Experimental investigation of fatigue in a steel-concrete interface

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ABSTRACT: A new type of composite bridge deck is currently under research. The concept is to achieve composite action by the adhesion between a thin layer of fiber reinforced concrete and a steel plate. Of special concern is the fatigue strength of the bond between the concrete and steel plate. In this paper, emphasis is put on the steel-concrete interface and how it performs under cyclic loading. A series of tests have been carried out on composite beams made by casting a layer of self-compacting concrete directly onto the sandblasted surface of a steel plate. A four point bending set-up was used, subjected to static as well as cyclic loading. A good performance of the steel-concrete interface under cyclic loading was observed. Furthermore, in order to analyze the stress/deformation situation in the interface, numerical modeling of the test set-up using the finite element method is carried out. This analysis mainly show that the fatigue threshold load corresponds to the static load level at which interfacial cracks are initiated in the numerical model.

Keywords: FRC, fatigue, fracture mechanics, steel-concrete interface

1 INTRODUCTION

A typical orthotropic steel bridge deck in Europe consists of a 12mm steel plate with supporting ribs welded to the bottom face. This type of bridge deck suffers significantly from increasing traffic loads, particularly from heavy trucks. The increased traffic intensity and higher wheel loads results in fatigue cracks in both welded structures and surfacing. Therefore the development of an entirely new concept of deck systems is of interest. Increasing the local stiffness of a typical orthotropic steel deck, using a cement-based overlay to form a composite plate, is the subject of an ongoing research project. Even casting a thin layer increases the local stiffness significantly and might be beneficial in a fatigue situation. It is hoped, that the concept under development can either be applied to retrofitting or in the design of new bridge decks.

To achieve high local stiffness, the steel deck must act compositely with the cement-based overlay. Since the overlay is treated as an integral part of the structural deck system, the strength of the steel-concrete interface is of major importance. Emphasis in this case is put on the interface, especially, how it performs under cyclic loading.

A typical deck according to the proposed system consists of a 40-60mm layer of Self-Compacting Steel Fiber Reinforced Concrete, (SCSFRC), bonded to an 8-14mm steel plate (Walter et al. 2003a). Whereas conventional composite constructions achieve composite action by mechanical fasteners, the idea here is to achieve composite action only through adhesion. The adhesion between concrete and steel is enhanced by sandblasting of the steel plate. The major concern is how the interface between the concrete overlay and steel plate performs under cyclic loading.

To illustrate stiffness effects under the influence of a thin overlay on a steel plate, an example taken from Wolchuk (2002) is used. A composite section consisting of an overlay fully bonded to a steel part is examined through a linear static analysis, cf. Figure 1. A bending moment with a magnitude of

4000Nmm/mm is applied to the composite section and illustrates the bending moment, which might be critical to the welding of the longitudinal ribs in an orthotropic steel deck. The geometry is defined by an overlay height h_c and a steel height h_s. The maximum stress for a given bending moment is observed for varying thickness of the overlay, cf. Figure 2, where σ_c and σ_s are the maximum stresses at the edges of the overlay and steel plate, respectively.

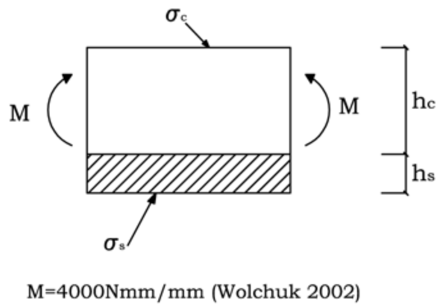

Figure 1. Composite section subjected to a bending moment M

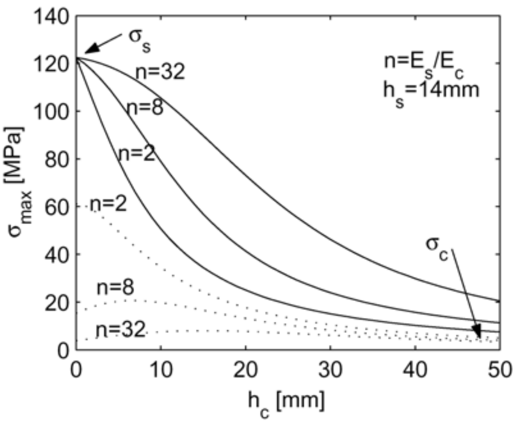

Figure 2. Stress reduction: (—— σ_s , ····· σ_c), due to overlay contribution to the deck plate rigidity for different heights h_c, in the case of three different elastic ratios denoted n.

Stress reduction in the steel deck is desirable because it substantially enhances fatigue safety. However, a fatigue problem may arise at the steel-concrete interface. This will be discussed in the present paper as it is the main topic of the project behind it (Jansen & Østergaard 2003).

2 EXPERIMENTAL SET-UP

A number of composite beams where prepared for the experiments. In order to ensure bond between the two materials, the steel plates where sand blasted before casting. Two types of steel plates where used in the tests: a plain flat steel plate and a checker steel plate. The motivation for using a checker steel plate is that the macroscopic roughness may play a role in the overall composite performance. The composite beams were tested in four point bending to investigate the behavior of the steel-concrete interface subjected to static and cyclic loading. The set-up is shown in Figure 3.

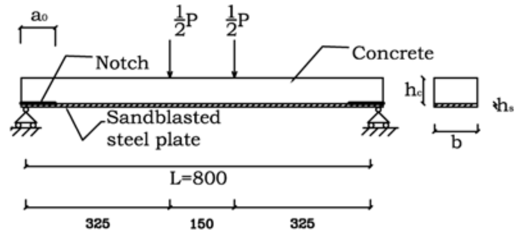

Figure 3. Test set-up, two types of steel plates where used: flat and checker, both sandblasted. The steel plate thickness is denoted h_s, concrete height h_c and a possible notch length a_0.

Loading the composite beam in four point bending creates a zone of constant shear at the steel-concrete interface between the support and the load point. It is expected that the shearing zone will be critical to the steel-concrete interface. In some experiments an interfacial notch (created by preventing adhesion) of length a_0 measured from the beam-end, was applied. Since large compressive stresses perpendicular to the interface exist close to the support, the interface here is more likely to sustain large shear forces, whereas an interface notch at the beam-end will eliminate this effect. The interfacial shear stresses will peak at the end of the notch, which makes it possible to observe crack propagation in the interface during the experiment.

3 MATERIAL PROPERTIES

Specimens were cast from four different batches, using the same recipe. The mix used in the experiment is given in Table 1. Emphasis was made on making the steel fiber reinforced concrete self-compacting in order to have the mix spread evenly and to create a uniform bond between the concrete and the sandblasted steel surface.

One percent of hooked end steel fibers were used with a diameter of 0.5mm and a length of 30mm. Workability and compressive strength of all batches were similar. For each batch, three cylinders were cast. The average ultimate strength for all batches was f_c=44.6 MPa with a standard deviation of 2.7 MPa.

Table 1. Mix Design

Mix	Kg/m^3
Cement (RAPID)	245
Fly ash	94.5
Silica fume	10.5
Water	142.9
Air entraining agent	0.4
Plasticizer	4.2
Sand, 00-04 mm	752.6
Aggregates, 04-08 mm	450.6
Aggregates, 08-16 mm	594.0
Fibers, l=30mm,D=0.5mm	78

4 EXPERIMENTAL RESULTS

Both static and cyclic tests on the composite beams have been carried out. In the static tests, the maximum interfacial shear stress and the fracture behavior are of interest. During the cyclic tests emphasis is put on the maximum number of cycles prior to failure.

4.1 *Static tests*

To measure the slip of the steel-concrete interface during loading of the composite beam, a special end-slip measurement arrangement is applied. A clip gauge was mounted between two small extending rods, which had been glued onto the specimen, one on the steel plate and another on the concrete, cf. Figure 4.

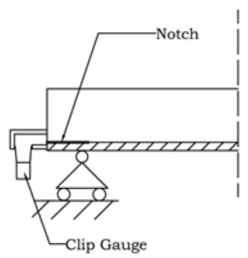

Figure 4. Mounting of clip gauge to measure end-slip

To illustrate the effect of an interfacial notch, two static examples are analyzed using the end-slip measurement. The load vs. end-slip diagram showed in Figure 5 reveals that a notched beam gives more information on the crack propagation during the test that of an un-notched beam. This information is essential to the comparison and validation of the numerical model and is discussed further, in the latter. A number of static experiments using the four point bending set-up were carried out to determine the maximum load of each batch. This has been repeated for each type of steel plate and the results are given in Table (2).

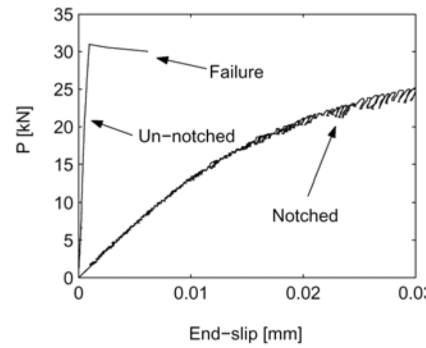

Figure 5. Load end-slip curves of a typical composite beam in static load using an un-notched and notched configuration.

Global failure is associated with debonding of the interface. Since the composite beam geometry is not the same for each experiment, the maximum linear static shear stress acting at the steel-concrete interface is calculated using the maximum load at global failure. The maximum shear stress was calculated using the classic shear formula for beams, see e.g. Gere & Timoshenko (1999), assuming a fully bonded steel-concrete interface. This maximum shear stress at failure is denoted τ_f and is shown for each batch in Table 2.

Table 2. Results of static tests for each batch using flat and checker steel plates, all beams un-notched.

Batch no.	Steel plate	h_c [mm]	h_s [mm]	τ_f [MPa]
1	Flat	62	10	3.09±0.24
1	checker	62	8	3.19±0.15
2	Flat	62	10	3.30±0.13
2	checker	62	8	3.29±0.10
3+4	Flat	70	8	3.04±0.02
3+4	checker	70	8	3.07±0.13

4.2 *Fatigue tests*

The experimental results related to cyclic loading involve 14 specimens, 6 with a flat steel plate and 8 with a checker steel plate. During the fatigue tests, a cyclic load was applied between two values P_{max} and P_{min} in the shape of a sinusoidal wave and at a frequency of 5Hz. Results from the cyclic tests are given for each beam in Table (3). For each type of plate, an additional two tests were carried out applying an interface notch with a length of a_0=40mm. The results for each series of flat and checker steel plates are presented graphically in

Figures 6 and 7, where the ratio τ_{max}/τ_f is plotted against $\log(N_f)$, τ_{max} being the maximum shear stress at the interface and N_f the number of cycles at failure. A fatigue threshold value for τ_{max}/τ_f of approximately 65% is observed for the un-notched beams. The notched beams exhibit a lower threshold value.

Table 3. Results of cyclic tests. FU: (Flat steel plate un-notched); FN: (flat steel plate notched); CU: (Checker steel plate un-notched); CN: (Checker steel plate notched).

Beam	h_c [Mpa]	h_s [Mpa]	τ_{max}/τ_f	Log(Nf)
FU1	62	10	0.64±0.04	*6.91
FU2	70	8	0.65±0.01	6.89
FU3	62	10	0.69±0.05	6.05
FU4	70	8	0.70±0.01	5.06
FN1	62	10	0.65±0.03	6.47
FN2	62	10	0.70±0.03	3.23
CU1	62	8	0.59±0.03	*7.00
CU2	70	8	0.68±0.01	*6.88
CU3	70	8	0.69±0.03	*6.18
CU4	62	8	0.69±0.03	5.26
CU5	70	8	0.75±0.03	3.90
CU6	62	8	0.78±0.04	3.41
CN1	62	8	0.66±0.02	6.56
CN2	62	8	0.60±0.02	6.44

* Test stopped before failure.

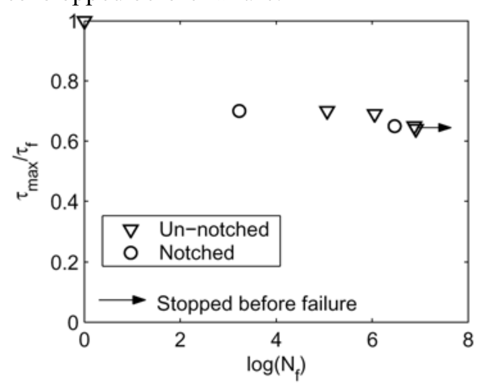

Figure 6. Results from tests of composite beams with a flat steel plate. The arrow symbolize that the test were stopped before failure.

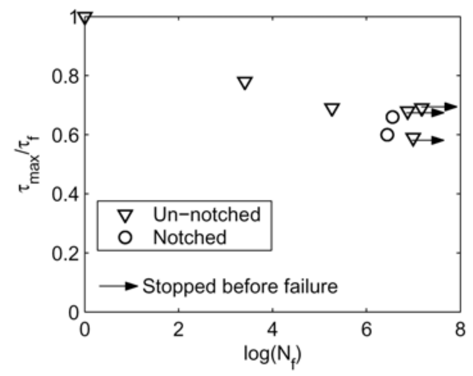

Figure 7. Results from tests of composite beams with a checker steel plate. The arrow symbolize that the test were stopped before failure.

5 NUMERICAL MODELING

To study the behavior of the test set-up a numerical model is used. A two dimensional configuration of the composite beam is considered. The set-up is modeled as a half beam, using a commercial finite element program package, (DIANA 2003). The half beam is modeled assuming a nonlinear behavior in the overlay and the interface. The steel plate is modeled as a linear elastic material. The steel-concrete interface is modeled using so-called interface elements. The interface elements have a thickness of zero and are placed between the steel and concrete and relate the forces acting on the interface to the relative displacement of the two sides of the interface. All elements representing the overlay are of quadratic shape having a size of $3.5x3.5\ mm^2$.

5.1 Material characterization

As the composite beam is loaded, fracture can occur in the overlay and/or in the steel-concrete interface. This requires two types of fracture modeling approaches, one for the overlay and a second for the interface.

Cracking of the overlay is modeled using the smeared cracking approach. A bilinear (σ-w) relation is used with constant shear retention. The stress-crack opening relationship is given by

$$\frac{\sigma(w)}{f_t} = b_i - a_i w = \begin{cases} b_1 - a_1 w, & 0 \le w < w_1 \\ b_2 - a_2 w, & w_1 \le w < w_2 \end{cases} \quad (1)$$

where $b_1=1$; and the limit w_1 is given by the intersection of the two line segments and w_2 correspond to the intersection between the second line and the abscissa. The material parameters used for the concrete are taken from Sigurdsson (2003), who measured the fracture mechanical properties of the same type of steel fiber reinforced concrete as used in these experiments (Table 1). The parameters in equation (1) used in the analysis were: $f_t=4.0MPa$, $a_1=10mm^{-1}$, $a_2=0.12mm^{-1}$, $b_2=0.9$.

The interfacial fracture is modeled using a composite interface model originally developed by Lourenço & Rots (1997), and implemented in DIANA. The interfacial failure criterion is of a Mohr-Coulomb type, and able to describe failure in either shear, tension or mixed mode. The governing parameters are cohesion, tensile strength and friction angle φ, as well as the fracture energy for pure (mode I and II), assuming exponential softening of the cohesion and tensile strength. For further details see either Lourenço & Rots (1997) or Walter et al. (2003b).

The steel is modeled as a linear elastic material with the following engineering constants: E_s = 210GPa, υ_s=0.3. The elements modeling the overlay and steel plate are 8-node isoparametric plane stress elements.

5.2 *Crack propagation*

To illustrate the interfacial crack behavior, with and without a notch, a numerical example is studied. Figure 8 shows how the interfacial crack propagates. For a given load P the figure illustrates where cracking occurs along the beam axis as defined in Figure 9. In the case of an interfacial notch, cracking starts at the tip of the notch at a relatively low load value and propagate towards the load point. In the case of an un-notched composite beam, interfacial cracking initiates somewhere in between the support and load, and the crack propagates towards the support and load point, resulting in a more dramatic global failure.

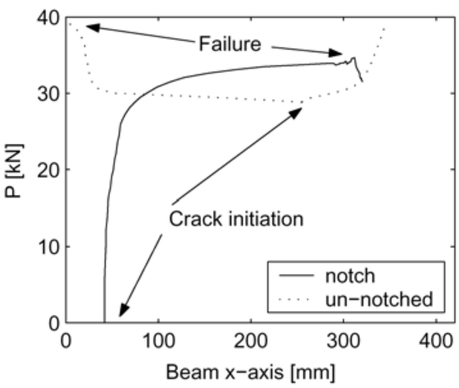

Figure 8. Crack propagation along the interface, calculated using FEM. Crack propagation is plotted for a given position on the x-axis according to Figure (9) versus the load for a notched and un-notched beam.

The significant differences between the two cases are: where the interface crack initiates and how it propagates. Running an experiment without a notch is somewhat less useful for the study of the interfacial crack propagation. However, when applying a notch, the crack initiates at the notch tip close to the support and propagates towards the load point. This is suitable for closed-loop testing using the end-slip as the controlling parameter. Photos of sample beams, with and without a notch, are shown after failure in Figure 10. It reveals that the notched beam has cracks running from the interface into the overlay, whereas the un-notched beam has only one dominant interface crack.

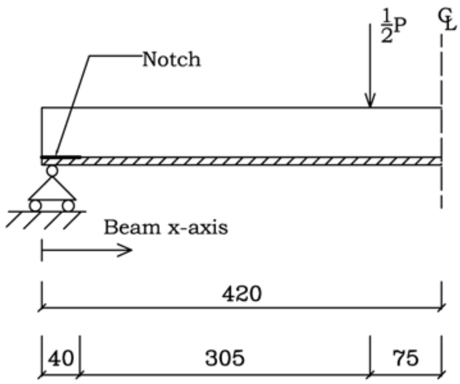

Figure 9. Definition of beam x-axis, position of support and load.

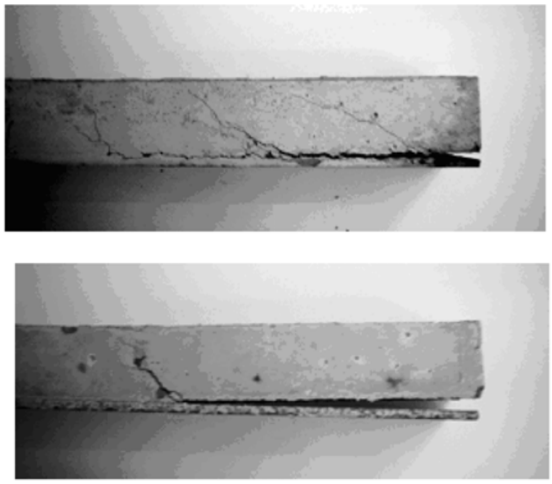

Figure 10. Failure modes. Top: Notched composite beam, beside the interfacial cracking a number of cracks in the bulk material is observed. Bottom: Un-notched composite beam after failure, a dominant interface crack is observed.

5.3 *Model predictions and experimental results*

Two characteristic experimental results using flat and checker steel plates, each with an interfacial notch, are compared to the FE-model. The comparison is carried out in a load vs. end-slip diagram. Two examples in which FE-calculations are fitted to experimental results are shown in Figures (11) and (12). The material data for the steel-concrete interface are obtained by such fitting and the following interfacial parameters (tensile strength, cohesion, friction angle and pure mode

I+II fracture energies) were found: f_t=4.0MPa; c=3.0MPa; tan(φ)=0.7; G_f^I =0.2N/mm; G_f^{II} =2.6N/mm for the checker steel plate, (Figure (11)) and f_t=4.0MPa; c=3.1MPa; tan(φ)=0.7; G_f^I =0.2N/mm; G_f^{II} =2.6N/mm for the flat steel plate, (Figure (12)). It is noticed that the numerical modeling captures the nonlinear behavior of the experiment.

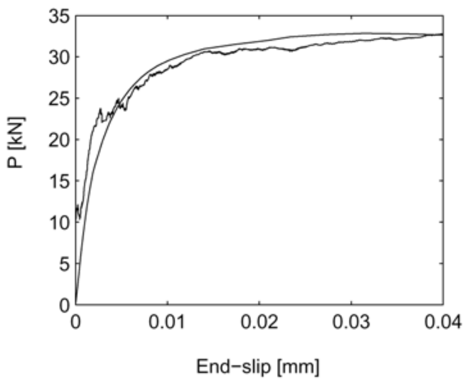

Figure 11. Fitting of FE-calculations to experiments for a checker steel plate.

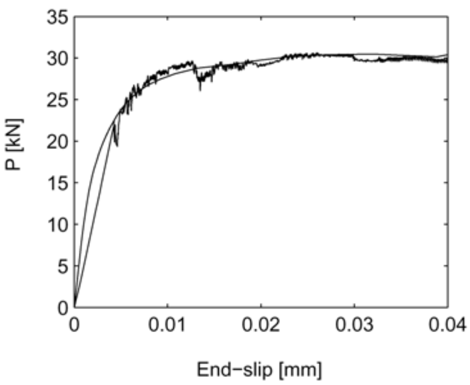

Figure 12. Fitting of FE-calculations to experiments for a flat steel plate.

According to the numerical model, interfacial cracking initiates at the interface for an un-notched beam at approximately 65% of the maximum static load (Figure 9). Comparing this with the results of the cyclic tests, it is seen, that this corresponds to the fatigue threshold value.

6 CONCLUSIONS

A test set-up using a composite beam consisting of a cement-based overlay cast upon a sandblasted steel plate has been investigated experimentally under static as well as cyclic loading. A checker and a flat steel plate were used in the experiments. The different steel plates did not reveal any significant differences in static or fatigue strength. A modified version of the test set-up was used, introducing an interfacial notch between the concrete and the steel plate near the support. This set-up has proven suitable for studying the interfacial crack propagation during loading. A number of different specimens were used in the study of a composite beam exposed to cyclic loading. A primary result is that the steel-concrete interface shows a good fatigue resistance, as a fatigue threshold level was observed around 65% of the static failure load for the un-notched beams.

Numerical modeling was carried out using FEM. The model has been validated, using the notched beam set-up. The modeling helped reveal the different fracturing behavior of the notched and un-notched composite beams. Finally, the numerical modeling confirms that cracking at the interface occurs at a load level of approximately 65% of the static failure load for an un-notched beam, which corresponds well to the observed fatigue threshold load. As expected, the notched beams have a lower threshold in fatigue, since interfacial cracking is initiated at a lower load.

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