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.

KEYWORDS

NSM FRP strips, RC beams, shear strengthening, shear interaction, debonding.

INTRODUCTION

Over the past decade, near-surface mounted (NSM) FRP reinforcement has emerged as a promising technique for strengthening concrete structures (De Lorenzis and Teng 2007). Since NSM FRP bars have a number of advantages over externally bonded (EB) FRP sheets/plates (e.g. improved bond performance, better protection against external damage and simpler anchoring and prestressing processes) (De Lorenzis and Teng 2007), they have attracted an increasing amount of research. The enhanced bond capacity between NSM FRP and concrete has special merits in the shear strengthening of RC beams (Rizzo and De Lorenzis 2009), as explained later. FRP bars used in the NSM FRP method may be in various cross-sectional shapes (De Lorenzis and Teng 2007), including round, square, elliptical and rectangular. The present study is concerned with NSM carbon FRP (CFRP) strips which are defined as bars with a narrow rectangular section (typically with an aspect ratio not smaller than 5). Compared with bars of other sectional forms, strips possess higher bond efficiency due to its higher perimeter-to-cross-sectional area ratio and its greater embedment depth for the same cross-sectional area. Compared to other FRP materials, CFRP is generally preferred in NSM strengthening applications as CFRP has the highest elastic modulus and tensile strength, thereby minimizing the concrete cover area required to accommodate the NSM reinforcement.

For RC beams shear-strengthened with NSM FRP strips, although an accurate shear strength model has yet to be established, some recent studies (Zhang et al. 2013; Teng et al. 2013) have provided a good basis for some good quality numerical modelling work. In particular, based on a systematic parametric study using an advanced meso-scale FE model (Teng et al. 2013), Zhang et al. (2013) developed a bond-slip model (Fig. 1) which describes accurately the bond-slip behaviour between NSM FRP strips and concrete. An example bond-slip curve for NSM FRP from Zhang et al.’s (2013) 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 an NSM FRP strip (width=15mm, thickness=2mm) than for an EB FRP strip of the same cross-sectional area (width=30mm, thickness=1mm), implying that the bond strength and the deformation capacity of an NSM FRP strip should be significantly larger than those of a corresponding EB FRP strip. The
higher bond strength and deformation capacity of NSM FRP strips also imply that RC beams shear strengthened with NSM FRP strips may have a 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.

![Figure 1: Bond-slip relationships (\(f_c' = 30\text{MPa}, \text{center-to-center spacing } s_f = 66\text{ mm for EB FRP and } f_c' = 30\text{MPa and } h_g/b_g = 3.6\text{ for NSM FRP})

Against the above background, this paper presents a numerical investigation into the effects of adverse shear interaction between shear strengthening NSM FRP strips and steel stirrups, aiming to provide a quantitative assessment of these effects. A computational model including the accurate modelling of the bond-slip responses of both NSM FRP strips and steel stirrups is first briefly introduced. Numerical results obtained using the computational model are then presented and interpreted.

**NUMERICAL MODELING**

**Computational Model**

The computational model adopted in the present study was extended from the computational model presented in Chen et al. (2010a) for studying shear interaction between EB FRP and steel stirrups. The extended computational model was implemented with 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 strips as explained next. In Chen et al.'s (2010a) model, the bonded FRP reinforcement is assumed to be evenly distributed and to be represented by a large number of FRP strips (regardless of whether the original FRP reinforcement is in the form of continuous FRP sheets or discrete FRP strips). In the present model, only discrete FRP strips are considered because continuous NSM FRP reinforcement does not exist in practice. As a result, an FRP strip in the present computational model represents a single real NSM FRP strip. Furthermore, it is assumed that the spacing between the NSM strips satisfies the following condition: the clear distance \(a_g\) between adjacent grooves is larger than 3 times the groove depth \(h_g\) (see Fig. 2(c)). Based on finite element results not presented herein, this condition ensures that the possible adverse interaction between adjacent NSM FRP strips is very small and can be neglected, although this 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 et al. (2013) [Fig. 1(a)]. The bond force \((F_{bx})\) between an FRP strip and its surrounding concrete in each shear spring is defined as

\[
F_{b_x} = P_f \times l_f \times \tau_f
\]

where \(P_f\) is the perimeter of the groove (sum of the length of the three sides which is \(P_f = 2h_g + b_g\)); \(l_f\) is the length of the FRP truss element (for shear springs at both ends of an NSM strip, \(l_f\) should be equal to the half length of the 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 \(f_c' = 30\text{MPa}, h_g = 19\text{ mm and } b_g = 6\text{ mm (thus } h_g / b_g = 3.2\text{), where } h_g\) 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.

![Diagram of Crack Shape](image)

(a) Overall review

(b) Interaction between concrete, steel stirrups and FRP strips

(c) Dimensions of grooves and FRP strips for reference beam

**Figure 2. Schematic of computational model for RC beams shear-strengthened with NSM FRP strips**

**NUMERICAL RESULTS**

**Reference Beam**

The following parameters and conditions are assumed if not otherwise stated for the parametric study. The concrete cylinder compressive strength $f_c = 30$ 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). For the grooves, $h_g = 19$ mm, $b_g = 6$ mm and $a_g = 60$ mm (satisfying $a_g > 3h_g$). The arrangements of the FRP strips and steel stirrups are as follows: $s_{f,1} = 33$ mm, $s_{s,1} = 30$ mm, $s_f = 66$ mm, $s_s = 60$ mm. The FRP strips have a cross-sectional area $A_f = h_{frp} \times w_{frp} = 15 \times 2 = 30$ mm$^2$, an elastic modulus $E_f = 150$ GPa, and a tensile strength $f_f = 2286$ MPa. The steel stirrups are assumed to be 8 mm diameter plain round steel bars with a yield strength $f_y = 460$ MPa. The height of the beam is such that $h_{f,e} = 600$ mm. For ease of reference, these conditions constitute a beam that is referred to as the “reference beam” or “reference case” in the remainder of this paper. It should be noted that in the parametric study, when one parameter was varied, all other parameters were kept unchanged and the same as the reference case.

**Element Size**

Meshes with a 1 mm element size were adopted except for beams with an effective height of 900 mm (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 for a spacing $s_s = h_{f,e}/20$ and $s_s = h_{f,e}/10$ (Chen et al. 2010a), $s_s = h_{f,e}/10$ 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:

$$K_s = \frac{\sigma_{e}}{f_y}$$
$$K_f = \frac{\sigma_{e}}{f_{f,e}}$$

(2)

(3)

where $\sigma_{e}$ and $\sigma_{e}$ are respectively the average stresses in the steel stirrups and the FRP strips intersected by the critical shear crack (CDC), $f_y$ 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 et al.’s (2013) bond-slip model for NSM FRP strips.

Effect of Crack Shape

Fig. 3(a) shows that the values of the mobilization factor $K_f$ for different crack shapes (defined by different values of $C$). It can be seen that in general, $K_f$ first 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 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 an inflection point exists at about $C=0.95$. Moreover, when $C=0.5$, $K_f$ reaches its maximum value at the smallest $w_{max}$ (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 stirrups: $C=0$, $C=0.5$, $C=0.95$ and $C=1$. They stand for the following extreme situations among all $C$ values: 1) the peak value of $K_f$ is the smallest; 2) the peak value of $K_f$ is reached at a minimum value of $w_{max}$; 3) the peak value of $K_s$ is the maximum; 4) the peak value of $K_f$ is reached at the maximum value of $w_{max}$. Fig. 4 presents the development of $K_f$ and $K_s$ with $w_{max}$ for these four key cases. Clearly in all cases, $K_s$ 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 all steel stirrups intersected by the CDC) at the peak value of $K_f$. Although deformed bars have better bond performance than plain bars, $K_s$ of deformed bars increases more slowly 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 $K_f$ value is no smaller than 0.9. For deformed bars, the $K_s$ value corresponding to the peak $K_f$ value 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 have reached yielding 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 value of $K_s$. Therefore, it can be said that $C=0$ represents the lower bound scenario for assessing the shear capacity. As a result, only results for the crack shape of $C=0$ 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 $w_{max}$ for three beam heights $h_{f,e}$=300, 600, and 900mm. The $K_f$ 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 only a small effect on $K_s$. At $w_{max}$ where $K_f$ peaks, $K_s$ generally decreases as $h_{f,e}$ 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, $K_s$ obtained from $h_{f,e}$= 600 mm (i.e. the reference case) provides a close approximation for $h_{f,e}>600$ mm and a slightly conservative approximation for $h_{f,e}<600$mm. When the value of $K_s$ at the peak value of $K_f$ is assessed, it can be found that the effect of beam height is insignificant. For deformed bars, when $h_{f,e}$ increases from 300 mm to 900 mm, the value of $K_s$ corresponding to the peak $K_f$ value decreases slightly from 0.95 to 0.92, with the value of $K_s$ for $h_{f,e}= 600$ being 0.90; for plain bars, the corresponding $K_s$ values are 0.96, 0.92, 0.94 for $h_{f,e}= 300$ mm, 600 mm and 900 mm, respectively. This means that most of the steel stirrups have yielded when $K_f$ peaks. Furthermore, the beam height has only a slight influence on the peak $K_f$ value: it increases from 0.629 for $h_{f,e}=300$ mm to 0.674 for $h_{f,e}=900$mm. As a result, it can be said that the effect of beam height on shear interaction is limited. This means that the conclusions reached using the reference beam are applicable to other beam heights. 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 in RC beams. Based on the numerical results obtained using the computational model developed in the present study, a quantitative assessment of the effects of shear interaction has been presented. The numerical results showed that for RC beams bonded with NSM FRP strips, most of the steel stirrups have yielded when the shear contribution of NSM FRP reaches its maximum value, so the adverse effect arising from shear interaction is insignificant and may be neglected in predicting the shear capacity of such FRP-strengthened RC beams.

![Figure 3: Effect of C value on mobilization factors](image3.png)

![Figure 4: Values of mobilization factors K_f and K_s for different C values](image4.png)
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