Second Conference on Smart Monitoring,
Assessment and Rehabilitation of Civil Structures

SMAR 2013

Debonding Failures in RC Beams Strengthened in Flexure with Near-Surface Mounted (NSM) CFRP Strips

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ABSTRACT: The method of strengthening reinforced concrete (RC) structures using near-surface mounted (NSM) FRP reinforcement has attracted increasing attention in recent years as a promising alternative to externally bonded FRP reinforcement. In the NSM FRP method, grooves are cut into the concrete cover of RC members for the embedding of FRP bars using an adhesive. Compared to the externally bonded FRP method, the NSM FRP method has a number of advantages including improved bond efficiency and better protection of the FRP reinforcement. Despite the improved bond performance, debonding failures of various forms are still likely to occur in RC members strengthened with NSM FRP bars. This paper presents a summary of a major recent study undertaken by the authors on such debonding failures in RC beams strengthened in flexure with NSM CFRP strips (i.e. bars of narrow rectangular section). CFRP strips were focused on in the study because they possess a larger perimeter-to-cross-sectional area ratio than bars of other shapes, and thus offer the best bond efficiency with the RC member being strengthened.

1 INTRODUCTION

Fibre-reinforced polymer (FRP) composites have been widely used to strengthen reinforced concrete (RC) structures. In particular, RC beams can be strengthened in flexure with FRP reinforcement that is externally bonded to the tension surface of the beam. This method, referred to as the externally bonded FRP method herein, has been extensively studied by researchers; design guidelines have also been established for use in practice. More recently, the near-surface mounted (NSM) FRP method has attracted significant attention as an effective alternative to the externally bonded FRP method. The NSM FRP method for the flexural strengthening of RC beams is illustrated in Fig. 1 using a cross-sectional plot. In the NSM FRP method, grooves are cut into the concrete cover of RC members for the embedding of FRP bars using an adhesive. Compared to the externally bonded FRP method, the NSM FRP method has a number of advantages (De Lorenzis & Teng 2007) such as the reduced likeliness of debonding failure. FRP bars of various cross-sectional shapes may be used in the NSM FRP strengthening of structures, including round, square, rectangular and elliptical bars. FRP strips, as a special form of rectangular bars with a large bar height-to-thickness ratio, are a common form of NSM FRP reinforcement due to their advantage over NSM FRP bars of other shapes in bond performance: an FRP strip usually has a much larger perimeter and a greater embedment depth for the same cross-sectional area than an FRP bar of other shapes, so its larger bond force with concrete leads to a fuller utilization of the tensile strength of the FRP material (e.g. El Hacha & Rizkalla 2004). FRP strips made of CFRP are particularly attractive as the high strength and stiffness of CFRP leads to a small cross-sectional area for the same tensile stiffness and capacity, which is desirable in NSM FRP strengthening applications. As a result, CFRP strips have been a popular form of bars for use in NSM FRP strengthening. The study presented herein was thus focussed on NSM CFRP strips. Although the bond performance of NSM CFRP strips is superior to that of their externally bonded counterparts, NSM CFRP strips are still likely to suffer debonding failures. The wide practical acceptance of NSM CFRP strips depends on the availability of a robust method to design against their debonding failures. To this end, the authors have recently completed a major study on debonding failures of RC beams strengthened in flexure with NSM CFRP strips. This paper provides a summary of the main findings from the study (Zhang 2012).

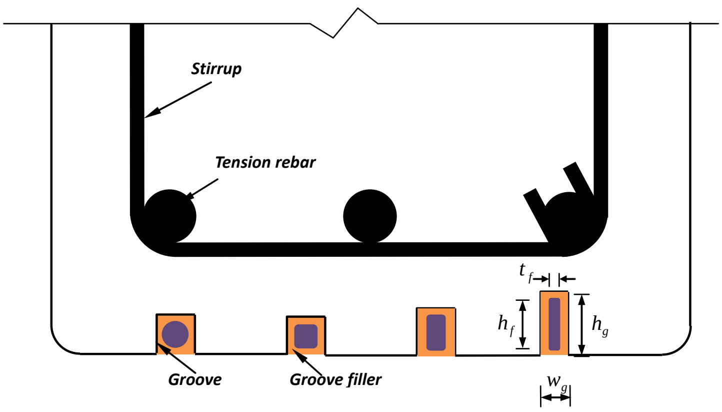


Fig. 1. Flexural strengthening of RC beams with NSM FRP bars

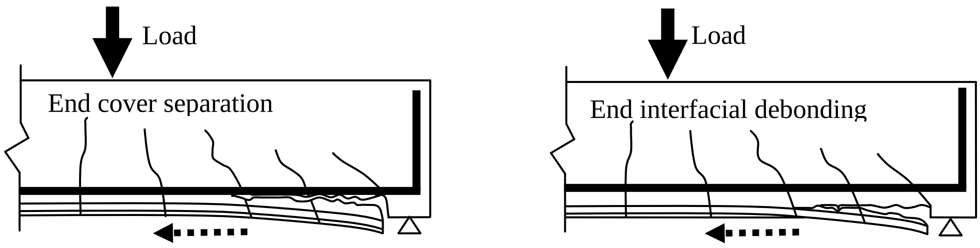


Fig. 2. Two types of end debonding failures

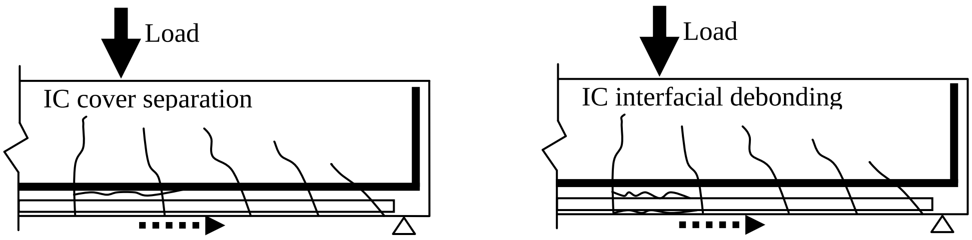


Fig. 3. Two types of IC debonding failures

2 DEBONDING FAILURE MODES

Before presenting the research results, it is necessary to clarify the possible failure modes of RC beams strengthened in flexure with NSM CFRP strips. In the following discussions, "debonding" is used as a generic term to refer to both adhesion failure at bi-material interfaces and the well-known concrete cover separation failure, as is commonly done in publications dealing with FRP-strengthened RC structures. That is, all failure modes that lead to the loss of composite action between the FRP and the RC beam are referred to as debonding. Existing laboratory tests on RC beams strengthened in flexure with NSM CFRP strips have identified the following failure modes (Zhang 2012):

1) **Flexural failure by crushing of concrete in compression**;
2) **Flexural failure by rupture of FRP in tension**;
3) **End debonding failure**. In this failure mode, debonding of a CFRP strip starts from one of the ends and propagates towards the mid-span of the beam (Fig. 2). End debonding failures can be further divided into two sub-types: **end interfacial debonding** and **end cover separation**; and
4) **Intermediate crack (IC) debonding failure**. In this failure mode, debonding of a CFRP strip starts from the maximum moment region and propagates towards one of the FRP strip ends (Fig. 3). IC debonding failures can also be further divided into two sub-types: ***IC interfacial debonding*** and ***IC cover separation***.

Of the four debonding failure modes discussed above, end cover separation has been observed most frequently in existing tests and is the main debonding failure mode of concern in the authors' recent study.

3 MESO-SCALE FINITE ELEMENT MODELLING OF BOND BEHAVIOUR

The bond behaviour of the NSM CFRP strip-to-concrete interface has commonly been studied using the single-lap shear test in which the CFRP strip is subjected to a tensile force at one of its ends (Fig. 4). Among the observed failure modes of such bonded joints, it has been concluded by De Lorenzis & Teng (2007) that the desired failure mode is the mode of cohesion failure in the concrete near the epoxy-concrete bi-material interface. With proper concrete surface preparation and the use of reasonably strong adhesives, this failure mode can generally be assured in practice. With this failure, the debonding strength is governed by the strength of concrete rather than that of the strengthening system, and as a result, the contribution of the strengthening system is maximised and the formulation of design provisions is simplified by excluding bi-material adhesion failures. Therefore, this paper is concerned only with the bond behaviour of NSM CFRP strip-to-concrete interfaces where the failure is governed by cohesion failure in the concrete substrate. Generally, it is highly challenging if not impossible to accurately capture the local details of bond behaviour between an NSM FRP bar and concrete in a laboratory test (e.g. the local bond-slip response) due to difficulties in placing strain gages on the NSM FRP bar without disturbing the bond properties. Given the above constraint, reliable finite element (FE) modelling is both attractive and necessary to supplement test results in understanding the bond behaviour between NSM FRP bars and concrete.

Fig. 4. Setup of single-lap Shear test

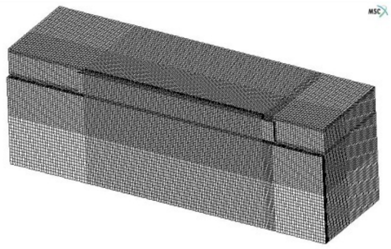


Fig. 5. FE mesh (half-specimen model)

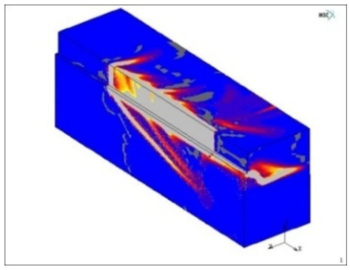


Fig. 6. Predicted failure mode (half-specimen model)

In the present study, a 3-D meso-scale FE model was developed using the general-purpose FE software package MSC.MARC (MSC.MARC 2005) for the bond behaviour of NSM CFRP strips in concrete (Teng et al. 2013). The concrete was simulated using the orthogonal fixed smeared crack model while the FRP and the adhesive are treated as linear brittle-cracking materials. The crack band concept (Bazant & Oh 1983) was employed to model concrete cracking with the fracture energy being that given by CEB-FIP (1993). The exponential tension-softening curve proposed by Hordijk (1991) and the shear stress-slip relationship proposed by Okamura & Maekawa (1991) were adopted based on careful assessments of available models. The uniaxial compressive stress-strain curve for concrete was defined using that proposed by Elwi & Murray (1979). The well-documented tests of Li et al. (2005) were used to calibrate and verify the proposed FE model. The FE mesh used for one of the specimens (specimen CS-150) tested by Li et al. (2005) is shown in Fig. 5, and the predicted failure mode is shown in Fig. 6. The FE predictions were found to be in close agreement with the test results. Most importantly, local bond-slip curves were extracted from the 3D FE predictions of the axial strains in the CFRP strip. For more details of the FE model and the comparisons, the reader is referred to Teng et al. (2013).

4 BOND-SLIP MODEL FOR NSM CFRP STRIPS IN CONCRETE

A review of the existing bond-slip relationships for NSM CFRP strip-to-concrete interfaces indicated that a sound bond-slip model had not been developed prior to the present study (Zhang et al. 2013b). By making use of the 3-D meso-scale FE model described above (Teng et al. 2013), a parametric study was conducted to generate numerical data for bond-slip responses, based on which a rigorous bond-slip model for such bonded joints was proposed. The numerical results showed that for NSM CFRP strip-to-concrete bonded joints that fail in the concrete, the concrete strength and the groove height-to-width ratio are the two key parameters that influence the bond behaviour (Zhang et al. 2013b). The former reflects how strong the concrete itself is while the latter represents the level of confinement provided by the surrounding concrete to the bonded interface. Other parameters of the bonded joint were found to have only rather limited effects on the bond behaviour.

Based on the numerical results from the parametric study, the following bond-slip model, including expressions for the interfacial fracture energy (G_f) and the maximum bond shear stress ($\tau_{\max}$), was formulated:

$$\tau = A(\frac{2B-s}{B})^2 \sin(\frac{\pi}{2}\cdot\frac{2B-s}{B}) \quad \text{with} \quad s \le 2B \tag{1}$$

$$G_f = 0.4\gamma^{0.422} f_c^{0.619} \tag{2}$$

$$\tau_{\max} = 1.15\gamma^{0.138} f_c^{0.613} \tag{3}$$

where τ and s are the bond shear stress and the shear slip respectively; $A = 0.72\gamma^{0.138} f_c^{0.613}$ and $B = 0.37\gamma^{0.284} f_c^{0.006}$; γ is the groove height-to-width ratio (h_g/w_g); and f_c is the concrete cylinder compressive strength.

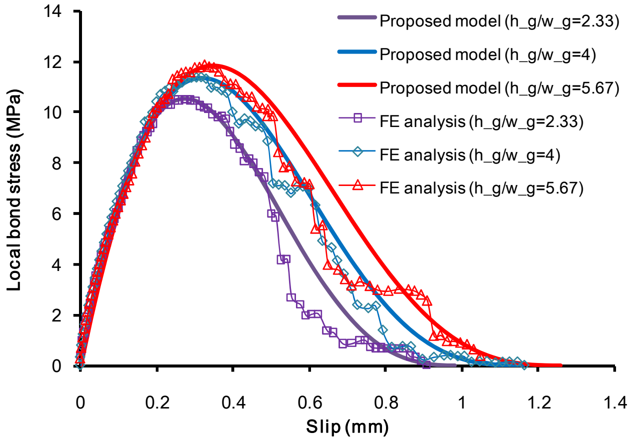


Fig. 7. Bond-slip curves for interfaces with a concrete cylinder compressive strength of 30 MPa

Comparisons of the bond-slip curves for three selected cases between the FE results and the proposed model are shown in Fig. 7, showing close agreement. For more details, the reader is referred to Zhang et al. (2013b).

5 BOND STRENGTH MODEL OF NSM CFRP STRIPS IN CONCRETE

The bond strength of an FRP-to-concrete bonded joint is commonly defined as the debonding failure load (i.e. the ultimate tensile force that can be resisted by the FRP reinforcement) of such a joint in a shear test similar to that shown in Fig. 4 (Chen & Teng 2001; Seracino et al. 2007a). The basic equation for the bond strength is (e.g. Yuan et al. 2004; Oehlers et al. 2008)

$$P_u = \sqrt{2G_f E_f A_f C_{failure}} \text{ when } L_b \geq L_e \tag{4}$$

$$P_u = \beta_L \sqrt{2G_f E_f A_f C_{failure}} \text{ when } L_b < L_e \tag{5}$$

where G_f is the interfacial fracture energy (Eq. 2); L_b is the bond length; L_e is the effective bond length; E_f and A_f are the elastic modulus and the cross-sectional area of the CFRP strip respectively; $C_{failure}$ is the cross-sectional contour of the failure surface which is here taken to be composed of the three side surfaces of the groove surrounding the adhesive layer (i.e. $C_{failure}$ is the sum of the three side lengths of the groove); and β_L is a reduction factor to account for the effect of insufficient bond lengths (i.e. bond lengths that are smaller than the effective bond length) and is thus a function of the bond length. Based on numerical results from a simple beam-spring numerical model, the following equations were proposed for the effective bond length L_e and the reduction factor β_L :

$$L_e = \frac{1.66}{\eta} \quad \text{where} \quad \eta^2 = \frac{\tau_{\max}^2 C_{failure}}{2G_f E_f A_f} \tag{6}$$

$$\beta_L = \frac{L_b}{L_e}(2.08 - 1.08\frac{L_b}{L_e}) \tag{7}$$

A comparison between the bond strengths predicted by the proposed model (i.e. Eqs. 4 to 7) and those predicted by the only existing bond strength model for such joints (Seracino et al. 2007b) with the results of 51 test specimens collected from 7 existing studies shows that the proposed model performs significantly better than Seracino et al.'s (2007b) model (Figs. 8 and 9). For more details of the comparison, the reader is referred to Zhang et al. (2013c).

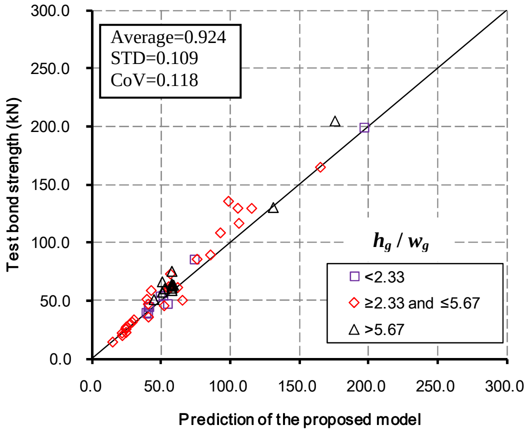


Fig. 8. Comparison of the proposed bond strength model and test results

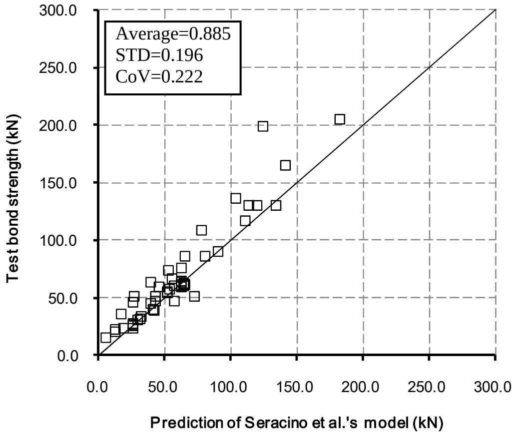


Fig. 9. Comparison of Seracino et al.'s bond strength model and test results

6 STRENGTH MODEL FOR END COVER SEPARATION

In order to develop a relatively simple strength model for end cover separation failures for use in design, a 2-D nonlinear FE model (also referred to as the full FE model) capable of accurate predictions of cover separation in RC beams flexurally-strengthened with FRP reinforcement was first developed (Zhang & Teng 2013a). Based on the findings from this full FE model, a simplified 2-D nonlinear FE model (i.e. the simplified FE model), in which only the segment of the RC beam between two adjacent cracks nearest to the FRP end is included, was proposed (Zhang & Teng 2013b) for the prediction of end cover separation failure. Finally, a simple strength model for end cover separation was proposed based on the results of a parametric study conducted using the simplified FE model (Zhang et al. 2013a).

6.1 Full FE model

A typical mesh of an FRP-strengthened RC beam is shown in Fig. 10. In the proposed full FE model, the tensile and shear behaviour of cracked concrete were properly represented; the bond-slip relationship between steel bars and concrete and that between FRP and concrete were accurately modelled; and the critical debonding plane along the level of the tension steel bars was given special attention. All the elements employed a full Gauss integration. The modelling of concrete and FRP was similar to that in the meso-sclae modelling of NSM CFRP strip-to-concrete bonded joints, and the steel reinforcement was modelled as an elastic-perfectly plastic material. Most importantly, a special cohesive-element-pair (CEP) (Fig. 11) was proposed to represent the effect of radial stresses generated by the steel tension bar (Zhang & Teng 2013a). Comparisons between predictions and test results, for the ultimate shear force of the 45 collected specimens and the crack pattern (Fig. 12) of one specimen (Beam 3 in Maalej & Bian 2001) at failure, suggested for the first time ever that these radial stresses play an important role in cover separation failure and need to be taken into account to achieve an accurate model. For more details of the comparisons, the reader is referred to Zhang & Teng (2013a).

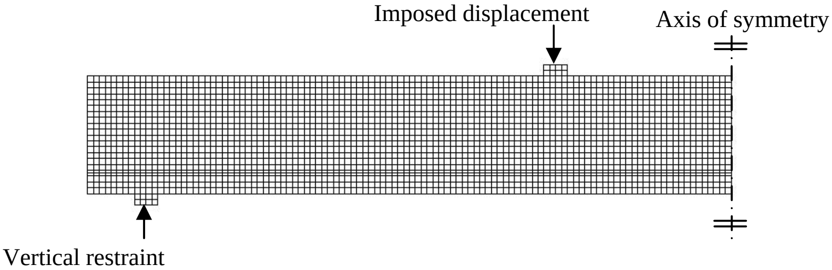


Fig. 10. Typical FE mesh for a beam

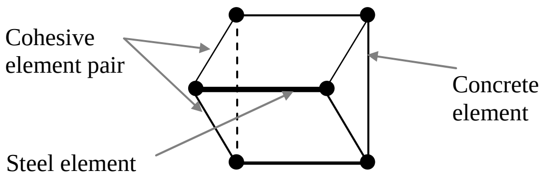
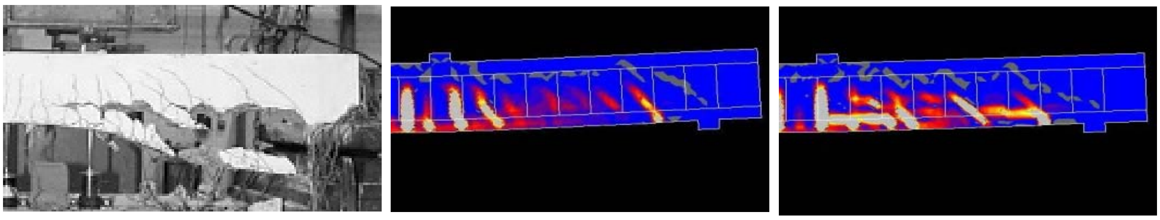


Fig. 11. Cohesive-element-pair (CEP)



(a) Test (b) Predicted, radial stresses ignored (c) Predicted, radial stresses considered

Fig. 12. Crack pattern at failure of Beam 3 tested by Maalej & Bian (2001)

6.2 Simplified FE model

During the process of end cover separation failure, an inclined crack usually occurs near the end of the NSM FRP bar, and another crack usually appears in the bonded region of FRP at a certain distance (i.e. the crack spacing) away from the bar end, as illustrated in Fig. 13. The ultimate shear force in an FRP-strengthened RC beam at end cover separation failure is as follows: if the strain in the FRP at the latter crack (Point A in Fig. 13) at end cover separation is known, the moment acting on the corresponding section can be easily found through section analysis if the plane section assumption is still adopted; the ultimate load can then be easily calculated. Therefore, the part of the RC beam between the two cracks near the FRP bar end can be isolated to form a simple model for FE analysis, with the moments on the two cracked sections being realized through external loads as shown in Fig. 13, to obtain the failure strain in the FRP at the inside cracked section (Point A in Fig. 13) (Zhang and Teng 2013b). A comparison of the failure shear forces between the predictions of the simplified FE model (a section analysis is necessary) and five test results for which the crack spacing of concern could be measured directly from pictures of crack patterns verified the performance of the proposed simplified FE model (Zhang and Teng 2013b).

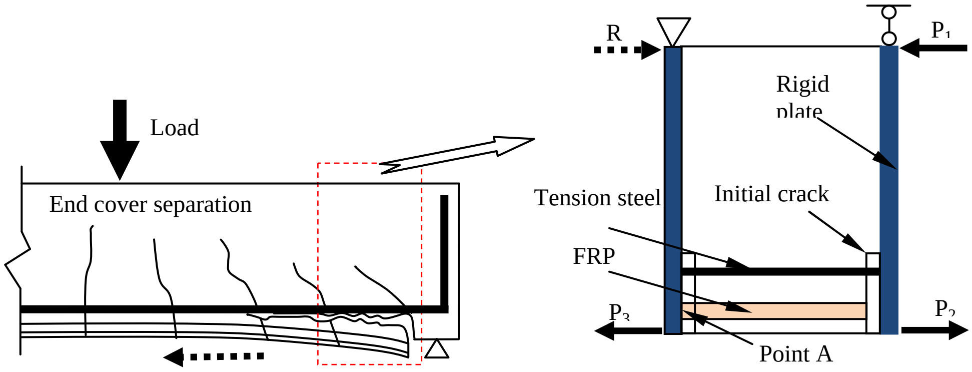


Fig. 13. Simplified FE model

6.3 Strength model for end cover separation

To predict the ultimate shear force of an FRP-strengthened RC beam at end cover separation, the failure strain in the FRP at the inside cracked section (Point A in Fig. 13) and the position of this cracked section both need to be known. The crack spacing determines both the failure strain in the FRP at the inside cracked section and the position of this cracked section (i.e. distance from the nearest support). In the present study, the crack spacing model proposed by Zhang et al. (1995) was adopted. A parametric study covering 168 numerical specimens was conducted using the simplified FE model described above to generate a large amount of data for the FRP strain at the inside cracked section at end cover separation failure (Zhang et al. 2013a). Based on a regression analysis of the numerical results, an expression for the FRP strain at the inside cracked section at concrete cover separation failure was established (Zhang et al. 2013a). This new debonding strain model offers much closer predictions of the available test results than the two existing models proposed by Hassan & Rizkalla (2003) and Al-Mahmoud et al. (2010). More evidence for the superior performance of the proposed debonding strain model can be found in Zhang et al. (2013a).

7 STRENGTH MODELS FOR OTHER DEBONDING FAILURE MODES

Although less often observed in existing experimental studies, several other debonding failure modes are also important and need to be duly considered in design. For the failure mode of end interfacial debonding, Hassan & Rizkalla (2003) proposed an model based on the interfacial shear stress between the NSM CFRP strip and the concrete. Vasquez & Seracino (2010) assessed this model and showed it to be significantly conservative. For IC interfacial debonding, following the method proposed by Teng et al. (2003) for RC beams strengthened with externally bonded FRP and failing by IC interfacial debonding, Seracino et al. (2007b) proposed a strength model based on experimental results from single-lap shear tests of NSM CFRP strip-to-concrete bonded joints. In this strength model, the debonding force in the NSM CFRP strip is given by the bond strength of the corresponding NSM CFRP strip-to-concrete bonded joint multiplied by an adjustment factor. This debonding strength model may be improved by giving explicit consideration to the effect of interaction between adjacent cracks in the RC beam. The bond-slip relationship presented in this paper can be used to study this effect. For the failure mode of IC cover separation, no strength model has been proposed so far.

8 CONCLUSIONS

Experimental studies conducted on RC beams strengthened in flexure with NSM CFRP strips have identified several debonding failure modes, and the end cover separation mode has been the most often observed debonding failure mode. This paper has presented a brief summary of a major recent study undertaken by the authors on the bond behaviour of NSM CFRP strips in concrete and the end cover separation failure mode of RC beams strengthened in flexure with NSM CFRP strips. In this study, a 3-D meso-scale FE model was first established for simulating the behaviour of NSM CFRP strip-to-concrete bonded joints. Using this 3-D meso-scale FE model, the bond behaviour of the NSM CFRP strip-to-concrete interface was studied in detail, leading to the establishment of a bond-slip model and then a bond strength model for NSM CFRP strips in concrete. A full 2-D FE model for FRP-strengthened RC beams and then a simplified 2-D FE model were subsequently established. These FE models incorporated the proposed bond-slip relationship for NSM CFRP strip-to-concrete interfaces and a special cohesive element pair to reflect the effect of radial stresses generated by steel tension bars. Based on the results from a parametric study using the simplified FE model, a debonding strength model for end cover separation was finally developed for RC beams strengthened with NSM CFRP strips.

While the present study was limited to end cover separation failures, the proposed bond-slip model and the general research approach reported in this paper may well prove effective for similar studies into other debonding failure modes in RC beams strengthened in flexure or shear with NSM CFRP strips. Such studies should be undertaken in the near future so that reliable design methods can be developed to facilitate the wide application of the NSM FRP strengthening technology.

9 ACKNOWLEDGMENTS

The authors are grateful for the financial support received from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project Nos: PolyU 5173/04E and PolyU 5315/09E) and The Hong Kong Polytechnic University.

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