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Nonlinear interfacial softening for concrete beams retrofitted with composite plate

C.K.Y.Leung, M.Klenke, W.K.Tung & H.C.Y.Luk
Department of Civil Engineering, Hong Kong University of Science and Technology, Hong Kong, China

ABSTRACT: Concrete beams or slabs can be effectively retrofitted through the bonding of composite plates. Failure of the retrofitted member often occurs through delamination of the composite. Experimental investigations show that unstable delamination growth at ultimate failure is preceded by material damage along a significant part of the beam/composite interface. It is hence appropriate to analyze the problem with a non-linear fracture mechanics approach, where the delamination is treated as a fictitious interfacial crack, and interfacial damage is modelled using a softening shear stress vs slip ($\tau_s - s$) relation at the crack wake. In this paper, a combined experimental/numerical approach is developed to obtain the ($\tau_s - s$) relation at the interface. Representative experimental results are presented to illustrate the novel approach. From our results, the softening behaviour exhibits a sharp drop followed by more progressive weakening, indicating sudden loss of cohesion/bond, followed by gradual decrease in interfacial friction with continued sliding and damage.

1 INTRODUCTION

After years in service, many concrete structures have deteriorated and are in need of repair. In some cases, due to change of use, members need to be retrofitted to provide a load carrying capacity higher than the original design value. For concrete beams or slabs, the bonding of fiber reinforced plastic (FRP) plates to the lower surface is found to be an effective and efficient strengthening technique. Depending on the design, a beam with a bonded plate can exhibit various failure modes (Meier, 1995, Arduini et al, 1997, Buyukozturk et al, 1998). For some failure modes, such as crushing of the compressive concrete, or fracturing of the composite plate, the ultimate load can be calculated from an analysis similar to that for conventional reinforced concrete members (Wei et al, 1991, Triantafillou and Plevris, 1992). However, for failure due to delamination (or peeling-off) of the plate, no accepted approach is yet available for failure load prediction. Since delamination is a commonly observed failure mechanism (Saadatmanesh et al, 1991, Meier et al, 1992) that often occurs with relatively little warning (compared to conventional flexural failure), the investigation of delamination failure is an important research topic for plate-strengthened beams.

From a theoretical point of view, delamination should initiate at locations of high stress along the interface. If there is no cracking within the concrete beam, the interfacial stresses should reach a maximum at the end of the composite plate (or the cut-off point). Interfacial normal and shear stresses for an uncracked retrofitted concrete beam have been derived independently by Taljsten (1997) and Malik et al (1998). In these papers, special attention has been paid to the concentrated stresses near the plate end. In reality, flexural and/or flexural-shear cracks often form in the concrete beam as loading is applied. The tendency for these cracks to open will also introduce high shear stress at the concrete/composite interface. For a beam under pure bending, the elastic interfacial shear stress distribution near the bottom of a flexural crack was derived by Leung (2001) with a LEFM approach. Effects of various parameters on the shear stress concentration have been studied.

From the above theoretical analyses, an important observation can be made. The stresses decrease rapidly with distance from the point of maximum stress, and so high stresses only occur over a relatively small part of the interface. Similar to the stress singularity in front of a crack tip, this kind of stress field is expected to induce yielding or damage processes in a region around the point of maximum stress before ultimate failure occurs. For a quasi-brittle material such as concrete, the size of such a process zone can be quite large. This theoretical argument is supported by recent experimental results. In the experiments of Wu et al (1997) on plain concrete beams strengthened with composite plates, stable growth of the delamination can be visually observed, indicating the gradual propagation of a damage process along a large part of the beam/plate interface. Buyukozturk et al (1998) and Taljsten (1999) tested strengthened beams with strain gauges placed along the composite plate. As loading increased, the measured strain values near the free end of the plate were found to increase initially but decrease after a certain load was exceeded. This decrease is an indication of the reduction in strain transfer capacity from the concrete to the plate, due to damage in the concrete adjacent to the interface. Based on experimental observations, the size of the damage process zone is large relative to the region of high stress indicated by the elastic analysis. As a result, purely elastic approaches, such as the models of Malik et al (1998), Taljsten (1997) and Leung (2001) as well as LEFM-based interfacial fracture analysis (e.g., Hutchinson and Suo,1992), are not expected to provide accurate predictions of the ultimate failure load.

To model progressive failure within the concrete after delamination was initiated, Buyukozturk et al (1998) and David et al (1999) have carried out finite element analysis with non-linear material constitutive relations to describe concrete, steel, as well as the concrete/steel bond. A non-linear analysis was carried out until the loading can no longer be increased. With this approach, four different retrofitted specimens were analyzed in Buyukozturk et al (1998) and the agreement with experimental result was only fair. In David et al (1999), numerical analysis for only one experiment was presented and good agreement was achieved. However, the authors pointed out that the determination of various parameters in the non-linear material models is a difficult task. From the paper, it was not clear if the material parameters were obtained from separate experiments, or simply selected to fit the experimental data.

For the delamination problem, the appropriate material parameters for concrete are indeed very difficult to obtain. Non-linear constitutive models for concrete are often determined from tests on standard cylinders or cubes, where the loading on the specimen generates a fairly uniform strain field. However, delamination is governed by concrete failure near the interface where high strain gradients exist. It is questionable if material parameters determined from standard specimens are representative of those in the critical region where delamination failure occurs.

In the authors' opinion, the best way to analyze the delamination problem is to adopt a non-linear fracture mechanics approach that explicitly models the softening behaviour within the process zone around the concrete/composite interface. Experimental methods should be developed for the 'in-situ' determination of material properties within the critical region. The non-linear fracture approach, which is essentially an extension of Hillerborg's fictitious crack model (1976), was first proposed by Taljsten (1996). To illustrate the modelling concept, Taljsten (1996) assumed a very simple shear stress vs slip relationship and derived analytical expressions to relate the direct force required for a bonded plate to delaminate. However, the critical issue of determining the constitutive behaviour in the process zone for real material systems, was not addressed.

The focus of this paper is on the determination of softening behaviour at the concrete/composite interface with a combined experimental/numerical approach. In the following, the modelling concept is first discussed in detail. An experimental set-up for the study of progressive delamination is then described. Using a representative set of experimental results, the derivation of interfacial softening behaviour (in terms of stress vs sliding) will be demonstrated.

1.1 A NEW MODELLING APPROACH USING NON-LINEAR SOFTENING ELEMENTS

The limitation of using conventional non-linear concrete elements in analyzing delamination failure has been discussed above. Here, a new modelling approach is proposed. The non-linearities of the retrofitted beam are divided into three types: (i) compressive damage at the upper part of the beam, (ii) flexural and shear/flexural cracking at the bottom part of the beam, and (iii) non-linear damage in concrete near the plate/beam interface. To model compressive damage, conventional concrete elements with non-linear stress vs strain behaviour can be employed. Flexural and shear/flexural cracking can be modelled with discrete cohesive cracks, following the approach originally proposed by Hillerborg et al (1976). To model progressive damage at the interface, a non-linear interface element is introduced. Rather than letting each concrete element near the interface to undergo cracking and damage on its own, effect of damage is lumped into the softening of the interface element. The justification is that on the scale of the structural component, delamination is a localized failure occurring near the bottom of the beam. Since the thickness of material over which damage occurs is small compared to the dimensions of the beam, the damage can be modelled in a discrete rather than diffuse manner.

The representation of concrete damage with non-linear interface elements is illustrated in Fig.1. As shown in Fig.1(b), after the non-linear effects are lumped into the interface elements, the concrete elements can be considered linear elastic at all times. The analysis can hence be greatly simplified as a non-linear concrete elements are no longer required near the interface. Only the constitutive relation of the interface element is needed, and its derivation will be described later. (Note: for clarity, no flexural cracks are shown. Flexural cracks, if present, need to be explicitly modelled as fictitious cracks with softening springs connecting the crack faces. The material outside the cracks can still be considered linear under tension.) In Fig.1(c), we show that the interface element actually consists of two springs. Movement of the horizontal spring represents sliding displacement between the concrete and the adhesive, while the vertical link models separation. In reality, material sliding and separation often occur inside concrete. The interface element should then be placed between two layers of concrete elements rather than at the concrete/adhesive interface. In the model, however, it makes no difference either way, as long as the determination of interface material parameters and the use of the interface element in actual analysis are done in a consistent way.

Here, a simple formulation of the interface element is given to illustrate the modelling concept. Depending on the experimental results obtained, a more complex formulation may be developed. In the interface element, the horizontal spring carried a shear force equal to the shear stress (τ_s) times the area the element represents. The vertical link carries a normal force equal to the normal stress (σ_n) times the area. Both the spring and link are considered perfectly rigid before a critical shear stress τ_{cr} is reached. τ_{cr} is assumed to depend on σ_n. After τ_{cr} is reached, the vertical link will be free to open. That is, $\sigma_n = 0$ for any positive opening displacement (u). When the gap closes (i.e. n returns to zero), the link will be able to transmit compressive stress again. After reaching τ_{cr}, the shear stress in the horizontal spring becomes a function of both the relative shear displacement (s) and opening displacement (u). The reduction of τ_s with increasing shear displacement is illustrated in Fig.1(d) for a given u. With a larger opening (u), the shear stress for a given sliding displacement will become smaller. In other words, the curve in Fig.1(d) is also dependent on the opening displacement (u). Theoretically, the τ_s vs s curve should be continuous and smooth. For modelling purpose, it can be approximated by a multi-linear relation. The determination of the maximum point on the τ_s vs s curve as well as the slope of each branch will be discussed in the next section.

1.2 DETERMINING THE CONSTITUTIVE RELATION OF INTERFACE ELEMENT

To obtain the constitutive relation of the interface element, a novel experimental procedure is developed. The specimen employed is shown in Fig.2(a). It consists of two parts: a cast concrete half-beam and a metal member of similar size. In the concrete half-beam, both flexural and shear reinforcements are incorporated. The two parts are connected together by a rod that acts as a hinge (Fig.2b). A composite plate is to be glued to the bottom of both the concrete and metal parts. When 4-point loading is applied, the composite plate is pulled in the middle. With this loading configuration, the pulling of the composite plate can be performed in a well-controlled manner, and progressive delamination can hence be studied. Also, proper alignment can be ensured by an approach to be discussed next.

We will first focus on an experiment with no opening displacement at the interface (u = 0). For this case, it is important to ensure that the composite plate on the concrete is always being pulled in a direction parallel to the concrete surface. This is achieved through two special design considerations. First, as shown in Fig.2(a), there is a separable plate at the bottom of the metal member. The separable plate is connected to the metal member with screws (see Fig.2(c)) and spacers are employed to adjust its

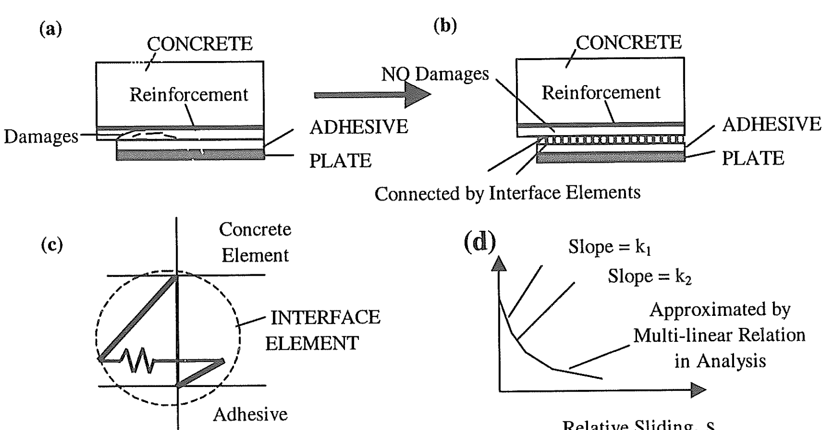

Figure 1 (a) and (b) Representation of concrete damage with non-linear interface elements
(c) the interface element, (d) Variation of element shear stress with sliding

level. With the appropriate spacer thickness, one can ensure that the bottom of the separable plate is at the same level as the concrete surface. The composite plate can then be glued. After loading is applied, the two parts of the beam tend to rotate away from each other, and the composite plate no longer stays straight. To ensure the straightness of the composite near the concrete surface, a roller is placed at the bottom of the concrete member. If we want to carry out experiments for non-zero opening displacement (u), thicker spacers can be employed so the separable metal plate is at a lower level than the concrete surface. In this case, the roller is no longer required.

Although the composite plate is also glued to the bottom of the separable plate, to assure delamination on the concrete surface (rather than sliding on the separable plate), another metal plate is glued on top of the composite, and screwed to the separable plate (Fig.2(c)). This forms an effective system for anchoring the composite to the metal member.

As shown in Fig.2(c), strain gauges are glued along the surface of the composite. During the test, the distribution of longitudinal strain along the composite is measured together with the applied load to the beam. A finite element model for the concrete member is set up. Interface elements such as the one illustrated in Fig.1(c) are placed along the plate/concrete interface. The strain distribution along the plate can hence also be theoretically predicted. Before the initiation of delamination, the strain field is elastic. The curves for strain vs distance stay similar in shape. Based on the applied load beyond which similarity no longer holds, the maximum shear stress in Fig.1(d) can be obtained. After the onset of delamination, the strain variation is a function of the shear softening behaviour. For a load that is just above the delamination load, the composite strain only depends on the first branch of the shear-softening curve. Based on the fitting of experimental data, the slope of the first branch is determined. This first branch is used for increasing loading until it no longer produces a good fit. The maximum shear displacement (s_1) on the last run (when the fit is still good) is recorded, and a new slope is prescribed for the next branch with $s \geq s_1$. The analysis can be continued in the same manner to find the slopes of subsequent branches. As mentioned before, the slope of each branch is also a function of the opening displacement (u). As a first attempt to determine the shear-softening relation at the interface, u is kept at zero in the present investigation.

2 EXPERIMENTAL RESULT AND ANALYSIS

To demonstrate the feasibility of the experimental approach described above, metal members like the one shown in Fig.2(a) are fabricated with aluminum. The size of the metal member is around 1.1m x 0.2m x 0.22m (LxWxD). Concrete half-beams, similar in size to the metal member, are cast with a mix of water:cement:sand:aggregate = 0.72:1:3:1.5. Inside each concrete half-beam, two 10 mm high yield steel bars were used as tensile reinforcement with a cover

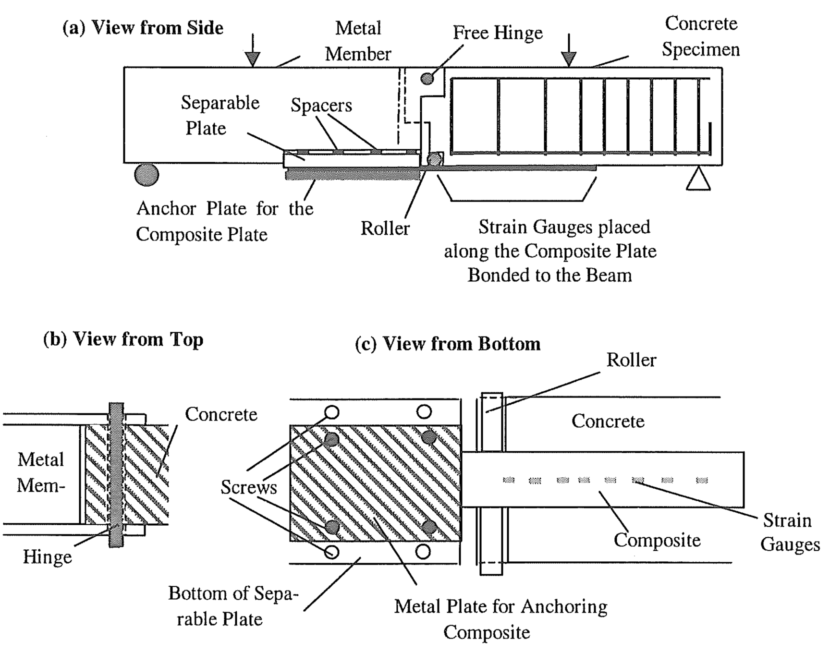

Figure 2. Experimental Set-up to Determine Constitutive Relation of the Interface Element

of 25 mm. The member was also over-reinforced in shear. The composite employed is a carbon fibre strip (Sika Carbodur S-512), 50mm in width and 1.2mm in thickness. The total length of the composite is 950mm, with 475mm bonded on the bottom of concrete. A filled epoxy (Sikadur-30) is used as the adhesive. Before gluing, the concrete surface is roughened by sandblasting. The lower surface of the separable plate is also roughened with coarse sand paper. After the composite is glued to the concrete surface, strain gauges are applied onto its surface. For each specimen, starting from the internal bottom edge of the concrete member, 11 strain gauges (of 5mm gauge length) are placed at a centre to centre distance of 21mm. Note that the gluing of composite and application of strain gauge are all carried out with the specimen turned upside down. To avoid high stresses at the plate/concrete interface when the specimen is turned over and placed onto the loading frame, a special fixture was designed to hold the metal and concrete parts tightly together.

The testing was carried out in 4-point bending, with 1.8m between the 2 supports, and 0.6m between the loading points. The hinge of the specimen was placed right at the middle of the two loading points. Testing was carried out when concrete reached 28-day age. Based on tests on 100mm x 200mm cylinders, the concrete strength was 33 MPa. Gluing of composite was performed 7 days before the test. According to the material supplier's data, the Young's modulus of the adhesive at 7 days should be 4.4 GPa. The thickness of the adhesive was estimated to be 2.5mm, from measurements taken on the composite plate after it delaminated (with the adhesive and a thin layer of concrete stuck to its surface).

Testing was performed under displacement control. Collected data included the applied loading and the strain along the composite plate at the gauge locations. All together, three tests have been carried out. In each test, stable propagation of the delamination can be observed. The ability to induce progressive delamination, rather than a sudden failure, is a major advantage of the present set-up for the investigation of the softening behaviour at the plate/concrete interface.

A number of tests have been performed in our laboratory. Here, only one set of results is presented. Fig.3 shows the variation of longitudinal strain with distance along the plate (measured from the cut-off point, or the end closer to the support). Each curve corresponds to one particular load value, and increasing loading will cause the whole curve to move upwards. From the figure, one can see that the five lowest curves are similar in shape, indicating elastic behaviour. From the sixth curve onwards, the shape of the curve starts to change, and the slope is found to decrease as the middle of the member (distance = 475mm) is approached. Since the slope represents the rate of strain change along the plate, which is proportional to the interfacial shear stress, a drop in the slope indicates shear softening at the interface. As loading increases, the slope change starts to occur at a larger distance from the middle, indicating progressive delamination along the interface.

To obtain theoretical values of strain along the plate, a finite element model was developed for the concrete member, using the program ADINA. The mesh was shown in Fig.4. Note that the cut-out at the bottom of the member, where the roller is inserted, has been neglected for convenience. We believe this will have very little effect on the results. The load acting on the plate is determined from the applied vertical loading through equilibrium. Since the model is 2-D, all phases, including concrete, composite and adhesive, have the same width. In reality, however, the concrete is 200mm in width, while the plate and adhesive are only 50mm wide. In the 2-D model, the modulus of the plate and adhesive are therefore reduced by 4 times. In the analysis, 8 node quadratic elements are used throughout the mesh. Interface elements, in the form of springs, are placed between the adhesive and the concrete. In this case, with only shear displacement at the interface (u = 0), spring elements are placed in the horizontal direction alone. Nodes on the two sides of the spring are constrained to move together in the vertical direction. Since there should be no interfacial sliding before a critical shear stress is reached, the initial slope of the spring is artificially assigned to be a very high number. Once the shear stress reaches the critical, the behaviour will follow a softening curve. For the same shear displacement, the force introduced in the middle node of an element was 4 times that in a corner node. This is consistent with the displacement interpolation for the quadratic element. Since stable delamination only occurs over a certain distance from the middle of the beam, interface elements are only placed over part of the plate/concrete interfae to reduce meshing effort and computational time.

Figs. 5 to 7 show the comparison between experimental strain measurements and strain values obtained from the finite element analysis. Fig.5 shows all the elastic cases, and results are normalized to that for 4.5kN. From the figures, the overall agreement, both before and after the initiation of delamination, can be considered quite satisfactory. The softening behaviour of the interface element is shown in Fig.8. Note that the curve exhibits a vertical drop (from 2.5 MPa to 1.0 MPa), followed by more gradual decrease in shear stress. We believe the sudden drop is due to bond/cohesion failure, while the con-

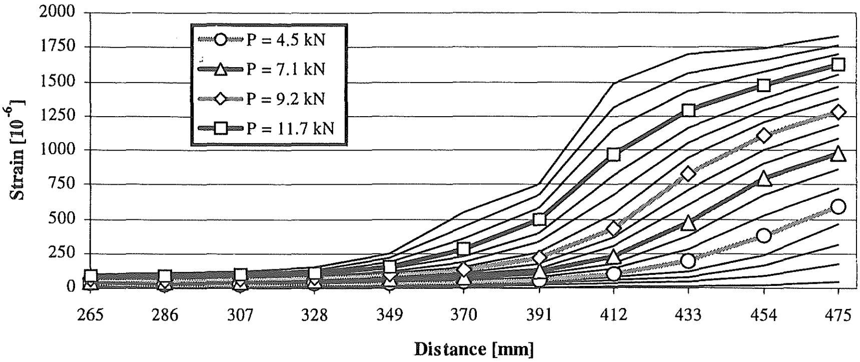

Figure 3. Variation of Measured Strain at Various Load Levels

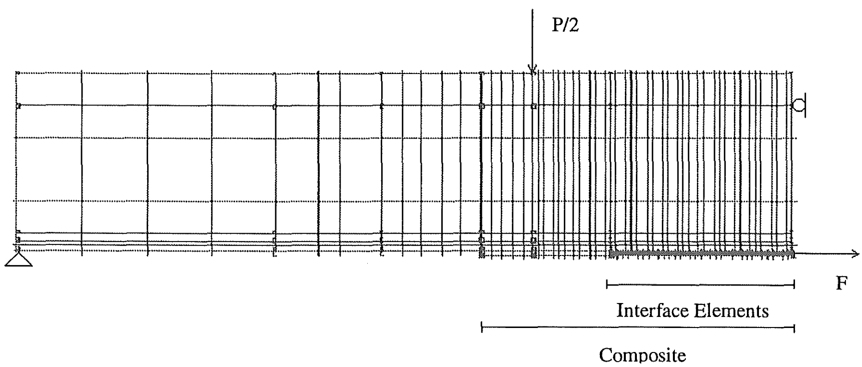

Figure 4. The Finite Element Mesh used in our Analysis

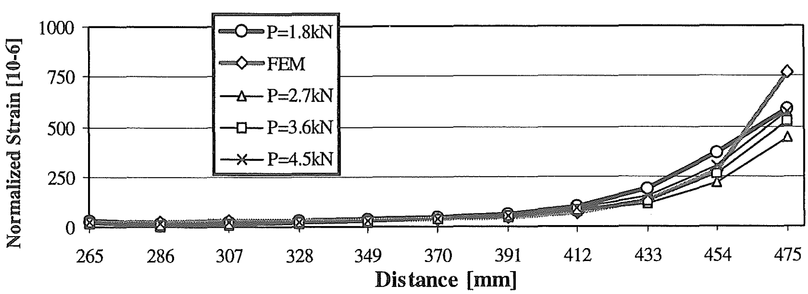

Figure 5. Comparison between Normalized Experimental and FEM results for P up to 4.5 kN

tinual change indicates the reduction in friction as sliding (and further damage) occurs.

An additional note regarding data fitting needs to be made. For the spring element used in our analysis, the softening slope cannot be too steep. Once a certain critical slope is exceeded, the analysis can no longer continue. To get around this problem, instead of representing interfacial behaviour with a single softening spring element, two spring elements are placed between the same two nodes. One of these elements is a softening spring element, while the other is a spring element that will rupture when a critical stress is reached. By making the second element ruptures at the same instance when the first element starts to soften, the two elements will combine to give a softening behavior with a sudden vertical drop (due to rupturing of one of the elements) followed by gradual decrease.

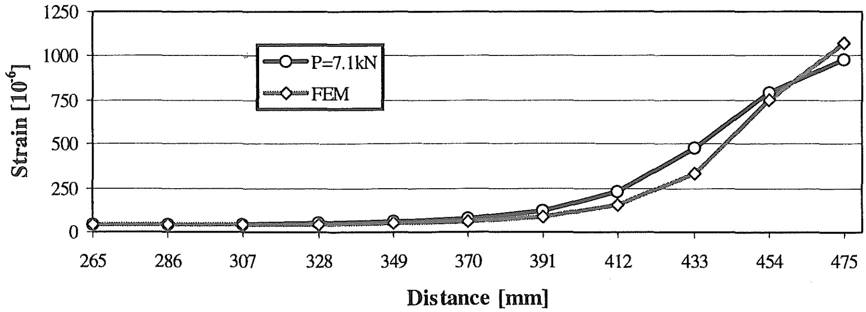

Figure 6. Comparison between Experimental and FEM results for P = 7.1 kN

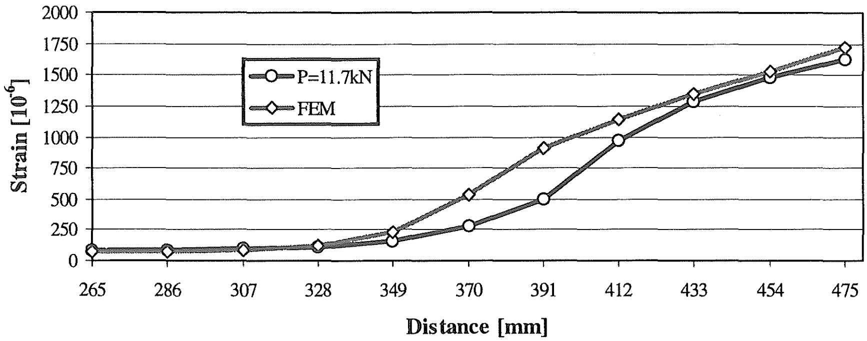

Figure 7. Comparison between Experimental and FEM results for P = 11.7 kN

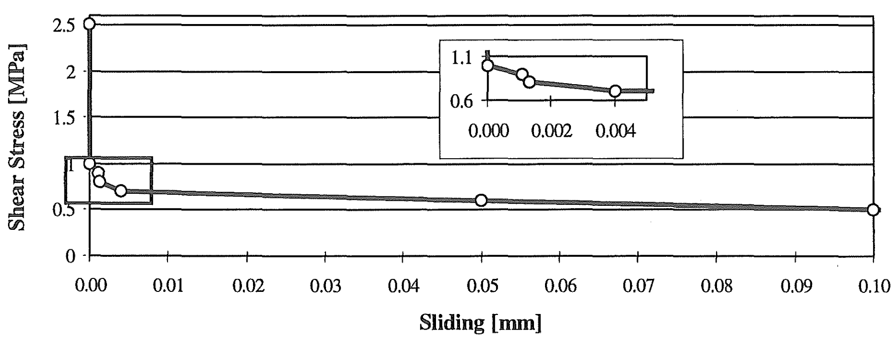

Figure 8. The Experimental Determined Interfacial Softening Relation

3 CONCLUSION

For the delamination of bonded plate from a concrete member, extensive interfacial damage was found to occur before ultimate failure in many investigations. In this study, a combined experimental/ computational approach was developed for the quantitative determination of shear softening relation during delamination at the plate/bond interface. The feasibility of the approach has been verified with experimental results obtained from concrete specimens with bonded carbon fibre composite plates. The result indicates that delamination leads to rapid initial interfacial softening followed by more gradual reduction in shear stress. In this work, we only focused on the case with zero opening displacement at the interface. In the future, the effect of opening displacement (perpendicular to the plane of the laminate) should also be considered to develop a general interface element for the analysis of concrete members retrofitted in different manners.

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