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NONLINEAR FRACTURE MECHANICS OF DELAMINATION FAILURE IN A COMPOSITE STRENGTHENED CONCRETE BEAM

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ABSTRACT

The bonding of composite plates to the tensile side of concrete beams or slabs has recently been accepted as an effective retrofitting method. A concrete member retrofitted in this manner often fails through the delamination of the composite. Most existing models for the analysis of delamination assume linear elastic material behaviour until ultimate failure of the component. This is contradictory to experimental observations that clearly indicate the occurrence of non-linear damage processes at load levels far below the ultimate load. In this paper, a novel nonlinear fracture mechanics approach for the analysis of delamination failure is introduced. The delamination is modelled as an interfacial crack, with progressive interfacial damage represented by material softening at the crack wake. The focus of the paper is on the determination of the interfacial shear stress vs slip ($\tau_s - s$) relation. A new testing method to study progressive delamination is first described. A finite element model for the specimen is then set up, with softening elements at the plate/beam interface. By comparing experimental measurements to finite element results using different softening behaviour at the interface, the constitutive relation of the interface elements, in terms of shear stress vs sliding displacement, can be obtained. From our results, the softening behaviour exhibits a sharp drop followed by more progressive weakening, indicating sudden loss of cohesion/bond at a critical stress level, and a more gradual reduction in friction with increased sliding and damage.

KEYWORDS
Non-linear fracture, delamination, composite, interfacial softening, retrofitting, concrete

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 [1], Arduini et al [2], Buyukozturk et al [3]). Delamination is the most commonly observed failure mechanism (Saadatmanesh et al [4], Meier et al [5]) that occurs with little warning (compared to conventional flexural failure). The investigation of delamination failure is hence an important research topic for plate-strengthened beams.

From a theoretical point of view, delamination may occur either at the end of the composite plate (cut-off point), or under a flexural (or flexural/shear) crack in the concrete member. Elastic stress fields at the plate end have been derived independently by Taljsten [6] and Malik et al [7], while that under the flexural crack has been obtained by Leung [8]. From these analyses, an important observation can be made. The stresses decrease rapidly with distance from the point of maximum stress, so high stresses exist over a relatively small part of the interface. Similar to the stress singularity at 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 [9] 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 [3] and Taljsten [10] 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 Taljsten [6], Malik et al [7] and Leung [8] as well as LEFM-based interfacial fracture analysis (e.g., Hutchinson and Suo [11]), 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 [3] and David et al [12] 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 [3] and the agreement with experimental result was not satisfactory. In David et al [12], 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 over a representative volume of materials. 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 [13] was first proposed by Taljsten [14]. To illustrate the concept, Taljsten [14] 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.

A new modeling approach using nonlinear interface elements

To model progressive damage at the interface, a new non-linear interface element is introduced. The effect of damage is lumped into the softening of the interface element instead of allowing damage in the concrete elements. The justification is that the thickness of material over which damage occurs is small compared to the dimensions of the beam, therefore the damage can be modelled using a discrete rather than smeared approach.

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 and the analysis is greatly simplified. Only the constitutive relation of the interface element is needed. As in Fig.1(c), the interface element 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 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. 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. u returns to 0), 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 u. The reduction of τ_s with increasing shear displacement is illustrated in Fig.1(d) for a given u. The curve in Fig.1(d) is dependent on the opening displacement. In the model, the τ_s vs s relation is approximated by a multi-linear relation.

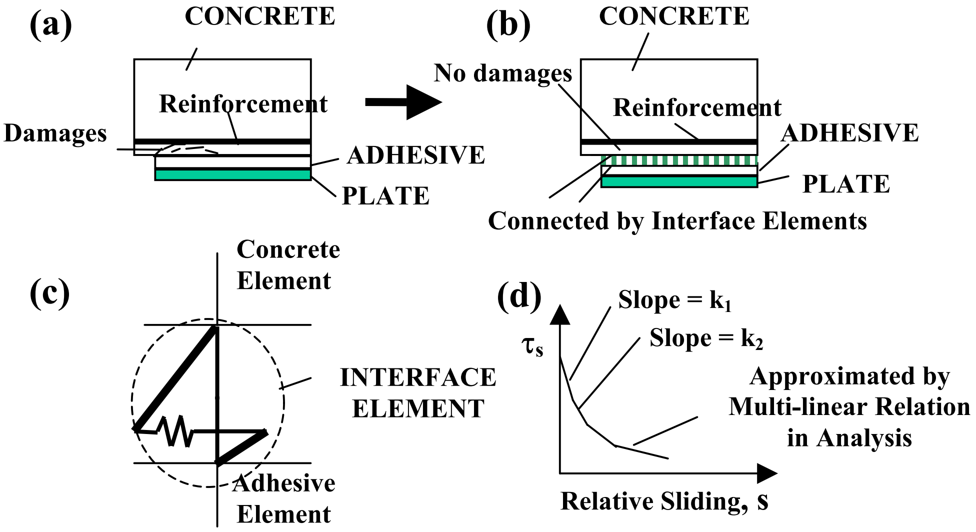

Fig.1 (a) and (b) Representation of concrete damage with non-linear interface elements (c) the interface element, (d) Variation of element shear stress with sliding

Determining the constitutive relation of interface element

To obtain the constitutive relation of the interface element, a novel experimental procedure is developed (Fig.2). It consists of a concrete half-beam and a metal member connected together by a rod that acts as a hinge. A composite plate is to be glued to the bottom part.

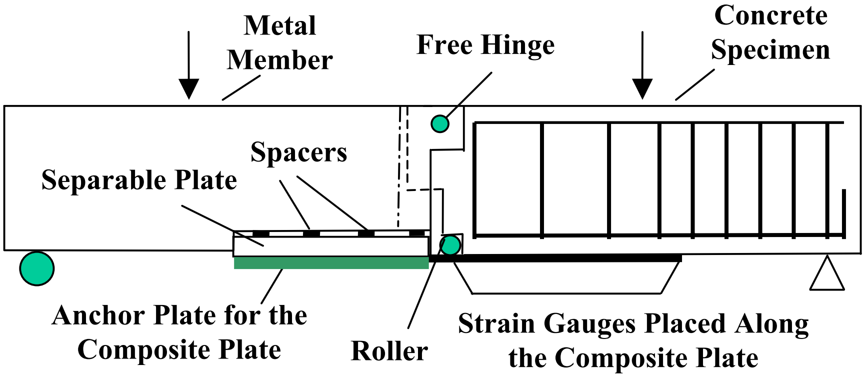

Fig. 2 Experimental set-up to determine constitutive relation of the interface element

As shown in Fig.2, strain gauges are glued along the composite surface and longitudinal strain is measured together with the applied load. A finite element model for the concrete member is set up. Interface elements such as those shown in Fig.1 are placed along the plate/concrete interface. The strain distribution along the plate can hence be theoretically predicted. Before the initiation of delamination, the strain field is elastic. The strain at any distance increases proportionately with the load. Based on the applied load when proportionality no longer holds, the critical shear stress can be obtained. After delamination starts, the strain variation is a function of the shear softening behaviour. For a load that is just above the delamination load, the composite strain is only dependent 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 branch is used for increasing loading until it no longer produces a good fit. The maximum shear displacement (s_1) on the last run is recorded, and the slope of next branch, which starts at $s = s_1$, is determined. Similar analysis can be continued to find the slopes of all subsequent branches. The slope of each branch is also a function of u. As a first attempt to determine the shear-softening relation at the interface, u is kept at zero.

Experimental Result and Analysis

The size of the metal member and concrete half-beams are around 1.1m x 0.2m x 0.22m (LxWxH). The composite employed is Sika Carbodur S-512. The total length of the composite is 950mm, half is bonded on the concrete. Starting from the internal bottom edge of the concrete member, 11 strain gauges are placed 21mm center to center on the composite. The testing was carried out in 4-point bending, with 1.8m support span and 0.6m between the loading points. The hinge of the specimen was placed at the middle of the two loading points. The concrete strength was 33 MPa. According to the supplier, the Young's modulus of the adhesive is 4.4 GPa. In each test, stable propagation of the delamination can be observed. The ability to induce progressive delamination is a major advantage of the present set-up for the investigation of the softening behaviour at the interface.

Here one set of results is presented. Fig.3 shows the variation of longitudinal strain with distance along the plate. From the figure, 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 (Fig.4) was developed for the concrete member, using the program ADINA. Interface elements, in the form of springs, are placed between the adhesive and the concrete. In this case, with 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. The spring is set to be very rigid before critical shear stress is reached. Once the shear stress reaches the critical, the behaviour will follow a softening curve.

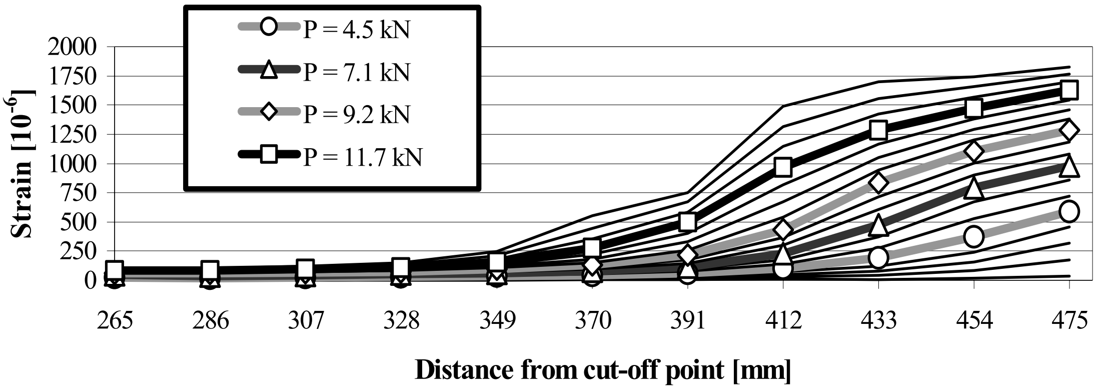

Fig.3 Variation of Measured Strain at Various Load Levels

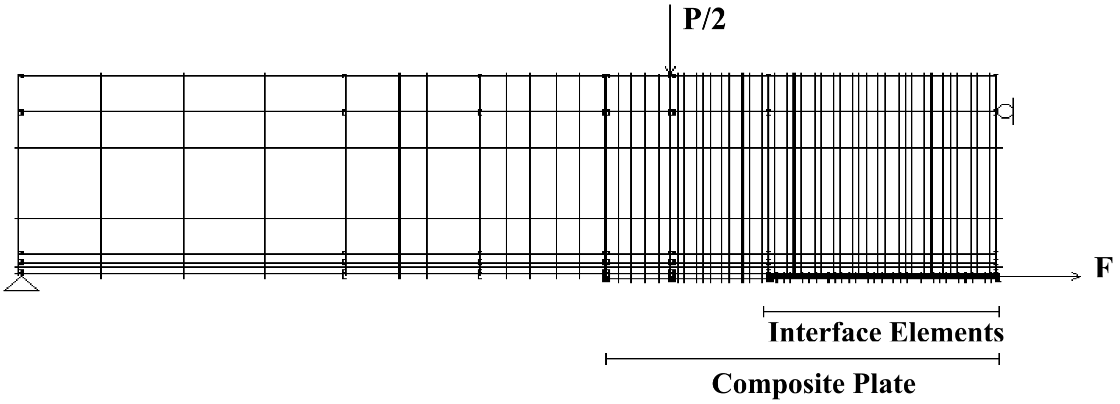

Fig.4 The Finite Element Mesh used in our Analysis

Figs. 5 to 6 show the comparison between experimental strain and finite element strain values. Fig.5 shows all the elastic cases, and results are normalized to that for 4.5kN. From the figures, the overall agreement can be considered quite satisfactory. The softening behaviour of the interface element is shown in Fig.7. Note that the curve exhibits a vertical drop followed by more gradual decrease. We believe the sudden drop is due to bond/cohesion failure, while the continual change indicates the reduction in friction with increasing sliding and damage.

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.

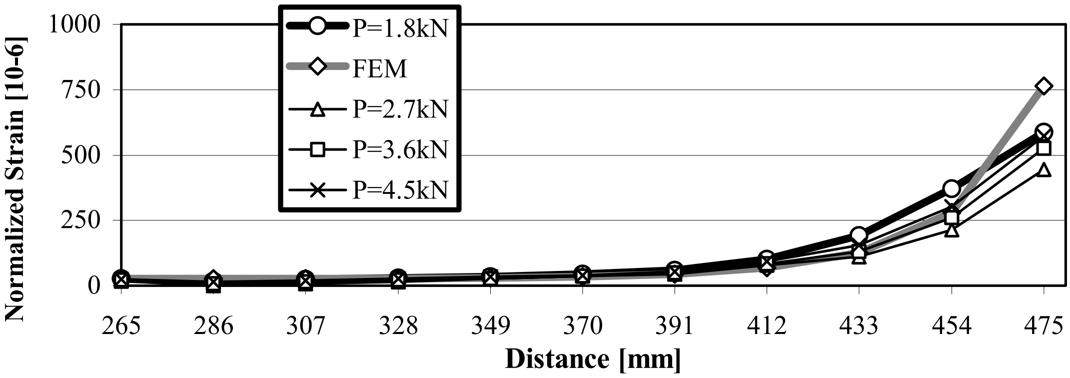

Fig.5 Comparison between normalized experimental and FEM results for P up to 4.5kN

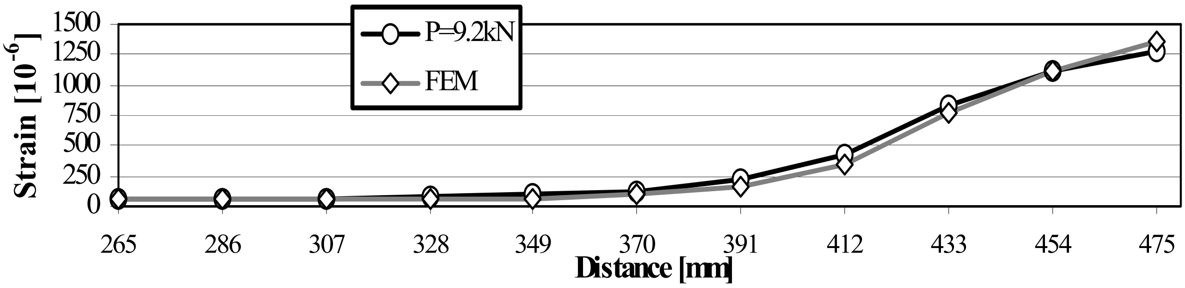

Fig.6 Comparison between Experimental and FEM results for P = 9.2 kN

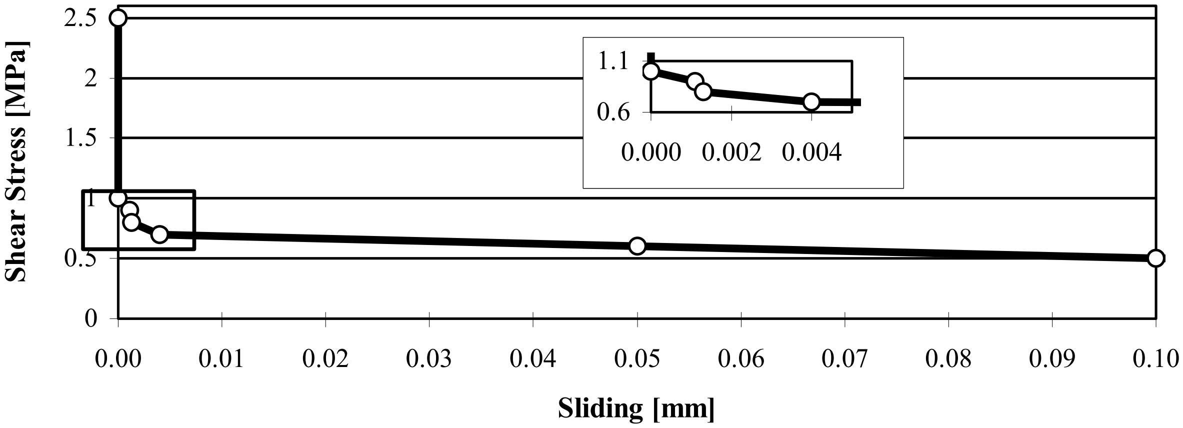

Fig.7 The Experimental Determined Interfacial Softening Relation

CONCLUSION

For the delamination of bonded plate from a concrete member, non-linear behaviour has been reported by many investigators. 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 have only studied the case with zero opening displacement at the interface. In the future, the effect of opening displacement should also be considered to develop a general interface element for the analysis of concrete members retrofitted in different manners.

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