet fully understood. Indeed, after the occurrence of inclined cracking, various interrelated shear carrying mechanisms are activated. Moreover, these mechanisms are affected by a multitude of influencing parameters. As a consequence, the design of structural concrete members according to international codes of practice is primarily performed using (semi)-empirical approaches. However, significant scatter between experimental results and theoretical predictions have been frequently reported in literature, specifically in the case of prestressed members [2, 3]. A clear need thus remains for optimizing analytical procedures for the design of structural concrete elements in shear.

The aim of the present work is to gain insight into the mechanical behaviour and failure properties of shear-critical ordinary and steel-fibre prestressed concrete members. An extensive experimental research program, consisting of 8 ordinary and 4 steel-fibre prestressed concrete elements, has therefore been developed. Each specimen was subjected to a four-point bending test until failure occurred. The main investigated variables are the amount of prestressing, the amount of shear and longitudinal reinforcement, fibre dosage and the shear span-to-effective depth ratio. Advanced optical measurement techniques, including stereo-vision digital image correlation (3D DIC), three-dimensional coordinate measurement machines (3D CMM) and fibre Bragg grating optical sensors (FBG), were employed. These techniques allowed for the detailed quantification of the experimental displacement and strain field during the loading procedure.

Firstly, a detailed parameter study is performed of the influence of the investigated variables on the failure properties of the reported test specimens. Secondly, a comparison is made between the experimental results and theoretical predictions obtained from current analytical models and discrepancies are identified. Finally, the displacement and deformation evolution is studied in full to identify the governing mechanical behaviour.

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# Fracture process analysis of recycled aggregate concrete with combined digital image correlation and acoustic emission techniques

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## ABSTRACT

The usage of recycled aggregate in new concrete is a good solution for the environmental protection and resources reservation problems. Studies in the past three decades have found that the recycled aggregate has higher water absorption, lower density, a more complicated microstructure and poorer mechanical property and durability compared to natural aggregate [1]. In order to get a whole understanding of the load carrying capacity and cracking process of recycled aggregate, three-point bending tests of both natural aggregate concrete (NAC) and recycled aggregate concrete (RAC) beams were conducted with the digital image correlation technique (DIC) and the acoustic emission technique (AE).

It is found that with the use of recycled aggregate the compression strength, the splitting tensile strength and the dynamic elastic modulus decrease. Nevertheless, the classical fracture test methods have difficulties to distinguish the differences in the mechanism of fracture process between RAC and NAC. Hence the DIC technique has been used to analyse precisely the fracture process of RAC [2]. The DIC analysis has shown that the cracking behaviour of RAC is different from that of NAC. The crack opening of the RAC beam initiates earlier and develops faster which indicates the increase of fragility due to the utilization of recycled aggregate. Moreover, the value of the fracture length is always larger for RAC during the whole loading process and all the facts show clearly the poor fracture resistance of RAC [3].

However, the DIC analysis only reveals the cracking process of the beam surface. In order to improve our understanding of the fracture process inside the specimen, the AE method was applied simultaneously [4]. It is shown that the acoustic hits with high amplitude and the events with high absolute energy appear earlier for RAC and more events are recorded with the RAC specimen. Moreover, the final crack tendency and the length of the fracture process zone calculated by AE correspond well with those by DIC and all of these confirm the efficiency of the two methods.

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# Analysis of Acoustic Emission Data in Reinforced Concrete using Wavelet Transform

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## ABSTRACT

The failure of reinforced concrete structures is governed by the yielding of steel after the concrete cracks. It is assumed that the component reaches its service life when the steel starts to yield. Hence, steel yielding is a critical stage prior to failure of the structural components. As the steel reinforcement delays failure through its ductility, it is important to detect the onset of yielding. As shown in the literature [1, 2, 3] the acoustic emission technique provides a good tool for studying the onset of failure in quasi-brittle materials such as concrete.

In this work, plain and reinforced concrete beams of different sizes are tested in a servo-controlled machine under crack mouth opening displacement control. The acoustic emission signals obtained during the test are collected and analyzed using the wavelet transform technique. The load-deformation characteristics are studied in conjunction with the acoustic emission data to understand the different stages of damage and failure occurring in the plain and reinforced concrete beams. A shift in the frequency content of the AE signals are clearly observed after the maximum load is reached. It is shown that the acoustic emission analysis could provide as a useful tool for understanding the behavior of reinforced concrete beams especially during the transition of failure from concrete cracking to steel yielding.

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# Studies on the Fatigue Crack Propagation in Plain Concrete beams Using the AE Technique

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## ABSTRACT

Civil engineering structures such as bridges, highways, offshore structures and gravity dams are subjected to fatigue loading. The result of fatigue is a process of progressive permanent internal damage to the structure. Concrete as a material is heterogeneous, which consists of cement phase, aggregate phase and transition zone phase. The transition zone is the weakest zone in the concrete which contains micro-cracks even before the structure is subjected to loading. The fatigue crack propagation in concrete is much more complex due to various toughening mechanisms [1] taking place in concrete. The mechanism of fatigue in concrete is not clearly understood as compared to metallic materials. Hence, in this work an attempt is made to understand the fatigue crack propagation in plain concrete using the acoustic emission technique.

The acoustic emission (AE) technique has been used extensively for studying fracture behaviour of concrete [2]. In this study, we use the AE technique for monitoring the fatigue crack growth in plain concrete specimens subjected to constant amplitude cyclic loading. Three different sizes of geometrically similar beam specimens are prepared and are tested under three point bending (TPB) in a closed loop servo-controlled testing machine. The fatigue crack growth is continuously monitored using six AE sensors mounted on the specimen. The output results from the mechanical sensors and acoustic emission parameters are simultaneously acquired using a data acquisition system. The CMOD compliances at different cycles are measured from the load-CMOD curves and the equivalent fatigue crack lengths are determined using the compliance calibration curve obtained from finite element analysis. AE parameters are used to measure and relate the crack lengths, damage, Paris law constants and fatigue life in the plain concrete beam specimens under constant amplitude fatigue loading.

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# An Acoustic Emission Study of Mixed Mode Crack Propagation in Reinforced Concrete Beams

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## ABSTRACT

The mixed mode fracture is of greater importance for the wide range of civil engineering structures subjected to combined flexure and shear loading. Current design codes for the shear resistance of reinforced concrete are still based on empirical models. In the presence of shear forces, a crack tends to propagate in opening and sliding modes. For the mixed mode fracture in reinforced concrete beams, the determination of crack trajectory [1, 2] is more difficult than the opening mode. Hence, in this study an attempt has been made to understand the mixed mode crack propagation in reinforced concrete beams using the acoustic emission method.

The paper presents experimental studies on mixed-mode crack propagation in reinforced concrete beams which are over–reinforced. Geometrically similar beams of three different sizes and having single longitudinal reinforcement with different percentages of reinforcement without stirrups are prepared. A notch was provided at the quarter span, as this was the region prone for crack initiation and propagation. The specimens were tested under displacement/stroke control in a closed loop servo controlled hydraulic testing machine. The results of load, displacement, CMOD and strain in the steel are acquired using a data acquisition system. Digital image correlation is used as tool in determining the parameters related to crack growth. The acoustic emission technique is used for monitoring the crack growth using six AE-sensors mounted on the specimen. The results of acoustic emission location, hits, events, amplitude, absolute energy and time are simultaneously stored in a computer during the testing. The failure mechanisms observed in reinforced concrete are delamination between steel and concrete, slippage, shear, crushing and yielding of steel. An attempt is made to relate acoustic emission parameters for crack initiation and growth for size effect and percentage variation of reinforcement for over reinforced beams.

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# Error Analysis of Displacement Gradients via Finite Element Approximation of Digital Image Correlation System

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## ABSTRACT

In the field of experimental solid mechanics, conventional strain measurement devices such as LVDT and strain gauges provide mean values of strains and displacements at selected locations and gauge lengths; this result is inadequate for the evaluation of a non homogeneous material behaviour. Consequently, during the last decades various full-field non-contact measurement techniques have been proposed for the material characterization and have become more and more popular in the experimental mechanics community. In this work, the Digital Image Correlation (DIC) non-interferometric technique has been used to monitor experiments on aluminum flat bars and to measure displacement distribution on the surface of the specimen for further evaluation and calculation of strains.

The results obtained by a Digital Image Correlation System are assessed and the error associated with the post processing of the experimental field data, obtained through the use of the Aramis software, is evaluated and analyzed with the aid of a least square approximation code. This code uses a finite element approximation of the displacement field in order to cover all the target points. A least square approximation of these data is performed and the best nodal displacement values are determined. Based on the nodal data, infinitesimal and finite strain distributions are determined over the surface image window of the specimen. It is observed that this post processing technique provides better results near perforations and edges that are not sensitive to the density of the captured displacement data.

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# 3D experimental detection and characterization of microcracking in porous cement based materials

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## ABSTRACT

The mechanical description of damage caused by cracking phenomena occurring in many civil engineering materials is still an open issue, in terms of initiation, propagation or localisation leading to macroscopic ruin. Detailed experimental characterization of cracking under mechanical loading is necessary to validate 3D models of crack nucleation and propagation in heterogeneous materials [1].

A dedicated experimental set-up was used to perform in-situ compressive tests on an X-Ray Computed Tomography (XRCT) laboratory scanner available at Laboratoire Navier, on a cylindrical lightweight concrete sample (~10 mm in diameter). The material is made from quartz sand and expanded polystyrene (EPS) beads embedded in a cement matrix [2]. Its high porosity is suitable for crack initiation at relatively low compressive loads and stable propagation. Several load levels were successively applied to the specimen and CT images of the whole sample were recorded under constant load. Cracks developed progressively during the last loading steps and can be qualitatively observed directly in the CT images. In order to quantify their precise location and extension and to detect early-age cracking, a method based on Digital Volume Correlation (DVC) has been developed. Because local contrast is too low in EPS beads and sand grains, DVC routines have been run on positions in cement matrix, especially near interfaces, to obtain a sparse evaluation of the mechanical transformation. The latter can then be continuously extended throughout the whole sample, by means of an adjusted interpolation/smoothing procedure that also filters DVC measurements errors. Finally, after back-convection of the deformed image to the same frame as the reference image according to the estimated transformation, the difference between reference and deformed images is computed and defines the “subtracted image”. It reflects the local evolutions of the material, not described by the fit of the coarse evaluation of the transformation. For a brittle material, it essentially gives access to the cracks. In fact, the path of cracks is clearly visible within the almost uniform grey level of the subtracted image. Segmentation of cracked areas is thus possible, while it would have been very hard to separate cracks from porosity in the deformed XRCT images. Moreover, very tiny cracks can also be detected and their sub-voxel opening evaluated. Using this DVC-assisted subtraction for all loading steps, the crack network and its evolution (propagation, opening) through the cement matrix and sand grains can be characterized in the whole sample. These results can especially be directly compared to numerical simulations computed on realistic microstructures. Because validation of numerical tools on such a complex microstructure is problematic, similar tests were performed on samples composed of EPS beads embedded in an almost homogeneous plaster matrix. Their simpler microstructure characterized by a limited number of EPS beads is easier to model and will serve for detailed comparisons between new numerical tools and experimental results.

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# Crack Propagation in ASR Damaged Concrete Detected by Image Analysis

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## ABSTRACT

The present study includes an experimental investigation on the crack propagation in the concrete cracked due to alkali-silica reaction (ASR). The fracture energy and tension softening curves of the ASR damaged concrete were obtained by three-point bending tests for single notched concrete beams [2, 3]. The concrete specimen is a beam in which the section is 100 mm of width, 50 mm of a ligament height and 800 mm of the clear span length. During loading test, an image analysis by using a digital image correlation method was carried out in order to detect the crack propagation behavior. This method of the image analysis is conducted based on a region-based matching technique [4] in order to calculate the displacement of any portion of the concrete surface.

Two series of the ASR expansion level that is that four specimens exposed outside for about 3 years and two specimens exposed for about 4 years were prepared in this experiment. It is confirmed that an expansion which has been measured by using reference prism specimens of 100*100*200 mm was around 1200μ or more at the day of bending test for the series of the outside exposure for 3 years.

As for the macroscopic damage in the concrete the ASR induced cracks that can be observed on the surface of concrete were evaluated. In addition, further investigation on the crack propagation in the ASR damaged concrete was conducted by using the specimen in which the raptured prism after terminating the loading test for a notched beam were curved within the thickness of around 10 mm and polished the surface of concrete. Hence the aggregate in the concrete can be confirmed from the specimen surface. A digital microscope was also used to capture the behavior of the micro cracks.

From the series of this study, we conclude that the experiments show that the ASR induced cracks visible on the concrete surface do not always influence the crack propagation occurred under the external loading. The quantitative evaluation on the state of the ASR-induced crack at the ligament portion is needed in order to evaluate the influence of the ASR-induced crack on the fracture properties of the concrete.

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# Component wedge-splitting/bending test of notched specimens enforcing various crack-tip constraint conditions: Experiments and simulations

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## ABSTRACT

A novel method for evaluation of fracture-mechanical parameters of quasi-brittle cementitious composites was introduced recently [1] by the BUT partner of the joint research which is presented in the paper. It should eliminate the drawbacks of most of the established models for determination of those characteristics, which is the dependence of values the fracture properties determined from fracture tests on laboratory specimens on the specimen's size, geometry and boundaries. Capturing of these effects shall be achieved via a (detailed) incorporation of the fracture process zone (FPZ) existence into the evolutional procedure. Results of the method may be regarded as very promising up to now, however, it still lacks a sound experimental validation. And this is caused by the fact that most experimental data available in literature are either/both obtained from tests with a limited range of constraint levels (i.e. the FPZ shape/size does not differ as much as it would be necessary to become conspicuous and take it into account for the fracture behaviour evaluation) or/and processed into a form that is not suitable for validation of the method (cumulative extents of the failure zone are mainly published instead of the current ones needed).

An experimental campaign focused on investigation of fracture processes in cases with various extents of FPZ (widths, lengths, of various shapes), and thus various progresses of energy dissipation within it, was conducted at TUW to validate of the method and compare the results to the existing fracture-mechanics evaluation procedures. A novel geometry utilizing combined boundary conditions of the Wedge Splitting (WS) [2] and Tree-Point Bending (TPB)/Four-Point Bending (FPB) test was used. This geometry, via tuning the specimen length to width and the span to length ratios (and/or simultaneously the wedge angle), provides a wide range of various stress distributions in the specimen ligament – from bending to a tension with (very) low eccentricity – resulting in the desired variety in the FPZ size and shape. Note that other available test geometries providing a low level of constraint, typically the tensile tests of notched specimens, are straightforward for the fracture parameters' evaluation, however, very demanding on their correct execution.

The paper presents results of the experimental campaign, their processing and analysis as well as some numerical simulations accompanying preparation of this experimental work.

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# *In-situ* tensile and corrosion damage characteristics of high-performance fiber-reinforced cementitious composites using X-ray micro-computed tomography

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**ABSTRACT**

The use of microfibers in high-performance fiber-reinforced cementitious composites has shown to have a significant influence on the overall toughening of the composite material compared to plain concrete. However, nondestructive analysis of microfiber-microcrack interactions may be difficult to obtain using conventional methods, including cracking caused by long-term internal expansive processes such as corrosion product formation. In this study, synchrotron X-ray micro-computed tomography (μCT) is utilized as a nondestructive method to obtain 3D spatial information of cracked microfiber-reinforced cementitious composites (MFRCC). Imaging of specimens was performed under two *in-situ* loading conditions – the first being under direct tension and the second being periodic scanning under long-term corrosion damage of reinforced MFRCC. For the latter series of experiments, specimens were subjected to various intensities of cracking prior to corrosion to investigate the effect of cracking on corrosion behavior. Tomographic results revealed distributed cracking could be successfully quantified, with new cracks forming at intermediate scanning intervals during direct tensile loading. The corrosion initiation time of cracked reinforced MFRCC was found to be delayed compared to reinforced plain cementitious composites subjected to similar levels of preload, as evidenced by detection of corrosion product growth in reconstructed tomograms. The formation of numerous fine cracks in MFRCC highlights the durability enhancement gained with microfiber reinforcement compared to plain cementitious composites.

# Adhesion and Interfacial Fracture Toughness Between Steel Pipe and Cement/Spacer/Mud System

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## ABSTRACT

The principle function of oil-well cementing is to bond and support the casing, and to provide downhole zonal isolation. However, the residual non-aqueous drilling fluids (oil-based mud) on the surface of steel pipe can weaken the bond to the hardened cement. The most practical way to analyze the bonding between cement slurry and steel pipe is to directly measure adhesion between these two materials. In the present study, the cement cylinder and the steel coin are separately fixed in two sides of a Brazilian disk, and then the force is applied along the diameter of the disk, at an angle to the interface between the cement and steel. The preliminary results from Brazilian disk tests show that shear bond strength is quite different for the two commercial spacers. Another important factor is the surface condition. Polished, sandblasted and rusted coins are used to examine the effect of surface conditions. Better adhesion is obtained on rusted steel surfaces.

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## Thermo-mechanical model for the material nonlinear analysis of cement based materials

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### ABSTRACT

Since most advanced cement based materials have relatively high binder content, the risk of cracking at an early age should be evaluated using models that can estimate the heat generated by the hydration of pozolanic components and the induced stress fields. For this purpose, a thermal model with general purposes has been developed, in order to be possible to perform steady state thermal analysis, transient linear thermal analysis or nonlinear thermal analysis. The heat development due to the hydration process during the concrete hardening phase was coupled to the thermal model, resulting a numerical approach capable of simulating the behavior of concrete structures since its early ages. This thermal model is integrated into a mechanical model that can simulate the crack initiation and propagation in structures discretized with solid finite elements. The mechanical model is a 3D multi-directional smeared crack model with the capability of simulating the behavior of structures failing in flexural, shear or punching. The thermo-mechanical model is presented and its performance and accuracy are assessed using results available in the literature.

**Keywords**: Finite element method, Thermal analysis, Early-age heat development, Smeared crack model

# Prediction of Analytical Bond Strength of Lap splices in Tension

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## ABSTRACT

Reinforced concrete (RC) structurers perform well only if the transfer of force from the reinforcing bar in to the surrounding concrete is effective. A number of factors such as rebar type, type of concrete and the state of stress in the materials, cover, spacing of rebars, number of layers, casting direction, position of bar, Poisson's effect, diameter of rebar, cyclic loading, bar geometry and rib geometry influence the bond. A significant experimental and analytical evidence of anchorage bond of ribbed bars under monotonic and cyclic loading has been reported (*Eligehausen et al. (1983)*). Concrete splits due to lack of lateral reinforcement. Two of the most commonly used modeling approaches have been provided by *Orangun, Jirsa and Breen (1977)* and *Zuo and Darwin (2000)* using nonlinear regression analysis of the test data.

Significant experimental data has been generated from ACI 408 and also from other sources. While additional test data have resulted in an increase in the accuracy of current statistical approaches, splice strength behavior remains not fully understood. The objective of this study is to develop a model for predicting the bond strength incorporating various influencing parameters for design applications. Overall, it delivers specifications in the codes of practice, and modeling of bond strength of lap splices in RC structures and hence the development or bond length. Some experiments have been performed to understand the bond strength in pullout specimen and also in beam specimens with varying bond length. Beam tests under symmetrical loading have been performed to verify the splice strength with and without coating on bars and modifying the bond strength, if necessary, by introducing a reduction coefficient. A large data base has been generated and mechanics based standard splice strength model has been proposed from a large database.

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# Non-proportional Loading for Sequentially Linear Analysis

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## ABSTRACT

Sequentially linear analysis (SLA) is an alternative to the Newton-Raphson method for analyzing the nonlinear behavior of reinforced concrete and masonry structures. In this paper SLA is extended to load cases that are applied one after the other, for example first dead load and then wind load. It is shown that every nonlinear analysis step can be made in just two linear elastic analysis. The algorithm is extremely robust, which is demonstrated on a prestressed concrete beam and on a push-over test of an unreinforced masonry wall for which the load orders are important. A comparison is made between analysis results of SLA and Newton-Raphson with arch length control.

## INTRODUCTION

Nonlinear finite element analysis is becoming a common tool for studying the behavior of reinforced concrete structures. Over the past years, techniques for nonlinear analysis have been enhanced significantly via improved solution procedures, extended finite element techniques and increased robustness of constitutive models. Nevertheless, problems remain, especially when cracking and crushing in real-world structures is analyzed. Sequentially linear analysis (SLA) is an alternative to the Newton-Raphson method when bifurcation, snap-back or divergence problems arise. The incremental-iterative procedure, adopted in nonlinear finite element analysis, is replaced by a sequence of scaled linear finite element analyses with decreasing secant stiffness, corresponding to local damage increments. The focus of most research is on reinforced concrete structures, where multiple cracks initiate and compete to survive [1] [2]. Compared to nonlinear smeared crack models in incremental-iterative settings, the sequentially linear model is shown to be robust and effective in predicting localizations, crack spacing and crack width as well as brittle shear behavior [3].

Until recently SLA could only be used for load cases that are applied simultaneously (proportional loading). However, in reality, non-proportional load combinations are very common, for example prestressing a beam before applying self-weight. The aim of the present study was to extend Sequentially Linear Analysis (SLA) to non-proportional loading such that SLA can be applied to pushover analysis for earthquake loading. The solution algorithm needs to support all element types and all failure criterions. In addition, the calculation time needs to be minimized.

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# Numerical Strategy for Developing a Probabilistic Model for Reinforced Concrete Structures (PMRCS)

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## ABSTRACT

This paper introduces a new approach to model cracking processes in large reinforced concrete structures, like dams or nuclear power plants. For these types of structures it is unreasonable, due to calculation time, to explicitly model rebars and steel-concrete bonds. To solve this problem, we developed, in the framework of the finite element method, a probabilistic macroscopic cracking model based on a multi-scale simulation strategy: the Probabilistic Model for Reinforced Concrete Structures (PMRCS). The PMRCS's identification strategy is case-specific because it holds information about the local behaviour, obtained in advance via numerical experimentations. This information is then projected to the macroscopic finite element scale via inverse analysis. The Numerical experimentations are performed using a validated cracking model allowing a fine description of the cracking processes. The method used in the inverse analysis is inspired from regression (supervised learning) algorithms: data on the local scale – the training data coupled with working knowledge of the mechanical problem – would shape the macroscopic model. Although the identification phase can be relatively time-consuming, the structural simulation is as a result, very fast, leading to a sensitive reduction of the overall computational time. A first validation of this multi-scale modeling strategy is performed on a reinforced concrete slab-beam subjected to 3 point bending. We achieved promising results in terms of global behaviour and macro-cracking (mainly crack openings), and an important reduction in calculation time – up to 99% reduction! So we believe this is a promising approach to solve bigger and more complex structures in shorter time.

# Numerical simulation of the fatigue behaviour of FRP strips glued to a brittle substrate

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## ABSTRACT

In the last decades, repairing and strengthening existing buildings made of brittle materials, such as concrete or masonry, emerged as key issues in structural engineering. Particularly, the need for seismic retrofitting was clearly highlighted by the consequences of the most recent earthquakes.

The use of FRP for structural strengthening, also in seismic areas, is getting more and more common as a result of their advantages in terms of structural efficiency and reduced times of installation. As a matter of fact, the interaction between FRP strips and the brittle substrate to which they are glued generally controls the actual efficiency of the FRP-strengthened members. Therefore, a significant research effort has been produced in the past two decades to investigate the bond behaviour of the FRP-concrete/masonry interfaces [1].

However, the large majority of studies on FRP-concrete interaction focused on the bond behaviour under monotonic actions which is certainly relevant for a wide class of practical applications, but cannot cover the behaviour of FRP strips in seismic retrofitting applications. Furthermore, only few contributions are currently available for describing the response of FRP-to-concrete/masonry substrates under cyclic actions, but they are generally limited to the quasi-static case [2,3].

The present paper is intended at formulating a theoretical contribution to simulate the bond behaviour of FRP strips glued to a brittle substrate and subjected to low-cycle fatigue loads, such as the ones applied to the anchorage zones of FRP strips employed in seismic retrofitting of concrete or masonry members. The constitutive proposal is formulated within the general framework of the Fracture Mechanics and is based on two alternative expressions for modelling the softening response of the bond-slip relationship. Closed-form expressions, obtained for determining the key damage-related quantities, are derived for the present formulation. The comparison between some experimental results, available in the scientific literature, and the numerical simulations performed by means of the present model are reported for investigating the formulations soundness and capabilities.

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# Modeling the evolution of a crack in a prestressed concrete structure

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## Abstract:

EDF – the French major electricity generation and distribution Company – manages 73 nuclear reactors. For some of them, the third protective barrier consists of a concrete double-walled containment building. In order to deal with the safety and durability of these concrete structures, Engineers require numerical tools to predict the current stress state. Indeed, creep and shrinkage result in pre-stress losses and stress redistribution which may increase the risk of propagation of an existing crack under high pressure loading. A mock-up of a containment vessel, VERCORS, was built with scale 1:3 in order to study the behaviour of the structure under severe accident conditions and the evolution of the leak tightness under aging. Therefore, this work focuses on following an existing crack in a pre-stressed concrete structure rather than describing the early stages of damage (which is still more difficult). This enables an estimation of the overall leakage of the structure.

A "global model" is proposed that represents most phenomena interacting with the behaviour of an existing crack. In principle, the model is built from a real cracking pattern. The existing cracks are taken into account through a cohesive zone model; steel reinforcements and pre-stressing tendons are modelled by means of homogenized membrane models [1]; the debonding steel-concrete [2] is represented by another specific cohesive zone model. The constitutive law used for modelling the concrete takes into account basic creep (through a rheological model distinguishing the deviatoric part and the spherical part [3]), shrinkage and drying creep.

The different ingredients have been validated independently through several tests from the literature. Then the global model is applied to the experimental campaign PACE1450 [4] in order to check its accuracy: in particular the opening of through-wall cracks is compared to the numerical results. In a near future, the modelling strategy will be applied to critical areas of the mock-up VERCORS such as the junction between the floor and the wall or the gusset where early stage cracks may reopen under high pressure. The numerical predictions will be compared against available strain measures obtained by Digital Inter Correlation.

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# A novel multi-fiber Timoshenko beam finite element formulation with embedded discontinuities to describe the reinforced concrete failure subjected to static loadings

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## ABSTRACT

A new multi-fiber beam finite element formulation based on the Timoshenko model [1] is proposed in this paper to simulate failure of reinforced concrete structural elements subjected to static monotonic loadings [2].

The beam section can have an arbitrary shape and each fiber has a local constitutive law representing a specific material. The embedded discontinuity concept is adopted to enrich the displacement field of the fibers in order to describe the opening of cracks and the development of plastic hinges. The material behavior at the discontinuity is characterized by a cohesive law linking the axial stress and the displacement jump by a linear relation, which allows capturing the released fracture energy. The variational formulation is presented in the context of the incompatible modes method. Moreover the additional modes are statically condensed at the element level. The corresponding computational procedure is detailed in the paper.

Several numerical applications and general remarks are finally provided to illustrate the performance of the proposed element.

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# Modeling of load-induced thermal strain of concrete at macro- and mesoscale

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## ABSTRACT

One of the most important aspects of concrete behavior at elevated temperature is the consideration of thermal strain. Under exposure to elevated temperature concrete tends to expand, the degree of which is mainly governed by the aggregate properties. However, when concrete is loaded prior to heating, the degree of expansion reduces depending on the level of load. The difference between the free thermal strain of load-free concrete and the thermal strain of loaded concrete is termed as load-induced thermal strain (LITS). A substantial amount of experimental research has been performed so far to identify the thermal strain of concrete. It has been observed that the effect is present for different types of concrete and relatively independent of the type of aggregates or cement. However, there is still disagreement regarding the underlying mechanism that governs thermal strain of loaded concrete. Some researchers consider it to originate primarily from the processes in the cement paste, while others distinguish between the effect of dehydration processes in cement paste and the incompatibility between the different concrete phases.

In the present work a 3D finite element numerical model is employed to investigate thermal behavior of concrete. The model is based on the temperature dependent microplane model for concrete. At the macro scale LITS are modeled explicitly, i.e. the thermal strain is a function of the level of compressive stress. It is demonstrated that such a model can realistically predict the overall thermal strain of concrete on macro-scale, when concrete is assumed to be homogeneous. However, such approach offers little insight into the origin of LITS.

To get better insight into the phenomena related to LITS, a meso-scale numerical analysis using the above mentioned model is performed. At meso scale concrete is discretized as a two-phase material consisting of mortar and coarse aggregates (two aggregate sizes). It is assumed that LITS mainly originates from the incompatibility of the two concrete components, i.e. as a consequence of the load induced damage of mortar. Hence, at meso scale LITS are not explicitly imposed in the model. The results are validated against experiments performed by Hager [1]. It is found that the meso-scale model is capable of predicting the total free thermal strain as well as reproducing the crack patterns observed in the experiments on the load-free specimens. More importantly, the meso-scale model realistically captures the vast amount of LITS in case of loaded concrete, particularly for temperatures above 250°C. The presented results confirm that LITS is a primarily a result of the incompatibility in concrete phases and only a small part of LITS is due to dehydration processes in the cement paste at temperatures up to approximately 250°C.

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# Random Lattice Particle Modeling of Damage Localization in Concrete Members Under Compression

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## ABSTRACT

The ability to predict the localization of damage in concrete members subject to uniaxial compression is investigated by means of a recently developed random lattice particle model. Such capability is of great interest in the modeling of concrete structures, since most of the existing mod- els rely on the a-priori definition of a zone in which the nonlinear behavior is concentrated. Lattice particle models, by explicitly representing the mesoscale structure of the material, are capable of sim- ulating the localization of damage. Herein, aggregate particles are represented by poly-sized spheres embedded in a cementitious matrix. The connectivity among particles is defined by a Delaunay tetra-hedralization of the sphere centers; the resisting areas of the lattice struts are evaluated by a graph that is dual to the tetrahedralization. The mesoscale mechanical properties used in the simulations were measured as part of a multiscale experimental campaign, which also served to validate the numerical macroscopic response of concrete elements subjected to uniaxial compression.

# Crack Propagation for Concrete Flat Plates Using XFEM Method

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**ABSTRACT**

Flat plate concrete structures are easy to construct and cheap to build. However, they are susceptible to a type of brittle failure known as "punching shear", where columns punch through the floor leading to progressive collapse[1]. This is a particularly dangerous type of failure as it occurs suddenly and without warning. A finite element model was developed and validated based on the author's previous tests for a square slab [2] with a single column stub. This arrangement simulates the type of column to slab arrangement found in many office buildings. The failure mechanics were examined and the model gave a good agreement with the experimental results identifying the correct crack pattern and the failure loads. With the modelling approach validated, it was possible to examine a range of further slab shapes such as circular slabs, and also the effect of varying parameters such as slab thickness. Then a 2-d axisymmetric model was taken for the circular slab to model the punching crack propagation in detail. This was possible using both a continuum approach and also a discrete crack approach using XFEM. The XFEM results show good agreement between crack location and areas of highest principle strain, as expected.

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## ABSTRACT

Concrete is composite, highly heterogeneous material, with randomly distributed defects of different sizes and shapes. The mechanical behavior of such material is greatly influenced by the geometry and the properties of the microstructural components. Since a reliable prediction of concrete behavior cannot be based only on experimental studies, computational analysis is a fundamental tool for better understanding of microstructural phenomena induced by the interaction between different components. Most of the engineering studies available in the literature consider concrete as a homogeneous material formulated within the framework of continuum mechanics. Although nonlinear macroscopic models for concrete can realistically predict its global behaviour, they are unable to capture some important phenomena from the meso level that are strongly influenced by material heterogeneity.

In the present contribution a meso scale model for concrete is proposed. In the model concrete is considering as a two-phase composite material, i.e. aggregate and mortar are discretized by three-dimensional finite elements. The presence of interfacial transition zone (ITZ) between aggregates and mortar is not explicitly accounted for. The numerical simulations are carried out using 3D finite element code MASA [1]. As a constitutive law for mortar the microplane model is employed [2]. Aggregate particles of different sizes are randomly generated. They are assumed to be linear elastic. Three-dimensional finite element simulations for concrete cylinder loaded in uniaxial compression are carried out. The results of numerical simulations show very good agreement with the experimental data reported in [3], confirming the validity of the proposed mesoscale model for concrete.

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# Determination of Size-Independent Fracture Energy of Granite Using Peak Loads of Beams

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## ABSTRACT

Fracture energy, defined as the amount of energy necessary to create one unit area of a crack, is a very important parameter in analyzing the behavior of quasi-brittle materials such as concrete, mortar, rock, et al.. Tests of three-point-bending notched beams are usually performed to determine the fracture energy and toughness of concrete or mortar. Previous studies proposed an analytical approach to correlate the local fracture energy at the crack-tip region with the peak loads of concrete [1] and mortar [2] beams. Then the size-independent fracture energy and free boundary effects can be obtained and boundary effect theory [3] is improved. The intention of this paper is to determine the size-independent fracture energy of granite by virtue of the peak loads of three-point-bending notched beams. An analytical model was presented to correlate the peak loads with the crack-tip local fracture energy in granite beams based on fictitious crack model [4]. A fracture test was then carried out on granite beams with two depths, i.e., 30 mm and 70 mm. For the beams with depths of 30 mm, the notches are cut with lengths from 3 mm to 18 mm. For the beams with depths of 70 mm, the notch lengths vary from 1 mm to 53 mm. The average value of the maximum tensile stress at the fictitious crack-tip is adopted as 8 MPa. Upon the comparison between the analytically predicted peak loads and the experimentally determined ones, the correlation between the crack-tip local fracture energy and notch length can be obtained. It can be found that the value of crack-tip local fracture energy almost keeps 300 N/m without free boundary effect for the notch lengths from 9 mm to 18 mm in the beams with depths of 30 mm and for the notch lengths from 21 mm to 45 mm in the beams with depths of 70 mm. Thus, the size-independent fracture energy is 300 N/m for this type of granite.

# Coupled Hydro-Mechanical Cracking of Concrete using XFEM in 3D

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**ABSTRACT**

The presence of cracks subjected to hydraulic pressures in plain concrete structures is a major concern for their durability, serviceability and stability. To assess the performance of cracked structures several mechanical and hydraulic response parameters have to be computed. The proposed paper presents the development, implementation and application of a new nonlinear strongly coupled finite element hydraulic fracturing model for concrete dams structural stability assessment.

Flow laws in cracks with varying parameters such as aperture, roughness, tortuosity and Reynold's numbers were first established by Louis [1]. Depending on these parameters, the formulation of the hydraulic problem leads to a system of nonlinear equations. The inclusion of drains, with nearby very strong hydraulic gradients, when computing flow, makes it necessary to have different (multi-physics) finite element models; one with a hydraulic mesh and one with a mechanical mesh. Therefore, the hydraulic and mechanical subproblems are solved using a partitioned procedure, as they have different resolution requirements and their computational domains have non-matching discrete interfaces. Thus, a key aspect is the transfer of the structural crack apertures to the hydraulic mesh, and the transfer of the hydraulic pressures to the mechanical problem by respecting the applied load equilibrium [2].

In this work, the regularized local anisotropic continuum poroelastic damage method (CPDM) is used to describe the first stage of the fracture process zone (FPZ) formation. When the damage has reached a critical value, a switch to the cohesive XFEM model is achieved by ensuring that the fracture energy that remains to be dissipated by the CPDM model is transferred to the XFEM model [3]. The XFEM formulation makes possible the computation of the crack aperture as well as the application of pressure on the crack surfaces for simulation of hydraulic fracture initiation and propagation. Finally, a crack-tracking technique is used to propagate the crack path along a single row of finite elements.

An application of the proposed hydro-mechanical constitutive model and numerical solution strategy on a gravity dam illustrates the effectiveness of the model to predict the structural response in cracked condition.

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# Micromechanical Characterization of Energy Dissipative Mechanisms in Fracture Process Zone

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## ABSTRACT

Concrete is extensively used as a construction material but little understanding has been gained to explain the complex mechanisms which affect its mechanical behaviour. The formation of a fracture process zone ahead of a crack tip in concrete is responsible for its quasi-brittle nature and other phenomena such as the size effect. There are various toughening mechanisms that occur in the process zone and an understanding of the physics of these mechanisms demand attention.

In the present study, the concepts of micromechanics have been used to characterize some of the mechanisms occurring in the fracture process zone. The overall behaviour of a material at the macro-scale is expressed in terms of various parameters that govern the behaviour of the micro-constituents in a systematic manner with the aid of micromechanics [1].

Concrete is modelled as a two phase composite at the meso-level; the coarse aggregate phase being dispersed in the mortar matrix phase. Debonding of the coarse aggregate from the surrounding matrix and friction between the aggregate and the mortar are assumed to dissipate considerable amount of energy in the fracture process zone. The aggregate-mortar interface is characterized by a nonlinear interface law showing softening. Coulomb friction is considered to cause inelastic effects at the interface. The Mori-Tanaka method is used as a homogenization scheme to obtain the effect of the aggregate debonding and friction on the macroscopic behaviour of concrete [2].

The different parameters such as aggregate size, elastic properties of the aggregates and the mortar, the volume fraction of aggregates and the interface properties affect the macro-behaviour of concrete to a large extent. The proposed analytical model helps us to gain a better understanding of the complex phenomena that occur at the constituent level of concrete and will enable us to design the material for better performance under tensile loading.

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# Constitutive Models and Arc-Length Control Method in Branch-Switching Analysis to Bifurcation Path for Diagonal Tension Failure of Reinforced Concrete Beam

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## ABSTRACT

Examined is the influence of constitutive models for cracking and Arc-length control method on branch-switching analysis to bifurcation path for diagonal tension failure of reinforced concrete beam.

In the first series of analysis branch-switching from fundamental to bifurcation paths for diagonal tension failure in reinforced concrete beam is performed by using eigenvalue analysis and Arc-length control method, and the results are compared with those of the bifurcation analysis by using direct displacement control method instead of the Arc-length control method. A lot of first-order eigenmodes corresponding to unloading are confirmed, but not those corresponding to diagonal and longitudinal cracks in eigenvalue analysis for the branch-switching analysis with Arc-length control method. Due to this fact the analysis with Arc-length control method fails in branch-switching to bifurcation path for diagonal tension failure.

In the previous analysis the Multi Equivalent Series Phase Model is utilized as the constitutive model for concrete. On the other hand, in the second series of analysis, Multi-directional Fixed Crack Model and Rotating Crack Model are utilized in the branch-switching analysis to examine the influence of constitutive modeling for crack. Convergence of both models in iterative solution is not so good. The post-bifurcation paths do not differ so much from the fundamental path in the case of the Multi-directional Fixed Crack Model, but branch-switching was not able to be performed with the Rotating Crack Model because of no bifurcation point obtained. The Multi-directional Fixed Crack Model evaluates the strength relatively well, but the Rotating Crack Model underestimates it.

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# Prediction of Shear Failure of Large Beams Based on Fracture

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## ABSTRACT

Authors are involved in the implementation of fracture mechanics-based constitutive model for concrete structures [1]. The model exploits the crack band approach for the regularization of strain softening localization in tension as well as in compression [3]. In theory, this approach aims for objective, low mesh sensitivity solutions of brittle failure. It should be suitable for the simulation of size effect due to brittle properties of concrete. During of this development, limits of this approach were observed [2]. This should be recognized in practical applications.

Blind prediction bench marks based on experiments are organized for assessment of model uncertainties [2]. The model developed by the authors was recently verified in the "Prediction contest for strength of four meter deep reinforced concrete slab strip" organized by M.P. Collins and E.C. Bentz from University of Toronto, where it provided the best prediction within the well attended blind prediction competition. The authors utilized this project for the investigation of robustness and range of application of the smeared crack approach.

It was recognized that the uncertainties in parameters of concrete in tension, tensile strength and fracture energy, are directly reflected in the model uncertainty of structural shear resistance. Other important parameters are shear strength, stiffness and compressive strength reduction of the cracked concrete. These parameters are in practical cases usually not tested. Instead they are related to compressive strength, which is the only verified parameter. The sensitivity to these parameters is investigated in the paper.

Sensitivity to mesh size and material parameters will be demonstrated. The study provided a unique chance for assessment of model uncertainties of numerical simulations based on fracture mechanics.

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# T-stress of Concrete under Four-point Bending

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## ABSTRACT

As the constant term of the infinite Williams series expansion for stress component parallel to the crack flank, *T*-stress is believed to significantly influence the stress and strain fields around the crack tip, and thus the failure of fracture. The authors have explored the *T*-stress influence on the fracture toughness from several concrete fracture models under pure mode I loading and concluded that *T*-stress values are so small compared to the singular term thus fracture. As an extension, the paper deals with the *T*-stress of concrete under mixed mode loading.

Mixed mode stress-intensity factors (SIFs) and the T-stress for different geometries of four-point bending specimens were calculated by means of finite element analysis through a software suite Abaqus, where the influence of the loading point and crack location were considered.

The fracture properties, $K_I$, $K_{II}$ and *T*-stress expressions for four-point bending were constructed based on pure bending and pure shear by means of finite element calculation. The results reveal that considerable values of the *T*-stress exist with different combinations of $K_I$ and $K_{II}$, and the stress biaxiality factor $B$ varies, including its magnitude and sign, along with the change in geometry size.

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# Session RS04: Durability/Coupled Problems

# Multi-physical and multi-scale deterioration modelling of reinforced concrete: modelling corrosion-induced concrete damage

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**ABSTRACT**

Deterioration of the civil infrastructure (bridges, tunnels, roads, and buildings) together with increasing functional requirements (e.g. traffic load and intensity) present major challenges to society in most developed countries. A major part of the infrastructure is built from concrete and costs for maintenance, renovation, and renewing are growing and by now taking up a major part of concrete structure investments. While engineering tools and methods are well developed for the structural design of new structures, tools for assessing current and predicting the future condition of reinforced concrete structures are less advanced. Existing prediction tools are largely empirical, and thus limited in their ability to predict the performance of new material, structural, or maintenance solutions. As such, the inability to reliably assess the long-term future ramifications of today's design decisions poses a major obstacle for the design of reinforced concrete structures. A primary reason for the lack of reliable modelling tools is that deterioration mechanisms are highly complex, involve numerous coupled physical phenomena that must be evaluated across a range of scales, and often cut across several academic disciplines and faculties.

In this paper a modelling approach for corrosion-induced concrete damage is discussed, which is embedded in an overarching cross disciplinary numerical framework that combines mechanical, chemical, and electrochemical processes on different length scales in reinforced concrete. Corrosion-induced concrete damage is thereby investigated by means of numerical simulations utilizing a coupled lattice and finite element method (FEM) modelling approach. While the reinforcement domain is discretized by the FEM, a lattice approach is used for the discretisation of the concrete domain. To describe corrosion-induced damages, a thermal analogy is used to model the expansive nature of solid corrosion products. The modelling approach further accounts for the penetration of solid corrosion products into the available pore space of the surrounding cementitious materials as well as non-uniform distribution of corrosion products along the circumference of the reinforcement. Finally, numerical predictions in terms of corrosion-induced deformations and cracking of the modelling approach are compared to experimental data obtained by digital image correlation.

# Permeability and relative permeability of mortar undergoing damage : a hierarchical capillary bundle approach

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## ABSTRACT

The purpose of this work is to achieve a better understanding of the relationship between mechanical damage and the transport properties of cementitious materials. In the literature, analyses are usually restricted to intrinsic permeability of the material and the evolution of the apparent permeability with respect to the pressure gradient and to the nature of the fluid considered are left aside. A new model capable to provide the apparent permeability of a porous material to gas, directly from the pore size distribution and from the properties of the gas is discussed. Comparisons with experimental data on mortar specimens show that the model can reproduce the intrinsic permeability and its evolution when the material is subjected to mechanical damage, provided the pore size distributions are available. For a given pore size distribution, the evolution of the apparent permeability is also provided by the model and test data with several types of gases compare quite well with the model.

Extension to the transport of different phases (e.g. water and water vapour) is discussed, with a view towards the simulation of nuclear accident in containment vessels. It is shown that small pores that are not affected by damage according to the pore size distribution are of great importance in the evaluation of the relative permeability to liquid and vapour as a function of the saturation. A tentative model based on the percolation of small pores into an equivalent homogeneous material is discussed and compared with the existing – standard – approach relying on Van Genuchten relationships. The advantage of the present model is that it relies on the measurement of the pore size distribution and on the physical properties of the considered fluid. The description of permeation does not require any additional fitting parameters.

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# Grizzly Model of Fully Coupled Heat Transfer, Moisture Diffusion, Alkali-Silica Reaction and Fracturing Processes in Concrete

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**ABSTRACT**

The use of concrete in nuclear power plants for containment and shielding of radiation and radioactive materials has made its performance crucial for the safe operation of those facilities. As such, when long-term operation is considered for nuclear power plants, it is critical to have accurate and reliable predictive tools to address concerns related to various aging processes of concrete structures and the capacity of structures subjected to aging-related degradation.

Idaho National Laboratory (INL) has been developing a fully coupled thermo-hydro-mechanical-chemical (THMC) concrete model, referred as Grizzly, with the ultimate goal of reliably simulating and predicting the long-term performance of concrete structures in nuclear power plants subjected to various aging and degradation mechanisms, such as external chemical attacks and internal volume-changing chemical reactions within concrete structures induced by alkali-silica reactions (ASR) and long-term exposure to irradiation.

Grizzly concrete model is built on the INL's Multiphysics Object Oriented Simulation Environment (MOOSE) framework, which provides an ideal multiphysics environment for solving arbitrary coupled systems of partial differential equations. In this paper, we present a fully coupled concrete model implemented in our Grizzly code for various coupled processes, including moisture diffusion, heat transfer, ASR-induced swelling and elastic/inelastic mechanics. Example simulation results and preliminary model validation results against experimental data reported in the literature will be provided also in this paper. In particular, we will present simulation results of using both smeared cracking and rate-dependent damaging mechanics approaches for simulating the ASR swelling induced degradation of concrete structures and its feedback to moisture and heat transport processes. The close match between the experiments and simulations clearly demonstrates the potential of Grizzly for reliable evaluation and prediction of long-term performance and response of aged concrete structures in nuclear power plants.

# Numerical and experimental study of ASR in concrete at the meso-level

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## ABSTRACT

In this paper, an ongoing research project on the mechanisms of concrete deterioration due to Alkali-Silica Reaction (ASR) is presented, together with some preliminary results. The research program includes both experimental and numerical modelling work.

The first part includes the development of two new experimental setups, one devoted to study the ASR expansion mechanisms at the level of a single matrix-aggregate interface [1, 2] and the other to the study of ASR expansions of cubic concrete specimens under triaxial confinement.

The second part includes the formulation and numerical implementation of a chemo-mechanical model for ASR expansions in concrete at the meso-level. The model considers three main diffusion/reaction field equations for the concentrations of silicates, calcium and alkalis in the pore solution, complemented by a number of chemical kinetics and chemical equilibrium equations. The volume fraction distribution of the solid constituents of the hardened cement paste and the reaction products evolve with the progress of the reaction, determining the diffusivity properties of the material and, eventually, inducing expansions [2, 3].

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# Meso-macro modelling of crack-induced diffusivity in heterogeneous materials

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## ABSTRACT

This paper presents a meso-macro numerical approach for the determination of macroscopic diffusivity tensors in heterogeneous materials such as concrete. These macroscopic tensors account for important features of heterogeneous materials such as cracking process - evolution from diffuse cracks in the bulk to localized macrocrack -, tortuosity and connectivity of the crack, induced-anisotropy and, presence of aggregates. The mesoscale coupling is based on the numerical work of Benkemoun et al. ([1]) for the mechanical aspect and Fick's law coupled to the experimental work of Djerbi et al. ([2]) for the chloride ions transport model ([3]). For the determination of macroscopic diffusivity tensors, we refer to the upscaling method proposed in Pouya et al. ([4]). This paper presents numerical examples in the context of concrete-like materials. We show the ability of the numerical upscaling process to model anisotropic macroscopic diffusivity tensors. We demonstrate how the crack pattern and the presence of aggregates induce the anisotropy of the macroscopic diffusivity tensor and confirm the intuitive idea that the whole set of fine cracks - globally speaking of heterogeneities - cannot lead to an isotropic diffusivity tensor.

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# Normal and tangential extraction of embedded anchor plates from precast façade concrete panels: experimental program.

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## ABSTRACT

The use of precast concrete elements like façade panels relies on embedded steel anchorages that are used to connect them by welding to the main structure and to each other. The present paper will be focused on four types of inexpensive non-certified anchorages, fairly used in the precast concrete industry, but not properly covered by design standards. Three of the anchorages are composed of four welded ribbed-steel bars connected to a steel plate. The fourth one has two ring-shaped bars welded to the plate at both ends. The anchorages are embedded in the concrete, thereby maintaining the external face of the plate at the surface of the panel in order to weld the connection elements to it.

Such connections may be subjected to normal or tangential forces, or even a combination of both. The connections may eventually fail in a complicated way involving concrete cracking, pull-out of the surrounding concrete, yielding of the legs welded to the plates or failure of the welded cords.

The objectives of the experimental program were to determine the mechanical response of the anchor plates and to study their failure modes by analyzing the damaged area of the concrete (crack propagation) and the load–displacement curves at the load application point. Each of the four anchorage-types were tested under two different load directions and the tests were repeated three times for each geometrical configuration in order to obtain a representative value. Therefore, a total of 24 tests were carried out.

In addition, it is important to highlight that the calculation methods for these anchorages are usually quite conservative, which fosters the need for ad hoc experiments that give accurate values for their real strength and that may also be used to validate more sophisticated methods to assess their load capacity. In this regard, we have developed a three-dimensional fracture model, wich is out of the scope of this paper.

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# Effects of Heating and Carbonation on Fracture Properties of Concrete

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## ABSTRACT

Concrete structures for nuclear power plant may be subjected to the heating action and carbonation action for a long period. Many studies have already reported that the concrete structure subjected to the heating action can be retained by maintaining the heating conditions of not more than 65°C under general control standards for nuclear power plant. The effect of the heating should be considered to discuss the long-term safety and durability of concrete structures in the viewpoint of compressive strength, however the fracture properties of concrete, which were important to discuss the crack resistance for the nuclear power plant, are not yet to be clarified. This paper reports on the investigation into the fracture properties of mortar subjected to the effects of heating and carbonation action. The water-cement ratios (W/Cs) of mortar used in this experiment is set to 0.6, 0.8, 1.0. Mortar specimen size was 40mm x 40 mm x 160 mm. After the 28-day water curing at 20°C, specimens were set in the heating condition of 20°C and 65°C and carbonation acceleration conditions of 0% and 5%. After the heating and carbonation acceleration, three-point bending tests were conducted to measure the load versus crack mouth opening displacement (L-CMOD) curves. The fracture energy was estimated by the tension softening diagram calculated by the L-CMOD curve based on the poly-linear inverse analysis. Effects of heating and carbonation on the fracture parameters were discussed.

## Session RS05: Novel Cementitious and/or Other Quasi-Brittle Materials

# Improving Fracture Toughness of Polymer Concrete Using MWCNTs

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**ABSTRACT**

Polymer concrete (PC) are used in bridge deck overlays due to its superior durability specifically freeze-thaw and corrosion resistance. The excellent durability of PC is related to its impermeable microstructure and good bond to concrete or steel substrates. However, there is an increasing need to improve PC resistance to crack propagation (fracture toughness) to enhance its fatigue resistance and extend its service life. Researchers showed that objective possible using dispersed chopped synthetic fibers (6-12 mm long). However, this approach was criticized for its dramatic impact on PC flowability. Here we suggest improving fracture toughness of PC using multi-walled carbon nanotubes (MWCNTs).

PC mixes were produced using epoxy polymer concrete and standard aggregate with varying contents of COOH-functionalized MWCNTs being 0 (Neat), 0.5, 1.0, 1.5 and 2.0 wt.% by weight of epoxy. Flowability of PC incorporating MWCNTs was tested. The tensile strength of PC incorporating MWCNTs was evaluated using splitting tension test. A closed loop notched beam three-point bending test fracture test was used to evaluate fracture toughness of PC. The crack mouth opening displacement (CMOD) clip gage was used to provide feedback and to control the rate of loading. The inverse analysis approach was used to extract the bilinear stress-crack opening displacement relation and calculate the fracture toughness ($G_f$) of PC with and without MWCNTs. It is shown that functionalized MWCNTs significantly improves the fracture toughness of PC without significantly impacting its flowability. Microstructural analysis of PC explains the effect of incorporating MWCNTs.

# Investigation on compressive fatigue damage process of ultra-high toughness cementitious composites

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## ABSTRACT

Ultra-high toughness cementitious composites (UHTCC) is a kind of cementitious material reinforced by random distributed short fibers, which was proposed by Li and Leung and was designed with micromechanical principles to achieve the strain hardening behavior [1]. This material has potential use in some complicated environment and the structures which sustain repeated or fatigue loads. Considering that the fatigue behavior of Ultra High Toughness Cementitious Composites under compression is crucial for its application in certain conditions (e.g. airport runway and road pavements) and fatigue damage of structural components might be affected by both the flexural and compressive fatigue behaviors, the available work is rather limited and a better understanding of the compressive fatigue behavior is required. In this study, a series of monotonic and fatigue tests were performed to investigate the fatigue behavior of this material under compression. Compressive fatigue tests were conducted on 27 cylinder specimens (70 mm in diameter and 140 mm in height). The loading frequency of fatigue tests was set as 4 Hz and the maximum stress was 90%, 85%, 80%, 75%, 70% and 65% of the compressive strength with the stress ratio set constant as 0.1. The fatigue life of Ultra High Toughness Cementitious Composites specimens obeys Weibull distribution and the $S$ - $N$ relationship was given, which indicates that the fatigue life of this material is higher than that of plain concrete and steel fiber reinforced concrete under the same stress level [2] [3]. It is observed that, the specimen failure mode and deformation pattern of Ultra High Toughness Cementitious Composites were similar to those of fiber reinforced concrete. The failure surface and damage process of this material were investigated. A new failure mode of PVA fiber with crush end was discovered with the help of SEM analysis and EDS analysis. This failure mode forms from that the ruptured end of fibers suffered repeated crush and friction. Besides, based on the various failure mode of PVA fibers, the fatigue failure surface could be divided into three regions, including fatigue source region, transition region and crack extension region. During fatigue failure process, micro cracks initiate in fatigue source region, propagate in transition region and form main crack in crack extension region. The results of this investigation could be proposed for potential application of Ultra High Toughness Cementitious Composites.

# Structural performances of RC beams strengthened with Steel Reinforced Geopolymeric Matrix (SRGM)

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## ABSTRACT

The most of the existing Reinforced Concrete (RC) members that need retrofitting have deteriorated cover concrete and/or corroded internal steel bars. To perform a strengthening intervention on these members, the following independent operations are requested: removal of the deteriorated concrete, application of a corrosion inhibitor on internal reinforcing bars, repairing/restoring of the cover concrete and then application of the external reinforcement with Externally Bonded (EB) technique [1]. These operations, due to the used materials, pollute environment.

In the present work an innovative eco-friendly solution, alternative to EB, for retrofitting of existing RC structures was conceived, designed and experimentally tested. The proposed solution includes three operations in one: Inhibiting-Repairing-Strengthening (IRS). It consists in the installation of a stainless steel fabric in the cover concrete, restoring the latter with a new geopolymeric fireproof matrix (Steel Reinforced Geopolymeric Matrix, SRGM). This inorganic matrix has significant advantages compared to the traditional epoxy resin used for Fiber Reinforced Polymer (FRP) system, such as: excellent resistance to corrosion, high value of transition temperature (about 800°C), no emission of toxic gases under intense fire, excellent durability even in strong aggressive conditions (coastal areas, deicing salts, acid rain), high resistance against sulfates [2, 3, 4]. A further advantage of geopolymeric matrix compared to epoxy adhesives is related to their inorganic silicoaluminate nature, which makes these materials similar and alternative to ordinary Portland cement, due to high mechanical properties and environmental advantages. In fact, geopolymers generates 80% less carbon dioxide and the global warming potential is 70% lower than Portland cement [5].

To investigate the effectiveness of the innovative IRS solution, a set of large-scale RC beams with different geometrical properties, low concrete strength, corroded smooth round/ribbed bars, were strengthened with IRS-SRGM/EB-SRGM systems and tested under four-point bending. Also theoretical predictions of the tested beams, through a fracture-based model, were performed.

The results showed that the IRS-SRGM system provided greater load carrying capacity and ductility than the EB-SRGM system. The beams strengthened with IRS-SRGM failed by concrete crushing and/or slippage at fiber-matrix interface, whereas the beams strengthened with EB-SRGM failed by brittle end debonding (detachment of the SRGM system). Furthermore, the axial strain in the IRS-SRGM system was about 1.8 times that of the EB-SRGM system. Consequently, the IRS solution guarantee a higher composite action and a better overall performance than the EB technique.

The proposed IRS solution could be an effective alternative to traditional EB technique, reducing the time and costs of intervention with an eco-friendly technology.

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# Using Calcium Carbonate Whisker in Engineered Cementitious Composites

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## ABSTRACT

A new kind of multi-scale engineered cementitious composite (MS-ECC), which contains polyvinyl alcohol (PVA) fiber and calcium carbonate (CaCO3) whisker, was designed from the perspective of multi-scale structure and fracture process of cementitious material. 12 series of MS-ECC proportions was casted and the mechanical properties including compressive strength, uniaxial tension behavior and flexural behavior of the mixtures were studied. The results indicates that the strength and ductility of MS-ECC was enhanced with proper addition of CaCO3 whisker. Moreover, it seems that the PVA fiber can be appropriately reduced due to the existence of CaCO3 whisker, which is beneficial in decreasing the production cost of fiber-reinforced cementitious composites for large-scale construction projects.

**Key words:** calcium carbonate whisker, polyvinyl alcohol fiber, mutil-scale, mechanical behaviors,

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# Nanoparticles from food waste: a "green" future for traditional building materials

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## ABSTRACT

With the development of "mega-constructions" and especially of slender components in ever higher buildings, new concrete needs to be more performing. So, compressive and flexural strength, toughness and durability are finding entry in concrete technology.

In recent work, to meet the challenge of "green" high-performance concrete, Ferro et al. investigated pyrolyzed particles from food waste as inerts in the cement composites [1]. In fact, in the EU, there are about 3000 million tons of organic waste per year, and 10% of these are agro-food industry wastes [2]. Pyrolysis is a promising approach that can be used to convert biomass wastes into energy, in the form of bio-oil, bio-char, and syngas [3].

In this work pyrolyzed hazelnut shells have been used. They are capable of generating high performance cement composites, by increasing the compressive strength, the peak load under bending, the fracture energy and the durability. Also, they modify the fracture path, thus resulting in a larger fracture zone. Moreover, having a low cost, they can contribute to produce concrete in a more sustainable way, inducing a reduction of energy consumption and reduction of $CO_2$ emissions.

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# Fracture of lightweight foamed concrete in evaluation of bond behavior of steel reinforcement embedded in LWFC

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## ABSTRACT

Low weight, self-levelling, high workability and thermal insulating properties make lightweight foamed concrete (LWFC) an attractive substitute for normal weight concrete (NWC). The unfamiliarity of LWFC and paucity of design guidance pose concern for its use in structural application. One such concern is the bonding of steel reinforcement within LWFC. The bond behavior of deformed steel reinforcement (rebar), embedded in LWFC and NWC was tested using pull-out (PO) and the beam-end (BE) tests[1]. The concretes used for testing were a reference NWC and LWFC with casting densities of 1200, 1400 and 1600 kg/m$^3$. The nominal diameters of rebar used were Y10, Y12 and Y20 at embedded lengths of 3, 4 and 5 nominal bar diameters. Characterization of these materials included compressive strength, Young's modulus, tensile splitting strength and wedge splitting fracture energy.

Recent progress in mix design and density control of LWFC [2] has led to the notion for its use in structural application. Structural use of reinforced LWFC (R/LWFC) has shown promise [3]. This paper reports on a study performed at Stellenbosch University (SUN) to address the bond behaviour of deformed steel reinforcement in LWFC. An earnest attempt is made to obtain design bond stresses that will be safe and suitable for use in structural design of reinforced LWFC. In parallel, durability enhancement studies of R/LWFC are performed at SUN.

The bond-slip envelopes of the denser LWFC yield significant bond stress magnitudes, but lack the ductility in failure observed in the NWC tests. The least dense LWFC exhibits ductility during failure, but lacks sufficient bonding stress magnitude. Whilst significant advances have been made in improved strength, both in splitting tension and compression, the LWFC developed in this research by comparison lacks in stiffness and fracture toughness. Through careful, closed-loop wedge-splitting tests on LWFC, the fracture energies could be determined. Of importance, is the significant difference in bond behavior observed in the PO tests from that in the BE tests. The interaction of LWFC fracture and rebar bond mechanisms in the BE tests in the presence of shear and bending moment, is the direct cause, and the relatively low fracture toughness leads to low apparent bond resistance. Through this understanding, material improvement is envisaged by inclusion of aggregate to increase cracking tortuosity and thereby fracture energy of LWFC, in order to improve rebar bond in LWFC.

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# Comparative Study between Microstructure of a Novel Durable Concrete and Normal Concrete Subjected to Harsh Environments

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## ABSTRACT

"Degradation of concrete members exposed to aggressive sulfuric acid environments is a key durability issue that affects the life cycle performance and maintenance costs of vital civil infrastructures" [1]. Groundwater, chemical waste [2], sulfur bearing compounds in backfill [3], acid rain in industrial zones [4] and biogenic acid in sewage systems [5] are the main sources of sulphuric acid affecting concrete structures.

In this research, microstructures of a novel acid resistant concrete (ARC) and a type of conventional concrete (CC), as the reference, have been studied in the laboratory subjected to an accelerated test. For this purpose, ARC and CC, were immersed in 7% sulfuric acid solution. Mechanical properties of both concretes as well as their microstructures were examined after 28 days of curing and then after two, four and eight weeks of exposure to acid. Scanning Electron Microscopy (SEM), Energy Dispersive Spectroscopy (EDS), X-ray Diffraction (XRD) and X-ray mapping (XRM) were employed to analyse the microstructure of concretes before and after exposure to acidic environment. The results of this analysis revealed interesting facts about the mechanism of sulfur penetration in both concrete samples. In addition, they showed differences in the crack locations and propagation patterns and in Interfacial Transition Zones (ITZ) of concretes, particularly after acid exposure. These changes of microstructures, as was proved in experimental tests, could significantly contribute to changing the mechanical and structural properties of concrete elements.

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# Fatigue-induced Fracture of Pervious Concrete: Physical and Numerical Experimentation

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**ABSTRACT**

Two types of pervious concrete are used to form beam specimens, which are subjected to fatigue loading. The first type is produced with monosized spherical aggregates; the second type is produced with a gap-grading of natural aggregates. Loading is applied via constant amplitude displacement cycles and reduction in specimen compliance is monitored. Loading is stopped at various stages prior to specimen failure to enable the investigation of damage progression using dye impregation techniques. The first type of pervious concrete, based on spherical aggregates, lends itself to computer modeling. Two lattice modeling strategies are employed: 1) a coarse discretization of material structure in which each aggregate is represented by a nodal point. The paste bridges between aggregates are represented by elements that interconnect the nodal points; and 2) a finer discretization in which the salient phases (i.e., aggregate, matrix, and their interfaces) are explicitly represented. With respect to the aggregate positions, a one-to-one correspondence is sought between the experimental and numerical models. This combined use of physical and numerical experimentation provides insight into the roles of paste distribution and the interface phase on pervious concrete performance under fatigue loading.

# Effect of hybrid fiber reinforcement on corrosion-induced damage of reinforced concrete

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## ABSTRACT

The corrosion of steel reinforcing bars in concrete structures is a primary durability concern in aging infrastructure. Cracks caused by the internal growth of corrosion products increase the permeability of the matrix and degrade the designed capacity of structural elements. In this long-term study, hybrid fiber-reinforced concrete (HyFRC) is investigated for its serviceability enhancement under a two-stage corrosion model (time to corrosion initiation and damage during corrosion propagation). HyFRC, which contains a synergistic blend of microfibers and macrofibers, is selected for its multi-scale approach towards crack control. Reinforced HyFRC and reinforced concrete beams were subjected to chloride penetration and monitored for corrosion activity for up to two years. Because concrete structures are subjected to various crack-inducing loads while in service, beam specimens in this study were placed under a cyclic, flexural preloading protocol prior to induced corrosion to account for such service conditions. The time to corrosion initiation was found to increase with reduced maximum flexural crack widths and suppression of surface splitting cracks during preloading, both of which were improved by HyFRC compared to concrete. Crack resistance provided by hybrid fiber reinforcement was evident during the corrosion propagation stage, as additional surface cracking was not detected with reinforced HyFRC and residual flexural testing revealed no significant degradation in flexural performance. In contrast, damage to reinforced concrete beams resulted in nearly complete loss of rebar-matrix bond due to extensive splitting crack formation and widening. The results suggest hybrid fiber reinforcement was effective in providing chemo-mechanical confinement of expansive corrosion product growth.

# Development of Sustainable Mortar and Concrete Made of Limestone Blended Cement – Influence of Particle Size

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**ABSTRACT**

Due to environmental and energy efficiency concerns there is a growing interest in the development of a blended Portland cement in which the amount of clinker is reduced and partially replaced with mineral additives. Three principal motivators behind these efforts are (1) ecological benefits due to lower CO2 emission to the atmosphere, (2) economic benefits since reduced clinker cement is cheaper to produce, and (3) scientific\technological benefits of improved cement and concrete performances. Two main types of mineral additives are commonly used: (1) pozzolanic such as fly ash, slag and metakaolin and (2) materials which are not considered as pozzolanic additives generally with low reactivity with the cement minerals such as limestone, which is one of the most attractive additives because it is considered natural, available, and economical. According to the literature, the research on limestone as an additive has mostly focused on it having a significant smaller particle size with a significant higher surface area relative to the clinker particles. Furthermore, during the past few years, there has been growing interest in the use of nano scale limestone particles which have a significant effect on the hydration rate and decrease of setting times. Not much work has yet been done on the influences of limestone particles with larger sizes than the clinker or the combined effect of particles with various sizes having different surface areas on the properties of the blended cement paste, mortar and concrete.

This work develops blended limestone cement with higher packing density related to the original cement to maximize the properties of the binder. The limestone particles are grinned separately and then added to the original cement. Limestone powders with several different particle sizes—larger, smaller, and similar to the original cement—were studied to partially replace the original cement. Single particle size distributions of limestone are compared with systems containing a multiple combinations of limestone particle size distributions. The setting history, hydration degree, packing density, fresh and harden properties of cement paste, mortar and concrete were investigated.

It was shown that the properties of cement paste, mortar and concrete made with limestone of different particle sizes were affected significantly by the packing density of the mixture, surface area and size of the particles. It was concluded that the replacement of an active material with an inert additive can improve cement paste, mortar and concrete performances by increasing the packing density of the mixture particles. Mortar and concrete with small size limestone particles exhibited the smallest packing density and hence the lowest compressive strength; whereas mortar and concrete with medium sized limestone particles, showed the highest packing density and hence the highest compressive strength and durability. In the case of cement paste a combination of several different particle sizes in one system provided the greatest performance. The main results of this work will be discussed.

# 3D Printing of Fibers and Reinforcements for Cementitious Composites to Maximize the Performance of FRCCs

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## ABSTRACT

Currently, FRCs (Fiber Reinforced composites) have been utilized with many different applications in various industries. However, Construction area has been adopted relatively late compared with other industries. As the needs for FRCs in this field increase, the research activities in this area have been boomed rapidly. Recently various cutting-edge technologies have been integrated with manufacturing matrixes and fibers to develop higher performance of FRCs. However, the technologies involved in current stages are usually focusing on the development of material properties and performances of matrix, fibers and interface between matrix and fibers with various newly immersed technologies. One of recently adopted hot technologies is 3D printing technique. Many different applications are currently attempting to utilize 3D printing technologies for the new direction of construction area.

The application of 3D printing methods in this field is developed for new materials and methodologies to print structure directly. In this study, reinforcements including rebars and fibers are printed using 3D printer to make FRCCs (Fiber Reinforced Cementitious Composites). Usually, when we make FRCCs, fibers are mixed with cement-based matrix during the process. The distribution of fibers, however, is impossible to control because of its random positions. In this study, the methodology is focusing how we can print fibers with controlled manner. The various materials of fibers are not considered because they will be developed in 3D printing technology research area in near future. If we can develop the suggested new fiber printing process, the mixing problems such as clumping, ill distribution and difficulty during mixing will easily be solved with SIFCON (Slurry Infiltrated Fiber Concrete) process. We are going to demonstrate how we can make fiber mat with controlled printing method and the composites will be made following the general making process of SIFCON. For further study, the three-point bending test will be tested for the beam-typed SIFCON specimen to examine the mechanical behavior of the specimen.

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# High Strength Lightweight Strain-Hardening Cementitious Composite Incorporating Cenosphere

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## ABSTRACT

High strength lightweight concrete was originally designed for potential structural applications. However, the brittle nature and higher permeability became the main drawbacks for further broad application. In this case, it is imperative to develop a special type of high strength strain hardening lightweight cementitious composite, offering higher ductility, lower permeability and considerable weight saving. Engineered cementitious composite (ECC) is a class of high performance fiber reinforced composite characterized by strain hardening behavior and tight crack width. In this study, the low density of below 1500 kg/m$^3$ was achieve by introduce lightweight fine aggregates of cenosphere obtained from coal-fired power station to fully replace silica sand generally used in ECC preparation. Binary and ternary binder systems (cement, silica fume and slag) were employed to tailor the matrix properties for obtaining higher strength of more than 50 MPa and lower permeability. Polymeric fibers having a good compatibility with matrix were used to implement strain hardening behavior and higher ductility. The permeability and thermal conductivity tests were conducted to evaluate the applicable performance of resulting lightweight cementitious composite. The correlation between mechanical, physical and thermal properties was build up to reveal the effect of cenosphere on the performances of high strength lightweight strain hardening cementitious composite. The single fiber pull out test and matrix fracture toughness test were conducted to reveal the micromechanical mechanism of strain hardening behavior of high strength lightweight composites.

## Session RS06: Structural Concrete Applications

# Damaged plasticity modelling of concrete in finite element analysis of reinforced concrete slabs

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**ABSTRACT**

Two interior slab-column connections, previously tested, are analysed using 3D nonlinear finite element methods. These slabs were tested under vertical monotonically increasing imposed displacement through the column till failure. One slab specimen was without shear reinforcement that failed in punching shear, while the other slab had punching shear reinforcement and failed in flexure. Both specimens are analysed using the concrete damaged plasticity model offered in ABAQUS. Concrete damaged plasticity model is employed with the fictitious crack model based on the fracture energy; where different failure mechanisms are predicted for tension and compression. Damage can be introduced in the model and it is defined separate in compression and tension. The model can be also equipped with viscoplastic regularization that provides additional ductility in the structure and helps to overcome convergence problems that have been created by cracking and strain localization that relies on the smeared crack approach. Parametric investigation based on the material and plasticity parameters is performed for both specimens. Then, mesh and element type analyses are conducted in order to investigate the proper modelling for each slab. All numerical results are compared to the test results in terms of load-deflection responses and crack patterns. Finite element analysis results are in good agreement with the experimental results and can give an insight into the failure mechanisms and crack developments of each slab. The predictive capability of the calibrated models confirms their ability for parametric studies examining the punching shear behaviour of reinforced concrete slabs with and without shear reinforcement.

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# Experimental investigations on concrete edge failure of multiple row anchorages with supplementary reinforcement

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## ABSTRACT

The presence of supplementary reinforcement, in the form of edge reinforcement and stirrups, have a significant influence on the load-carrying capacity of the anchorage groups with multiple anchor rows loaded in shear perpendicular to the edge. For the anchorages close to an edge provided with supplementary reinforcement, under the action of shear forces towards the edge, the possible failure modes are (i) anchor steel failure, (ii) stirrup yielding (following the concrete cracking), (iii) strut (compression) failure, and (iv) node (anchorage) failure. The current models available in the codes and standards [1, 2, 3] are conservative for low to medium amounts of supplementary reinforcement but tend to be unconservative for high amounts of reinforcement.

This paper presents the results of a comprehensive test program carried out to investigate the behavior of the anchorages with supplementary reinforcement loaded in shear towards the edge. Systematic experimental investigations were performed on the anchorages with multiple anchor rows with supplementary reinforcement loaded in shear towards the edge. The tests were performed on anchorages with 2 to 8 headed studs (one to 4 anchor rows) cast in concrete with 4 different levels of supplementary reinforcement. The test results are discussed in detail to highlight the influence of supplementary reinforcement on load carrying capacity of the anchorages. It has been observed that in case of anchorages with multiple anchor rows, the failure crack always initiates from the back row of anchors, which is in contrast to the current assumption in EN1992-4 [1]. Due to this, more number of stirrups is activated in reality and the anchorage length of the activated stirrups is significantly more than that assumed in current model of EN1992-4. Consequently, for low amounts of supplementary reinforcement, the failure loads calculated by the current model are very conservative when compared to the experimental results. At high amounts of supplementary reinforcement, the concrete strut failure may govern the failure, which is ignored in the current models. Based on the evaluation of these test results, a realistic and rational model has been developed to predict the concrete edge failure loads for anchorages with supplementary reinforcement that will be presented in another paper.

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# Analytical model for concrete edge failure of multiple row anchorages with supplementary reinforcement

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## ABSTRACT

For multiple row anchorages, the failure load corresponding to concrete edge failure is permitted to be calculated either by assuming the failure crack initiating from the front anchor row [1] or by assuming the failure crack initiating from back anchor row [2, 3]. If the failure crack is assumed to originate from the front row of anchors, only the stirrups close to the anchor group are considered as active while the stirrups farther away are ignored. Furthermore, a small anchorage length of the stirrups intercepted by the crack is calculated which results in a small capacity of the hook. In reality, the failure crack initiates from the back row of anchors activating more stirrups and also a larger anchorage length for stirrups results in a higher anchorage capacity of the stirrups. Although by providing higher amounts and closely spaced supplementary reinforcement the capacity of the anchorage could be significantly increased, this increase is not unlimited since beyond a certain point, the concrete strut may undergo compression failure. This forms an upper limit to enhancement of the capacity of the anchorage due to supplementary reinforcement. However, in the current standards [1,2,3] the strut failure is neglected. Furthermore, for anchorages with supplementary reinforcement, the current models consider the contribution of only concrete ‘or’ reinforcement, whichever is greater. Therefore, the current models are very conservative for low amounts of supplementary reinforcement but for relatively high amounts of reinforcement and edge distances the failure loads calculated by the current models become unconservative.

This paper gives the details of a new analytical model developed to evaluate the failure load of anchorages with multiple anchor rows with supplementary reinforcement. The model is developed on the basis of the detailed evaluation of the results of an experimental campaign carried out on anchorages with up to four anchor rows. It has been shown that with the new model, the failure loads for the anchorages with supplementary reinforcement can be evaluated realistically considering different possible failure modes.

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# Numerical Strategy for Developing Macroscopic Model for Reinforced Concrete Structures (MMRCS)

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**ABSTRACT**

The aim of the present work is to present a new approach concerning the cracking modelling of very large reinforced concrete structure as a dam or a nuclear power plant. For these type of structures it is not reasonable and possible, due to calculation time, to model explicitly the rebars and the steel/concrete bonds. To solve this problem, it has been developed a Macroscopic Model for Reinforced Concrete Structures (MMRCS) taking into account cracking in a probabilistic way. This development is based on a multi-scale strategy which consists to built the global approach of modelling by using a fully validated local one (based on the use of a probabilistic explicit cracking model for concrete cracking and a interface element model. It means that the MMRCS is built through the use of a numerical experimentation.

A first validation of this multi-scale strategy of modelling is presented. It concerns the cracking behaviour of a small reinforced concrete beam-slab. It leads to very promising results in terms of global behaviour and macrocracking information (mainly in terms of crack opening).

# Numerical Simulation of the Anchorage Behavior using Meso-scale Finite Element Method

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## ABSTRACT

Nowadays, seismic design code in Japan is becoming more stringent. To satisfy the strict requirement, lager amounts of reinforcement must be placed in RC members, resulting in increased reinforcement congestion. This problem particularly occurs in beam-column joints, where reinforcements meet from many directions. As the spacing between reinforcements becomes smaller, it becomes difficult to ensure proper concrete compaction, and hence to ensure adequate anchorage to the reinforcements.

To study the effects of reinforcement spacing on the performance of reinforcement anchorage, it is necessary to obtain information such as the stress distribution and crack pattern in the concrete around reinforcement. For this purpose, the authors consider that the meso-scale analysis, which can provide detailed descriptions of local response of the concrete and their detailed interactions, is appropriate. In this study, meso-scale finite element method is used to investigate the bond behavior of reinforcements placed in closely clear spacing between itself. In simulations, three kinds of elements, namely mortar, coarse aggregate and steel, are used to define the geometry of a RC specimen. The tetrahedron unstructured grid is used to represent the complicated geometric shape of reinforcements and heterogeneous concrete. The constitutive model of mortar is adopted isotropic damage model with nonlinear softening [1], and for the boundary between different materials, interface element and cohesive surface model are introduced [2].

To investigate the effects of rebar clear spacing between longitudinal reinforcements in a beam-column joint, four simulations are carried out. Simulations are modelled the beam-column joints experiments conducted by Yoshitake [3]. The experiment results show that rebar anchorage capacity decreases when the rebar clear spacing is smaller than the coarse aggregate size and when the beam's and column's reinforcements do not splice on the same plane. This indicates the presence of weak concrete between the closely-spaced reinforcements. The analysis results success to replicate this trend, assuming the absence of coarse aggregates in clear spacing. The simulations show good agreement with experiment data in terms of anchorage capacity, crack patterns, and failure modes. Furthermore, the meso-scale FE analysis shows advantage to investigate the anchorage performance by demonstrating different propagation pattern of internal crack corresponding to the rebar arrangements.

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# Probabilistic evaluation of concrete strains for assessing prestress loss in nuclear containment wall segments

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## ABSTRACT

The main function of the prestressed concrete containment structure is to prevent any radioactive leakage to the environment. The CSA inspection guidelines [1] provide approaches for periodic inspection of the containment prestress system, while these inspections are not possible to provide direct assessment of the condition of the bonded tendons. Thus, the main objective of this research is to investigate how these inspections can evaluate the prestress loss of these bonded systems.

In this study, already tested prestressed concrete wall segments are selected [2], which correspond to 1/4 scale wall portion of a prototype nuclear containment structure. First the selected specimens are modelled and analyzed using the commercial software ABAQUS. The concrete is modelled using the concrete damage plasticity model, where the fracture energy approach is used for modelling its tensile strength. The prestress force is modelled using two ways, i.e., introducing initial stress or initial thermal strain to the tendons. Both ways of prestressing give similar results, while the initial stress approach is more time consuming due to an extra required step. The finite element analysis (FEA) results are in good agreement compared to the test results, indicating the accuracy of the adopted modelling approach.

Then, probabilistic FEA is performed using the Monte Carlo simulation (MCS), while python programing is developed in order to link ABAQUS with the uncertainty problem. In this study as random variables are considered the material properties and the prestress loss, where hypothetical scenarios of excessive degradation are assumed for the prestress loss. Based on the leakage rate test requirements [1], the concrete strain is calculated for each MCS trial and scenario and the probability distribution of the hoop concrete strain is estimated using the probability paper plot [3]. The probabilistic FEA results indicate that the average hoop strain is increasing with the increase of the prestress loss. Thus, the average hoop strain can be correlated with the prestress loss, while the axial concrete strain will also be examined. In addition, is calculated the reliability index which indicates that the probability of measuring an increased average hoop strain increases due to the increase of the prestress loss in tendons. Therefore, the proposed probabilistic framework can be used as an approach for estimating the prestress loss magnitude during the leakage rate test inspection.

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# Experimental and Numerical Assessment of Shear Strengthening Effectiveness of Reinforced Concrete Beams with HCPs

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**ABSTRACT**

The aim of this paper is to demonstrate experimentally and numerically the excellent performance of Hybrid Composite Plates (HCPs) for the shear strengthening of reinforced concrete (RC) beams. HCP is a thin plate of Strain Hardening Cementitious Composite (SHCC) reinforced with Carbon Fiber Reinforced Polymer (CFRP) laminates applied according to the Near Surface Mounted technique (NSM). Due to the excellent bond conditions between SHCC and CFRP laminates, these reinforcements provide the necessary tensile strength capacity to the HCP. However, the shear behavior of SHCC material has not been yet fully understood due to lack of an appropriate and accurate direct shear test method. For this purpose, Iosipescu shear test was selected, where loads are applied in antisymmetric four points bending, assuring a pure shear section at the center of the specimen. A special geometry for the specimen was adopted in order to assure a uniform shear stress distribution in the pure shear section. This experimental test can characterize the shear behavior of SHCC material.

For better understanding the effectiveness of HCPs technique, advanced numerical simulation was carried out by FEMIX computer program that includes a crack shear softening law to simulate the crack shear stress transfer degradation with the crack widening. The values of the parameters of SHCC that define this law (fracture energy mode II, crack shear strength) were derived by simulating the results of the Iosipescu shear test. After have been demonstrated that the adopted model is capable of fitting with high accuracy the results of the Iosipescu shear test, the beams strengthened with HCP have been simulated.

# The use of Ultra High Performance Fibre Reinforced cement-based Composites in rehabilitation projects: a review.

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## ABSTRACT

Ultra High Performance Fibre Reinforced cement-based Composites (UHPFRC) is a novel material developed and adopted over the last two decades. A set of special traits, such as durability, outstanding material properties, and ease of application, render UHPFRC particularly attractive for the improvement (rehabilitation, strengthening) of concrete structures. Laboratory tests indicate a compressive strength, which ranges from 150 to 200 MPa, while tensile strength lies in the range of 7-15 MPa. The fibres play an important role in defining the range of these properties depending on the content (3-6%), orientation, length and composition. As a consequence, UHPFRC delivers a workable material whose mechanical properties may be properly adjusted according to the desired application scheme. As indicated via laboratory testing, the durability of the structure may be extended not only due to the properties of UHPFRC but also due to the additional protection it offers to the reinforcement.

This paper provides a critical overview on existing findings of UHPFRC implementations, focusing in the domain of improvement of structures. Within this context, UHPFRC may be applied on top of existing bridge decks [1], with or without steel rebars, ensuring full bond conditions via mere surface preparation prior to casting. Fatigue tests have also been carried out, for investigating the behaviour of a) the material alone; b) reinforced UHPFRC; as well as c) its performance when attached to standard concrete beams. Moreover, the increased durability is confirmed by the results obtained in natural weathering tests, pointing out the convenience of this material compared to traditional concrete. Contrary to the tensile behaviour of those ordinary mixes, UHPFRC presents a hardening strain of more than 2 ‰. In exploiting the attributes of UHPFRC within a rehabilitation context, further applications are being explored, such as strengthening of orthotropic steel decks in order to prevent fatigue issues [2].

Nonetheless, it should also be acknowledged that certain aspects related to long-term effects are still not thoroughly identified. Amongst others, the knowledge about explosive spalling of elements exposed to fire under compression loads needs to be improved, as well as the development of a multi scale analysis framework, able to provide a detailed computational method without detriment to time efficiency. The introduction of monitoring technologies in structures with UHPFRC would unquestionably provide valuable insight into its long-term performance and help validate this scheme for the next generation of rehabilitation measures.

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# EXPERIMENTAL RESERCH OF SHEAR STRESSES IN STRENGTHENED CORBEL BY BONDED CARBON FIBRE FABRICS

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## ABSTRACT

This paper describes an experimental program for strengthening of four reinforced concrete corbels by bonding inclined carbon fibre plates. The main objective is to compare the horizontal carbon plate with inclined carbon plates and validate the numerical model. In according to this program, strain gauges were applied to evaluate, to describe the behaviour of different materials used and experimental model of strengthened reinforced concrete corbel. The experimental models are showed in Figure 1.

Figure 1. Strengthened reinforced concrete corbels

The study showed that the composite fibre fabrics using bonding technique could be a convenient and effective strengthening method for concrete structures. The test results with strengthened corbel is nearly twice to unstrengthened corbel. So bonding technique is a good reinforcement approach of concrete structures to member performance in flexion, shear and tensile strengths. Thus, steel bar and carbon fabric played a major role in the repair of corbels. Is know that, most of the structures in Civil Engineering meet the current safety standards or have excessive cracks. Then carbon fibre fabrics are used as external support to strengthen the reinforced concrete corbel. Carbon fibre materials have many advantages: their weight, flexibility, implementation easier and also their physicochemical properties are interesting. The technique of strengthening compensated the loss of stiffness and withstand cracking. In fact, this technics improves performance and durability of the structures. In this investigation, strain, cracking modes and collapse mechanisms are noted.

**Keywords**: Strengthening, short corbel, reinforced concrete, mechanical behaviour, composite.

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# Performance of Partially Damaged Squat Shear Walls under Reversed Cyclic Loading

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**ABSTRACT**

The reinforced concrete (RC) shear walls can resist lateral loads effectively in a high rise structural system, by providing adequate quantities of horizontal and vertical web reinforcement along with geometric stiffeners. Squat shear walls are preferred in nuclear power plant structures to safe guard against earthquake effects. The scope of the present study is to compare the behaviour of RC squat shear walls with different aspect ratios, before and after repair. This paper reports on some experimental investigations on the behaviour of RC squat shear walls partially damaged under quasi-static loading (monotonic and reversed cyclic). Six large scale RC squat shear walls constructed with boundary elements at the ends, were fixed to a heavily reinforced foundation block at the bottom and connected to another top beam with monolithic construction. The important variable is the height of the wall maintaining all the other parameters constant. Two shear walls were cast with aspect ratios (1.5, 1.25 and 1.0) with one wall subjected to constant monotonic lateral push and second wall with displacement reversals under push and pull type of loading. The top beam cast monolithically with web of the wall facilitated for transferring lateral quasi-static loading through displacement controlled actuator along with constant axial load during testing. Control walls were subjected to quasi-static loading up to failure in the first stage. The deteriorated shear walls were repaired and retested under the above loading sequence in the second stage. The repair methodology involves removal of damaged concrete, straightening of steel bars (no rupture of reinforcement was observed) and filling of voids with cement grout. Testing of walls was terminated after achieving significant strength loss and damage of specimens in subsequent cycles. The load vs. displacement hysteresis loops, mode of failure, and crack pattern and the overall response of the shear walls have been discussed. Similar behaviour of both control and repaired shear walls was observed. The seismic performance of all the shear walls has been assessed in terms of shear strength; stiffness degradation and ductility factor. Shear walls exhibited a significant increase in peak lateral load with decrease in the aspect ratio. At small aspect ratios, the failure was more brittle with horizontal cracking at the lower most part of the web.

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# Fracture Behavior and Failure Analysis of Self Compacted Concrete Deep Beams Reinforced By CFRP Bars

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## ABSTRACT

The behavior of deep beams is significantly different from shallow beams, the reinforced concrete plane section does not remain plane after deformation. The utilization of fiber reinforced polymer, (FRP) and self-compacted concrete in the construction fields has received a special attention in Egypt during the last decade. An experimental program was carried out to investigate the structural behavior and failure analysis of self compacted concrete deep beams reinforced by CFRP or steel bars. The experimental program consists of five self-compacting reinforced concrete deep beam models that have a constant cross section of 100 mm×500 mm and of a total length 1200 mm. These models were classified into two groups. The first group contains two control beams without opening. The second group contains three beams with opening. The cracking, failure loads, deflections and rotations at different loading stages as well as the crack patterns and modes of failure for the tested beams were recorded and discussed. The results showed that the flexural cracks in deep beams are not critical except in the case where tensile reinforcement ratio is less than the minimum suggested by the codes.

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# Investigation of Flexural Load Carrying Performance of RC Beams Repaired with Ultra High Performance Fibre Reinforced Concrete

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## ABSTRACT

In Japan, deterioration has been widely spread in concrete structures constructed from the late 1950s to the early 1970s. Especially in snowy cold regions, the progress of frost a/o slat damage becomes serious issue, and offers the opportunity of the adoption of new materials or structures to prolong the life of structures. Ultra high performance fibre reinforced concrete (UHPFRC) with ambient curability, self-compacting ability and low permeability as well as high strength is one material which is expected to be applied to repairing or reinforcing deteriorated concrete structures.

To investigate the flexural behaviour of RC beams repaired with UHPFRC, this study conducted 3 tests: pull-out test of rebar embedded in UHPFRC, flexural test on UHPFRC beams containing rebar and flexural test on UHPFRC-RC composite beams. In first and second tests aiming to examine fundamental mechanical properties, not only deformed bar but also round bar is provided, because round bar is often installed in structures subjected to rehabilitation. In third test, both the position of UHPFRC section and repaired thickness are taken into account for test parameters.

The results show that UHPFRC repairing in both tension and compression section improves flexural load carrying capacity of RC beams. However, when tensile zone was repaired with the thickness which exceeds cover thickness and UHPFRC layer contains existing rebar, extremely high bond strength between UHPFRC and deformed bar induced catastrophic failure due to rupture of rebar, and resulted in significantly decrease in flexural deformation capacity. When UHPFRC was located in compressive zone, the balance between repaired depth and the amount of tensile rebar is dominant factor for failure modes, and composite beams with relatively small amount of tensile rebar also collapsed by the rupture of rebar.

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# A study on the Effect of Diagonal Cracks Opening on the Failure Behavior of RC Beam-column Joint with Mechanical Anchorages by 3D RBSM

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## ABSTRACT

Mechanical anchorages can be one way to reduce the reinforcement congestion in a beam column joint by introducing a simpler detail of anchorages and a shorter length of anchorages. However, the use of mechanical anchorages is still limited because when they are placed near the surface of the beam column joint, local failure occurs in the beam column joint that is caused by local stresses from anchorage plates. Since the internal stress condition and the internal cracking pattern have not been well understood, a rational method to strengthen this anchorage system has not been obtained. Numerical simulation can be a beneficial tool to reveal the internal stress condition and the internal cracking pattern.

A meso-scale analysis by 3D discrete method, called Rigid Body Spring Model (RBSM), is conducted in this study where the 3D shape of a reinforcement bar is modelled directly and cracks occur as the results of the discontinuous of concrete and interaction between concrete and reinforcement bar at meso-scale level. It is considered that the opening of diagonal cracks in the beam column joint plays an important role on the failure behaviour of the beam column joint with mechanical anchorages. To confirm that, parametric studies by 3D RBSM are conducted by modelling stirrups placed along the anchorages as deformed and plain bars.

Based on the simulation results, before the occurrence of diagonal cracks, the bond along the development length of the anchorages does not differ significantly between deformed bar stirrups case and plain bar stirrups case. However, after the diagonal cracks occur in the beam column joint with mechanical anchorages, the behaviour changes significantly. If stirrups are modelled as plain bars, the diagonal cracks open easily compared with deformed bar stirrups.

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# SEISMIC BEHAVIOR OF STEEL REINFORCED ECC OR ECC/CONCRETE COMPOSITE SHORT COLUMNS

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**ABSTRACT**

Engineered cementitious composites (ECC) are a class of advanced fiber reinforced cementitious composite with strain hardening and multiple cracking behavior. For a reinforced concrete member, substitution of concrete with ECC can significantly improve the deformation characteristics and energy dissipation ability. In this paper, it is proposed that concrete in the bottom region of short columns is substituted with ECC to form ECC/RC composite short columns to improve the seismic performance and economic efficiency. Three ECC or ECC/RC composite short columns and one RC short column have been tested under reversed cyclic loading to study the seismic behaviors of composite short columns. The influence of shear reinforcement ratio in the column has been investigated as well. The experimental results indicated that the use of ECC in the column bottom can change the failure mode from brittle shear failure to flexure failure mode. The ultimate load capacity, ductility and energy dissipation capacity of the ECC or ECC/RC composite short columns are superior to those of RC short column. Due to higher shear strength, ECC can partly replace stirrups and reduce the stirrup ratios of short columns, resulting in avoiding the construction difficulty from dense steel reinforcement. In a word, the substitution of concrete with ECC in the bottom region of short column was experimentally proved to be an effective method to increase the seismic resistance of short column specimens.

# The Role of the Structural Characteristic Length in FRC Structures

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**ABSTRACT**

In the framework of the CEN Committee involved in the writing of the fiber reinforced concrete structure standards, a strong debate has been focused on the possibility to use a stress-strain rather than a stress- crack opening constitutive relationship, even if only the second one is physically meaningful after the cracking of the matrix. The use of a stress-strain model, even if it can be regarded as an effective simplification in many cases as it is in r/c structures, can be justified by the rough choice of a unique crack spacing in the range of 125 mm.

In the paper, the modeling of different FRC cross sections and in particular of a thin-walled open cross-section profile longitudinally reinforced with steel bars or prestressed strands like a FRC box-culvert, a U-channel or a roof precast element highlights as only the use of a correct structural characteristic length when a simplified Navier-Bernoulli plane section model is adopted prevents the overestimation of the bearing capacity in bending. A comparison with F.E. model and previous experimental tests on full-scale structures is also proposed.

# Fatigue Behavior of Lightly Reinforced Concrete Beams in Flexure due to Overload

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## ABSTRACT

Concrete pavements and top slab of box-girder bridges are the examples of lightly reinforced concrete (RC) structures which are under fatigue loading conditions. This paper presents behavior of lightly reinforced concrete beams subjected to an overload at different instants of fatigue loading. Effect of size on fatigue response of RC beams was also investigated. Notched RC beams under three-point bending were tested. Control beam was tested under constant amplitude fatigue loading without any overload. One beam was tested to understand the effect of initial overload followed by constant amplitude fatigue loading; whereas another beam was overloaded after few lakh cycles. The overload was approximately equal to yield load on the beam. Similar beams were also tested under monotonic loading to establish their yield and ultimate loads. Mid span vertical deflection, crack mouth opening displacement (CMOD), Strain in reinforcing steel were monitored throughout the loading history until failure of reinforcing steel bar. Since range of the constant amplitude loading is below the cracking load, the number of load cycles required for cracking of concrete also noted. In addition size effect on fatigue of concrete also reviewed.

The test results show that overload alters the crack growth curve and fatigue life of RC beams. The fatigue fracture surface of steel reinforcing bar is compared with static fracture surface. Fatigue fracture surface has a clear distinction in crack initiation, crack propagation and final fracture. Stiffness degradation, CMOD, Crack growth (length), strain in steel as influenced by number of cycles are discussed. Since the applied constant amplitude fatigue loading was well below the cracking load of the beam, the crack from notch begun to grow, after few thousands of cycles, showing increase in the steel strain. Results show quasi-brittle nature. The tensile strength of concrete need to be accounted for the exact prediction of fatigue life of lightly reinforced concrete beams. Maximum mid span deflection and maximum CMOD were also compared. In a nutshell, it shows that the effect of overload on fatigue life of RC beam is significant and there is a need to improve existing analytical and mechanistic models.

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# Experimental and numerical characterisation of load-induced damage in reinforced concrete members

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## ABSTRACT

The durability of the cooling towers of nuclear power plants (NPP) is an up-to-date issue: some of them have a state of damage more or less advanced, visually characterized by the presence of cracks. Cracks formation is accompanied by damages at the steel-concrete interface. These load-induced damages facilitate the diffusion of atmospheric carbon dioxide in the concrete and along the steel-concrete interface [1]. Carbonation at the interface induces steel corrosion which could cause the development of new cracks in the structure, thus, threaten its durability [2]. It is known that the corrosion of steel is the main pathology affecting reinforced concrete structure and therefore it is a determining factor for its durability.

Because the development of carbonation-induced corrosion in cracked concrete is still a subject in debate, it is necessary to better understand it in order to ensure for the cooling towers a service life of 60 years.

First of all, to understand the effect of cracking, both in terms of corrosion initiation and propagation, a cracking protocol leading to cracks and steel-interface damage representative of those existing on the cooling towers should be found. The objective of this paper is to show numerically and experimentally that the three point bending test generates load-induced damages which are representative of those appearing on the cooling towers. This paper examines the experimental results of the crack opening obtained on 140 specimens and then compares them to a numerical analysis performed using the finite element code, CAST3M, developed by the CEA. The results indicate that there is a correlation between load/unload cycles and residual crack opening. Moreover, the length of the damaged steel / mortar interface observed after the three-point bending test, is quantified experimentally and numerically. This length could be key parameter in the initiation and the propagation processes of corrosion.

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# SHEAR DAMAGE MODELING OF RC BEAMS; A SIMPLIFIED APPROACH BASED ON MAZAR DAMAGE MODEL

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**ABSTRACT**

Numerical simulation of cracking behavior of RC beams weak in shear is important to be carried out to study the damage evolution with increasing loading and to avoid expensive and time consuming experimentation. In this research study, damage/fracture modeling of RC beam weak in shear has been carried out. For plain concrete, damage model of MAZAR and for steel bar, elastic perfectly plastic behavior law was used. For modeling of steel-concrete interface, volumic bond elements with elastic plastic isotropic behavior law were used. To carryout simulation, Finite Element Code CASTEM was employed. In order to validate the proposed approach, a comprehensive experimental program was designed and carried out. Under this program, three-point bending tests on RC beams weak in shear were performed to get experimental results. Comparison of numerical simulation results with experimental data showed good agreement.

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# Effect of Non-uniform Corrosion on the mechanical properties of corroded steal bars

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**Abstract:** In order to predict the mechanical property of corroded steel bars in concrete, an experiment of chloride salt drying-wetting cycles was carried out for pre-cracked reinforced concrete specimens. The total duration of testing and natural corrosion is nearly 4 years. Based on notch depth measurement and tensile testing, the non-uniform coefficient and mechanical property of corroded reinforcements have been studied and discussed. Following conclusions can be concluded: (i) Significant localized corrosion can be observed for reinforcement around cracked areas, while slight uniform corrosion occurs for reinforcement in sound concrete; (ii) In this paper, the non-uniform coefficient *S* is used to describe the reinforcement corrosion longitudinal nonuniformity, which increases initially with the increase of corrosion rate then decreases; (iii) Based on the existing literature data including 225 data points, an mathematical model for reinforcement with diameter of 16 mm has been built to predict corroded rebar mechanical properties; (iv) The impact of the corrosion nonuniformity on the ductility of steel bars is more significant. It is indicated that the main reason which cause the plasticity reduced and the yield platform disappeared is the nonuniformity of corrosion. It obviously leads to the tensile with eccentricity and produce the additional bending moment, thus making for the brittle fracture of corroded reinforcement.

**Keywords:** chloride salt drying-wetting cycles; corroded steal bars; non-uniform coefficient; mechanical performance; additional bending moment

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