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Numerical study on interaction between steel stirrups and shear-strengthening NSM FRP strips in RC beams

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Abstract
RC beams shear-strengthened with externally bonded or near-surface mounted (NSM) FRP reinforcement usually fail by the debonding of FRP in a brittle manner. When the FRP reinforcement debonds, the internal steel stirrups may have not reached their yield strength, so the contribution of the latter to the shear resistance of the beam is compromised to some extent. This phenomenon is referred to as the adverse shear interaction between the steel stirrups and the bonded FRP shear reinforcement. This paper examines such shear interaction in RC beams shear strengthened with NSM FRP strips using a simple computational model. Numerical results obtained from this model show that in such beams, most of the steel stirrups reach their yield strength, so the interaction does not have a significant adverse effect on the shear resistance of the beam. This may be seen as yet another advantage of the NSM FRP strengthening method.

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NUMERICAL STUDY ON THE INTERACTION BETWEEN STEEL STIRRUPS AND SHEAR-STRENGTHENING NSM FRP STRIPS

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ABSTRACT
RC beams shear-strengthened with FRP usually fail by the debonding of FRP strips in a brittle manner. When FRP strips debond, the internal steel stirrups may not all reach their yield strength and so adverse interaction between steel stirrups and FRP strips exists in such FRP-strengthened beams. As a result, the steel stirrups may contribute less than their full capacities as those in the shear failure of normal RC beams. This paper examines the shear interaction between internal steel stirrups and shear strengthening NSM FRP strips using a simple computational model. Numerical results obtained from this model show that for RC beams shear-strengthened NSM FRP strips, most of the steel stirrups reach their yield strength, so the shear interaction is not a significant issue for RC beams shear-strengthened with NSM FRP strips.

KEYWORDS
NSM FRP strips, RC beams, shear-strengthening, shear interaction, bonding.

INTRODUCTION
In the last decade, near-surface mounted (NSM) FRP reinforcement has emerged as a promising technique for strengthening concrete structures (De Lorenzis and Teng 2007). Since a NSM system has a lot of advantages compared to an externally bonded (EB) FRP system such as higher bond strength, easier to anchor and prestress, and more convenient for installation (De Lorenzis and Teng 2007), it has attracted an increasing amount of research. The strong bond strength between NSM FRP and concrete has special merits in shear strengthening of RC beams (Rizzo and De Lorenzis 2009), as explained later.

For RC beams shear-strengthened with NSM FRP, although an accurate shear strength model has yet to be established, some recent studies (Zhang 2011, Teng et al. 2013) have provided a good basis. In particular, based on systematic parametric analyses using an advanced meso-scaled FE model (Teng et al. 2013), Zhang (2011) developed a new bond-slip model (Fig. 1) which makes it possible to accurately model the bond-slip behaviour between NSM FRP strips and concrete. An example bond slip curve from Zhang’s (2011) model is shown in Fig. 1. Also shown in Fig. 1 is a typical bond-slip curve for EB FRP based on Lu et al.’s (2005) bond-slip model. Fig. 1 clearly shows that the interfacial fracture energy, the maximum shear stress and the maximum slip at which the bond stress is reduced to zero are significantly larger for a NSM FRP strip than those of an EB stirrup, implying that the bond strength and the deformation capacity of NSM FRP should be significantly larger than those of EB FRP strips. The higher bond strength and deformation capacity of NSM FRP strips also imply that RC beams shear strengthened with NSM FRP may have larger shear strengthening efficiency and better ductility than those with EB FRP. As a result, the conclusions drawn on the adverse shear interaction between EB FRP and steel stirrups (e.g. Chen et al. 2013a) may not be applicable to beams shear strengthened with NSM FRP strips.
Against the above background, this paper presents a numerical investigation on the effects of the adverse shear interaction between shear strengthening NSM FRP strips and steel stirrups, aiming to provide a quantitative assessment of the effects for the shear strengthening NSM FRP strips. A computational model including accurate modelling of the bond-slip behaviours of both NSM FRP strips and steel stirrups is proposed based on the computational model of Chen et al. (2010a). A brief introduction to the proposed model is presented next, followed by some numerical results.

**NUMERICAL MODELING**

**Computational model**

The computational model adopted in the present study is developed from the computational model presented in Chen et al. (2010a) for assessing the shear interaction between EB FRP and steel stirrups. The model has been implemented in ABAQUS (ABAQUS 2010). As shown in Fig. 2, the only difference between the current model and that presented in Chen et al. (2010a) is the modelling of FRP as explained next. In Chen et al.’s (2010a) model, the FRP strips are assumed to be evenly distributed (regardless of whether the strips are continuous FRP sheet or discrete FRP strips) and simulated by a large number of FRP strips. In the present model, only discrete FRP strips are considered because continuous NSM FRP strips are impracticable. As a result, an FRP strip modelled herein represents a single NSM FRP strip. Furthermore, it is assumed that the spacing between the NSM strips satisfies the following conditions: the clear distance $a$ between adjacent grooves is larger than 3 times the groove depth $h_g$ (see Fig. 2(c)). According to the Hong Kong FRP guideline (2011), these conditions ensure that the possible adverse interaction between adjacent NSM FRP strips is minimal although the interaction is an important issue needing further research (Oehlers et al. 2008). The main features, especially those pertinent to the simplifying assumptions underlying the current model are briefly described below as an introduction to the proposed computational model while more details can be found in Chen et al. (2013b).
Bond-slip Model

The bond-slip model for NSM FRP strips adopted in this study was proposed by Zhang (2011) [Fig. 1(a)]. The bond force \( F_{b,f} \) between an FRP strip and its surrounding concrete in each shear spring is defined as

\[
F_{b,f} = P_f \times l_f \times \tau_f,
\]

where \( P_f \) is the perimeter of the groove (sum of the length of the three sides which is \( P_f = 2hg + bg \)); \( l_f \) is the length of the FRP truss element; and \( \tau_f \) is the bond shear stress. Fig. 1(a) shows the bond stress-slip curve of NSM strips for the case of \( f_c' = 30 \text{MPa}, h_g = 19 \text{mm} \) and \( b_g = 6 \text{mm} \) (thus \( h_g / b_g = 3.6 \)), where \( h_g \) and \( b_g \) are the height and width of the groove respectively.

Crack Shape

In the present study, the parabolic form suggested by Chen and Teng (2003) is adopted to describe the shape of the critical shear crack.

NUMERICAL RESULTS

Element Size

Meshes with 1mm element size were adopted except for beams with an effective height of 900mm (in which case the adopted element size was 2 mm) based on the mesh convergence study in Chen et al (2010b). For steel stirrups, since there was little difference between the computational results of spacing \( s_{s,1} = h_f,e / 20 \) and \( s_{s,1} = h_f,e / 10 \) (Chen et al. 2010a), \( s_{s,1} = h_f,e / 10 \) was adopted in all calculations in this study for simplicity.

Mobilization factors

This study adopted the mobilization factors proposed by Chen et al. (2010a) for steel stirrups \( (K_s) \) and FRP strips \( (K_f) \) to quantify the development of their shear contributions:

\[
K_s = \frac{\sigma_{s,e}}{f_y}
\]

\[
K_f = \frac{\sigma_{f,e}}{f_{f,e}}
\]

where \( \sigma_{s,e} \) and \( \sigma_{f,e} \) are respectively the average stresses in the steel stirrups and FRP strips intersected by the critical shear crack (CDC), \( f_s \) is the yield strength of the steel stirrups, \( f_{f,e} \) is the average value of the maximum bond stresses of NSM FRP strips crossed by the CDC by assuming that each of the NSM strips reaches its full bond strength which can be calculated from Zhang’s (2011) bond strength model for NSM FRP strip.

Interaction between Internal Steel Stirrups and FRP Strips

The following parameters and conditions were assumed if not otherwise stated. The concrete cylinder compressive strength \( f_c' = 30 \text{MPa} \), which corresponds to a cube compressive strength of 37 MPa. NSM FRP strips are fully embedded into the grooves with detailed configurations and dimensions as shown in Fig. 2(c). The grooves have \( h_g = 19 \text{mm}, b_g = 6 \text{mm} \) and \( a_g = 60 \text{mm} \) (satisfying \( a_g > 3h_g \)). The arrangements of the FRP strips and steel stirrups are as follows: \( s_{f,1} = 33 \text{mm}, s_{s,1} = 30 \text{mm}, s_{s,1} = 66 \text{mm}, s_{s,1} = 60 \text{mm} \). The FRP strips have a cross-sectional area \( A_{f} = h_{frp} \times w_{frp} = 15 \times 2 = 30 \text{ mm}^2 \), an elastic modulus \( E_f = 150 \text{ GPa} \), and a tensile strength \( f_{f} = 2286 \text{MPa} \). The steel stirrups are assumed to be 8mm diameter plain round steel bars with a yield strength \( f_y = 250 \text{MPa} \). The deformed bars have a diameter \( D = 10 \text{mm} \) and a yield strength \( f_y = 460 \text{MPa} \). The elastic modulus of all steel bars is \( E_s = 200 \text{GPa} \). The beam has such a height that \( h_e = 600 \text{mm} \). For ease of reference, these conditions will be referred to as the “reference case” and the beam with the conditions as the “reference beam” in the remainder of this
paper. It should be noted that in the parametric study, when one parameter is changed, all other parameters are kept unchanged and as the same as the reference case.

**Effect of crack shape**

Fig. 3(a) shows that the value of the mobilization factor $K_f$ under different crack shapes (defined by different values of $C$). It can be seen that in general, the $K_f$ for NSM FRP strips firstly increases as the crack widens and then decreases as the strips debond in a sequential manner. The maximum value of $K_f$ reached before the the commencement of debonding is smaller than 1.0 for all $C$ values. Fig. 3(b) shows that the maximum $K_f$ value against parameter $C$. It is seen that $K_f$ increases from 0.67 at $C=0$ to 0.96 at $C=1$ and there is an inflection point at about $C=0.95$. Moreover, when $C=0.5$, $K_f$ reaches its maximum value at the smallest $w_{\text{max}}$ (Fig. 3(a)). A thorough examination of the curves for all $C$ values reveals that there are four key cases needing further examination in terms of shear interaction between FRP strips and steel stirrup: $C=0$, $C=0.5$, $C=0.95$ and $C=1$. They stand for the following extreme situations among all $C$ values: 1) the peak $K_f$ is the smallest; 2) the peak $K_f$ is reached at a minimum value of $w_{\text{max}}$; 3) the peak $K_f$ is the maximum; 4) the peak $K_f$ is reached at the maximum value of $w_{\text{max}}$. Fig. 4 presents the development of $K_f$ and $K_s$ with $w_{\text{max}}$ for these four key cases. Clearly in all cases $K_f$ increases continuously as the crack opens up and approaches 1.0 when the crack is very wide. For $C=0$ and 0.5, there exists some adverse shear interaction between NSM FRP strips and steel stirrups; for $C=0.95$ and 1, such adverse shear interaction becomes very weak as $K_s$ has already reached 1.0 (full mobilization of the yield strength of all steel stirrups intersected by the CDC) at the peak $K_f$. Although deformed bars have better bond performance than plain bars, $K_f$ of deformed bars increases slower than plain bars due to the higher yield strength of the former. For both plain and deformed bars, the $K_s$ value corresponding to the peak $K_f$ is no smaller than 0.9. For deformed bars, the $K_s$ value corresponding to the peak $K_f$ is 0.90, 0.95, 1.0 and 1.0 respectively for $C=0.0, 0.5, 0.95$ and 1.0; for plain bars, the corresponding $K_s$ value is 0.92, 0.96, 1.0 and 1.0. As a result, it can be concluded that most of the steel stirrups yield when $K_f$ reaches its maximum value. From Figs 3 and 4 it is clear that $C=0$ leads to the most conservative prediction for the maximum value of $K_f$ and its corresponding $K_s$. Thus, it can be said that $C=0$ represents the lower bound for assessing the shear capacity. As a result, only the results for the crack shape with $C=0$ are discussed below if not otherwise stated.

**Effect of beam size**

The effect of beam height on the mobilization factors is considered next. Fig. 5 shows the development of the mobilization factor for NSM FRP with the maximum crack width $w_{\text{max}}$ for three beam heights $h_{\text{f,e}}=300$, 600, and 900mm. $K_f$ curves for deformed bars are also shown in Fig. 5 for comparison. It can be seen that the beam height has a significant effect on the development of $K_f$ but small effect on $K_s$. At the $w_{\text{max}}$ where $K_f$ peaks, $K_f$ generally decreases as $h_{\text{f,e}}$ increases because the stiffness of the steel stirrups reduces in higher beams, but the difference is insignificant especially in larger beams as the steel bars can reach yielding due to the concrete-steel bar bond alone. In this parametric study, $K_f$ obtained from $h_{\text{f,e}}=600$mm (i.e. reference case) provides a close approximation for $h_{\text{f,e}}\geq600$mm and a slightly conservative approximation for $h_{\text{f,e}}<600$mm.

When the value of $K_f$ at the peak $K_f$ is assessed, it can be found that the effect of beam height is insignificant as explained next. For deformed bars, when $h_{\text{f,e}}$ increases from 300 mm to 900 mm, the value of $K_f$ corresponding to peak $K_f$ decreases slightly from 0.95 to 0.92, with the value of $K_s$ for $h_{\text{f,e}}=600$ being 0.90; for plain bars, the corresponding $K_s$ value is 0.96, 0.92, 0.94 for $h_{\text{f,e}}=300$mm, 600mm and 900 mm, respectively. This means most of the steel stirrups yield when $K_f$ peaks. Furthermore, the beam height has slight influence on the peak $K_f$ value: it increases from 0.629 for $h_{\text{f,e}}=300$mm to 0.674 for $h_{\text{f,e}}=900$mm. As a result, it can be said that the effect of beam height on the shear interaction is limited. This means that the conclusions reached using the reference beam are applicable to other beam height. Numerical results not shown in this paper (see Chen et al. (2013) for details) indicate that the above conclusion is also valid for other crack shapes (represented by different values of $C$).

**CONCLUSIONS**

This paper has presented a numerical study on the shear interaction between internal steel stirrups and shear-strengthening NSM FRP strips. Based on the numerical results obtained from the computational model developed in the present study, a comprehensive quantitative assessment on the effects of the shear interaction has been conducted. The numerical results showed that for RC beams bonded with NSM FRP strips, most of the steel stirrups yield when the shear contribution of NSM FRP reaches its maximum value, so the adverse effect arising from the shear interaction is insignificant.
Figure 3 Effect of $C$ value on mobilization factors

(a) $K_f - w_{max}$ curves for typical $C$ values

(b) Peak $K_f$ value

Figure 4 Values of mobilization factors $K_f$ and $K_s$ for different $C$ values

(a) $C=0$

(b) $C=0.5$

(c) $C=0.95$

(b) $C=1$
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