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Finite element study of plate-end stresses on near-surface mounted FRP strips

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ABSTRACT: Two sets of simply supported reinforced concrete beams strengthened with near-surface mounted CFRP strips were modeled in 3D using the finite element analysis software ANSYS, with the aim of studying the stress distribution near the strips' cut-off points. The geometry and material properties of the beams were modeled accurately, allowing for the nonlinear behavior of concrete, steel reinforcement and epoxy adhesive, and using a refined mesh at the strip ends to improve accuracy locally. After establishing reasonable accuracy of the finite element analyses through comparison with experimental results, the concrete stresses at the concrete-adhesive interface along the strip's length were studied at increasing load levels up to failure. It was observed that the concrete adjacent to the adhesive layer is subject to longitudinal and transverse shear stresses as well as stress normal to the strip face throughout the entire load history. Although the distribution is highly variable along the strip length after cracking, overall tendencies of the stress distributions are discernible. Hence, it is concluded that these orthogonal stresses must be considered in the plate-end debonding mechanism, and therefore, the currently available analytical models to predict this type of debonding in near-surface mounted strips are not in agreement with the behavior observed through 3D finite element analysis and published experimental data.

1 INTRODUCTION

Adhesively bonding FRP sheets and plates to the faces of concrete elements has proven to be an effective strengthening technique, which has been validated through research and field applications. The technique does have some drawbacks, including tendency of the FRP to debond at low strains, interference with floor and pavement finishes, exposure of the FRP to the elements and vandalism, and the necessity of extensive surface preparation prior to installing the FRP to ensure an appropriate bonding surface. All of these problems are overcome by the near-surface mounted (NSM) technique, in which narrow FRP plates or "strips" are adhesively bonded into grooves cut in the concrete cover.

However, as opposed to the externally bonded retrofitting technique, for which extensive research has been carried out for over a decade now, the existing knowledge on NSM strengthening or repair is much more limited. Hence, reliable models to predict debonding failures of concrete flexural members retrofitted with this technique are currently not available for all the possible failure mechanisms.

One of such mechanisms is the plate-end debonding mechanism, in which stresses induced at the strip cutoff points by bending of the strengthened member generate cracking in the concrete, that when propagates causes the strip to debond. Given that quantifying experimentally such localized stresses in concrete is not possible, finite element analyses were deemed appropriate to study the debonding mechanism in a way that allows assessing the adequacy of the currently available debonding theoretical models, and to yield clues towards the formulation of a rational plate-end debonding analytical model for NSM strengthening.

2 FINITE ELEMENT MODELING

After an extensive review of the available literature, all beams tested by Teng et al. (2006), and beams B0, B2 and B3 tested by Hassan and Rizkalla (2003), were chosen to be modeled for being the only ones in which plate-end debonding of NSM strips occurred experimentally. Figure 1 shows details of a typical finite element model for Hassan and Rizkalla's beams, Teng et al.'s typical models being very similar, but with a 300x150 mm rectangular cross-section.

All beams were modeled in 3D using the finite element analysis software ANSYS, and both the geometry and materials of the specimens were modeled accurately, including FRP strips, epoxy adhesive, longitudinal rebar and concrete, as illustrated in Figure 2. The ANSYS library of elements has one 8-noded hexahedral isoparametric element "Solid 65", specifically developed to model reinforced concrete and brittle materials, which was used to model the concrete and the epoxy adhesive, and a compatible element (same number of nodes, dofs and shape functions) "Solid 45", that allows for the modeling of orthotropic materials, which was used to model the FRP strips.

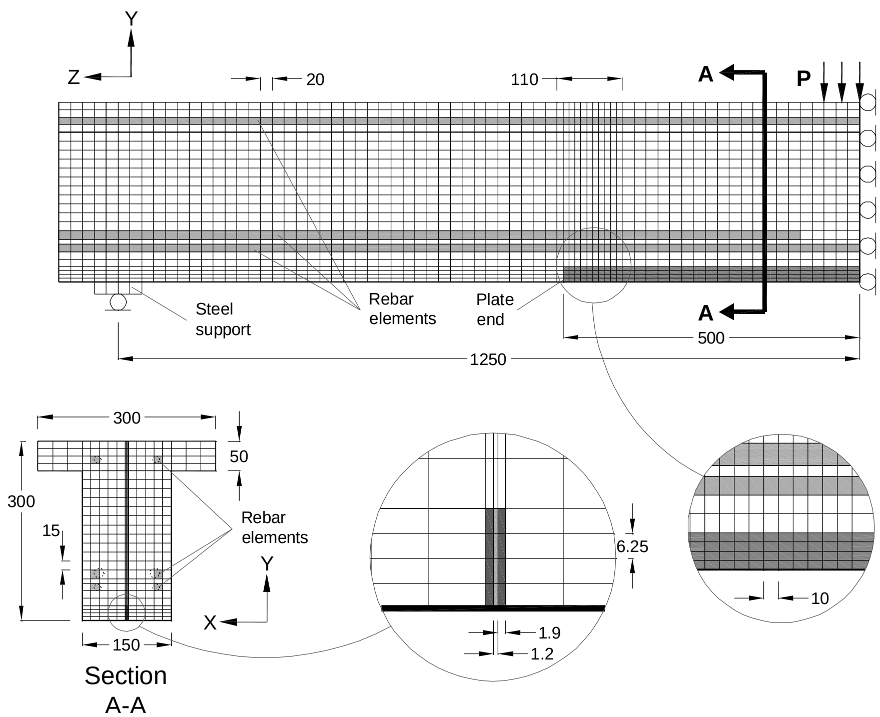

Figure 1. Typical finite element model of Hassan and Rizkalla's beams (all measures in mm)

The "Solid 65" element allows for the modeling of the nonlinear behavior of concrete based on a constitutive model developed for triaxial stress states. Cracking of the concrete under tension is modeled through a "smeared" crack analogy and the possibility of crushing in compression is accounted for using a plasticity algorithm. The element behavior is linear elastic until any of the principal stresses at any of the element's eight integration points exceeds the specified tensile or compressive strengths. Cracked or crushed regions are formed perpendicular to the relevant principal stress direction and stresses are redistributed locally. When cracking occurs, it is modeled through an adjustment of the material properties which introduces a plane of weakness in the element. The amount of shear transfer across a crack can be varied by means of coefficients defined by the user ranging from 1.0 for full shear transfer (a rough crack) to 0.0 for no shear transfer (a totally smooth crack). If the material fails at an integration point in uniaxial, biaxial or triaxial compression, it is assumed to have crushed at that point, which is treated as a complete deterioration of the structural integrity of the material, and hence the contribution to the stiffness of the element at that integration point is ignored. Subsequently second and third mutually orthogonal cracks can develop at each integration point.

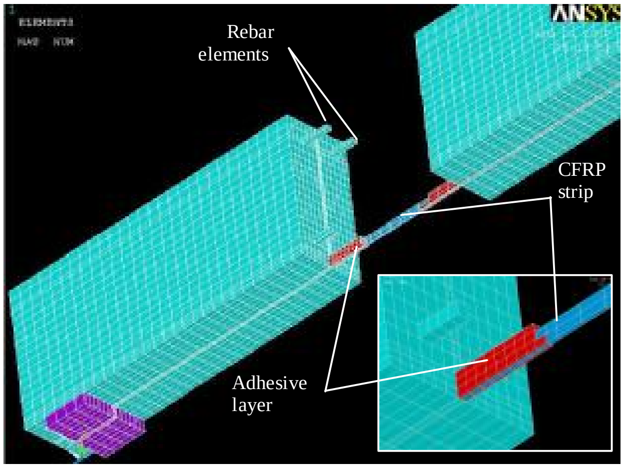

Figure 2. Cutaway finite element model showing the different components

The longitudinal rebar was modeled using a feature of the "Solid 65" concrete elements that simulates reinforcement behavior by modifying their stiffness based on given rebar material properties, the rebar orientation and a ratio of the volume of rebar to the volume of concrete in each reinforced element. The reinforcement is then considered to be "smeared" throughout elements and it is capable of tension, compression, plastic deformation and creep.

The "Solid 65" element was also considered appropriate to model the epoxy adhesive layer, as it is capable of simulating the behavior of a brittle material. This approach would allow studying stresses at the interface in three dimensions and would not force the interface to behave following a specified bond-slip model. CFRP-adhesive interfaces have accurately been modeled using ANSYS "Solid 65" and "Solid 45" elements for the adhesive and CFRP respectively by Dawood et al. (2007).

The "Solid 45" elements allow for plasticity, creep, swelling, stress stiffening, large deflection and large strain behavior, and were given the appropriate FRP orthotropic material properties. As the orthotropic material properties of the FRP used in the experimental programs were not available, typical Young's modulus values for the matrix and the fibers of 3000 MPa and 200000 MPa respectively, were assumed to calculate all the necessary material properties. Table 1 summarizes the material properties and the coefficients of shear transfer across cracks used in the different models.

Taking advantage of symmetry only half beams were modeled using the appropriate dof restrains. For all specimens a finer mesh was produced around the FRP plate ends as these were the main areas of interest, while a coarser mesh was used elsewhere to improve computational time. However, the level of detail with which the FRP and adhesive were modeled meant the transition to a coarser mesh was limited by the need to maintain acceptable aspect ratios and to use hexahedral elements throughout. The cross-sectional mesh was kept constant throughout the beams to facilitate the modeling of specimens strengthened with FRP strips of different lengths.

To avoid undesirable high stress concentrations on concrete elements, metal plates were modeled at the beams supports and the loads were applied as pressures on several elements rather than concentrated loads at nodes. As nonlinear behavior was being modeled for the concrete and adhesive, an iterative solution was necessary, as well as a gradual application of the load to avoid convergence problems.

Table 1. Material properties used in finite element modeling

Specimen set	Concrete				Rebar		FRP		Adhesive			
	f'_c	E	Coef. open crack	Coef. closed crack	f_y	E	f_r	E	f_t	E	Coef. open crack	Coef. closed crack
Hassan and Rizkalla	35	28000	0.60	0.85	532	400	2068	151000	42.6	42.6	0.01	0.02
Teng et al.	57	30000	0.60	0.85	210000	200000	2000	160000	2620	2620	0.01	0.02

All units MPa

3 RESULTS

Figures 3 and 4 show the experimental and finite element analysis load-deflection response of the modeled specimens. In general it can be seen that first cracking of the concrete and the initiation of yielding in the steel were modeled accurately, except in Teng et al. specimens B1800 and B2900, where yield of the steel occurred experimentally at higher loads. Within the specimens corresponding to the same experimental program, the only differences in the finite element models are the length of the FRP strip and for the reference specimens, the absence of FRP. Then it can be seen that the finite element models were reproducing the strengthening effect of the FRP strips, and were sensitive to change in the length of the FRP, as specimens with longer strips showed decreased deflections for a given load level.

The ultimate detachment of the FRP strips, indicated in Teng et al.'s specimens by the descending branches in the load-deflection response, was not captured by the finite element models, in which the stiffness of the beams keeps steadily decreasing but never drops suddenly to a negative stiffness as recorded experimentally, and hence the analyses were terminated when the concrete strain reached 0.003. This is due to the decrease of stiffness being simulated by the software through gradual propagation of cracking in concrete and adhesive, which means the FRP strip always remains attached to the beam, even when some of the adhesive and concrete elements considerably loose stiffness. This also explains the considerably different load-deflection response obtained for Hassan and Rizkalla's specimen B2, which experimentally behaved essentially as an unstrengthened beam, meaning complete debonding of the FRP occurred at a very low load. Similar results were obtained by Barbosa and Ribeiro (1998) when modeling 3D FRP-strengthened beams in ANSYS.

As can be expected, the behavior at ultimate load is very complex and difficult to model in a highly heterogeneous material as concrete. Nonetheless, the aim of the finite element analysis in this investigation is not to obtain a model that can accurately predict ultimate capacities of strengthened beams, but to serve as a tool to help understand the distribution of stresses near the ends of near-surface mounted FRP strips, and yield clues on the plate-end debonding mechanism that can aid the assessment of the currently available theoretical models and the formulation of a rational analytical model.

Bearing the above in mind, the results obtained were deemed appropriate and reliable enough to study the stress distribution near the strips' cut-off points.

4 COMPARISON WITH EXISTING THEORETICAL MODELS

A comprehensive literature review showed that there are currently two theoretical models suitable for predicting plate-end debonding of NSM FRP strips. The first one, presented by Oehlers and Nguyen (2000), considers in its derivation shear stress τ_{XY} and normal stress σ_{XX} shown in Figure 5, assuming τ_{XZ} would tend to zero near the plate ends. It must be mentioned that this model was actually developed for plate-end debonding of externally bonded side plates, and not for NSM strips, but by simply doubling the bonded area as a rough approximation to NSM behavior, the authors of the present document evaluated the applicability of the model to NSM plate-end debonding.

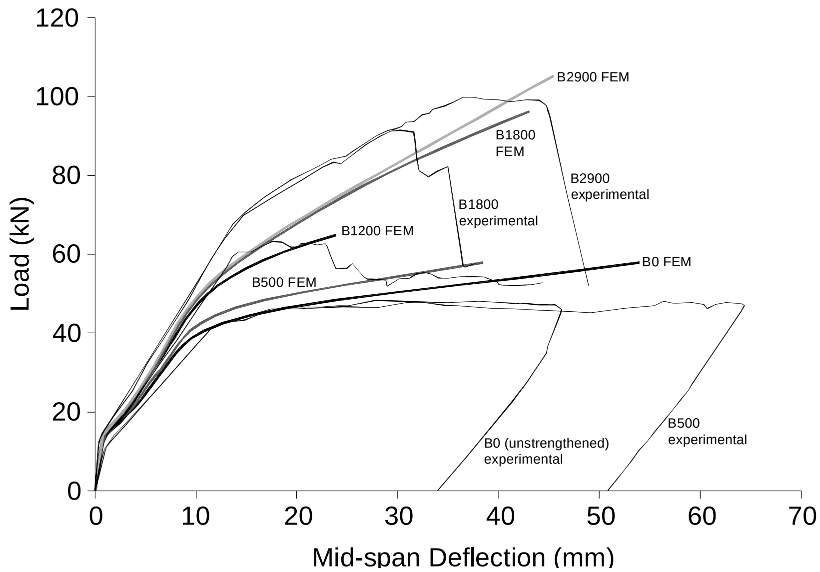

Figure 3. Experimental and finite element load-deflection response for Teng et al.'s specimens

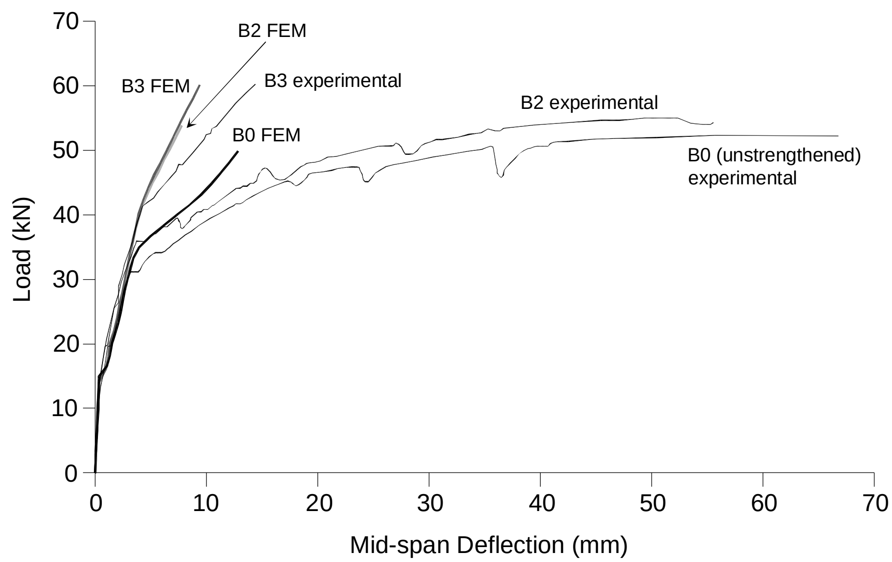

Figure 4. Experimental and finite element load-deflection response for Hassan and Rizkalla's specimens

The second model, proposed by Hassan and Rizkalla (2003), was developed for near-surface mounted strengthening, and considers only the longitudinal shear stress τ_{XZ} in Figure 5, arising from bending of the strengthened element.

Study of stresses in the concrete σ_{XX}, τ_{XY} and τ_{XZ} near the plate ends from the finite element results, shows that, as seen in Figure 6, although the stress distribution is highly irregular after cracking, the magnitudes of the three stresses up to the initiation of debonding are all significant, and hence none of the three stresses should be disregarded when modeling the plate-end debonding mechanism, as done in the existing theoretical models.

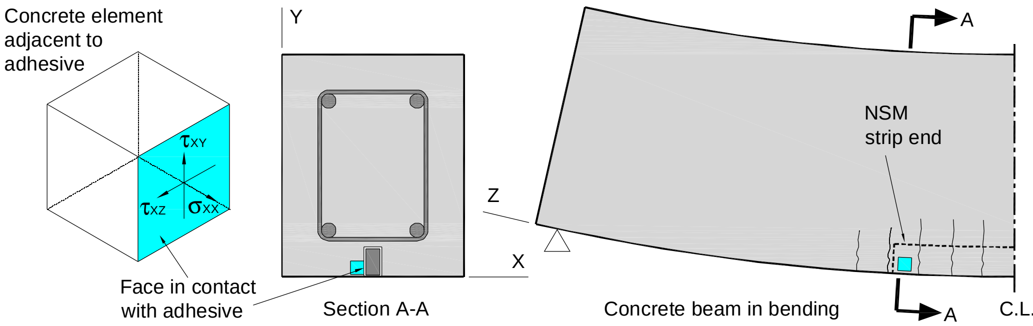

Figure 5. Stresses considered in plate-end debonding of NSM strips for beams in bending

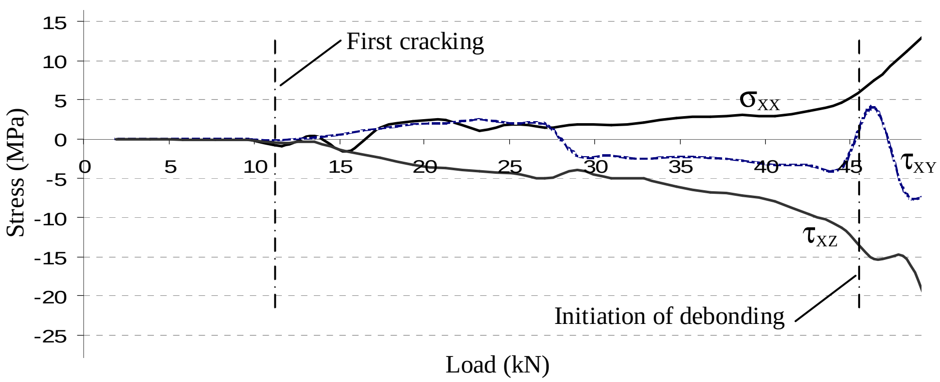

Figure 6. Typical σ_{XX}, τ_{XY} and τ_{XZ} distribution near a NSM strip cutoff points for different load levels

5 CONCLUSIONS

Detailed 3D finite element analyses that allow the study of stresses around the cut-off points of NSM FRP strips on flexural elements have been presented. The analysis of the results, along with comprehensive literature review, allowed to conclude that the currently available theoretical models for plate-end debonding of NSM strips are not in agreement with the actual debonding mechanism, and hence a model to predict this type of debonding based on a more rational approach is still required. That approach, based on the results of this investigation, should include the consideration of the transverse and longitudinal shear stresses, as well as the normal stress that develop in the concrete on the bonded surfaces of an NSM FRP strip.

6 REFERENCES

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