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# Possible Interaction between the Existing Transverse Steel and the Rehabilitating FRP Shear Reinforcement in RC Beams Strengthened with EB, NSM, ETS and L-Shaped FRP Methods

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**Abstract**

The main objective of this study is to gain insight into a possible interaction between internal transverse steel and strengthening Fibre-Reinforced Polymer (FRP) reinforcement used to strengthen RC beams in shear with different FRP rehabilitation methods. To better investigate the interaction between internal steel and FRP shear reinforcement, experimental results of fifteen specimens strengthened with Externally-Bonded (EB), Near-Surface Mounted (NSM), and Embedded Through-Section (ETS) methods that were tested by the authors are studied. In addition, the results of seven shear-strengthened specimens with anchored EB FRP fabrics and L-shaped FRP plates are used to evaluate a possible diminishing effect of FRP reinforcement on the internal transverse steel shear contribution. The results of this study show that although the presence of transverse steel has an adverse effect on the effectiveness of shear strengthening EB FRP, the presence of EB FRP does not inhibit yielding of the transverse shear reinforcement at ultimate. Moreover, unlike EB FRP, the diminishing effect of existing steel shear reinforcement on strengthening FRP does not seem to exist for specimens strengthened in shear with NSM and ETS FRP methods. Meanwhile, as for specimens strengthened with EB FRP method, the steel shear reinforcement also yields before final failure for specimens strengthened with NSM, ETS, anchored EB and L-shaped FRP.

**Keywords:** Concrete beams; fibre-reinforced polymers; retrofitting; shear resistance; externally-bonded; near-surface mounted; embedded-through section.

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## Introduction

In the last three decades, fibre-reinforced polymers (FRP) have gained significant recognition and attention as a retrofitting material for existing reinforced concrete (RC) members. Different methods such as externally bonded (EB) FRP sheets, near-surface mounted (NSM) FRP rods, embedded through-section (ETS) FRP rods, and L-shaped FRP plates have been successfully tested for strengthening of RC beams in shear [e.g., 1-5].

In 2002 experimental studies by Chaallal *et al.* [1] and Pellegrino and Modena [2] reported major discrepancies caused by the presence or absence of internal transverse steel stirrups in RC beams in the measured values of the experimental shear contribution of EB FRP fabrics/strips ($V_{frp}$) in shear-strengthened RC beams. Thereafter, studies were conducted by different researchers [e.g., 3-5] to justify the diminishing effect of transverse steel shear reinforcement (hereafter, transverse steel) on $V_{frp}$.

To provide a logical justification to this effect, Mofidi and Chaallal [3] proposed one of the most accurate existing theoretical models that predicts $V_{frp}$ of RC beams strengthened in shear by introducing the 'cracking pattern effect' of the concrete substrate on the debonding of EB FRP. Formation of several concrete compression struts in the RC beams with transverse steel results in a more distributed shear crack propagation, due to more distributed stress distribution in the concrete substrate, compared with that of RC beams without steel stirrups. In general, the debonding process starts from a shear crack in the cracked zone where bonding shear stresses become too high at the crack.

Meanwhile, a numerical modelling approach to justify the aforementioned effect, showed that the discrepancies in the shear contribution of strengthened specimens with and without transverse steel can be due to the fact that the presence of the FRP inhibits the transverse steel yielding at ultimate [e.g., 5 and 6]. Therefore, the contribution of transverse steel to the shear resistance should be reduced for the FRP-strengthened beams to justify the experimental smaller shear resistance of the strengthened beams with transverse steel compared to that of the unstrengthened specimens. This prompted legitimate questions and concerns as to whether the assumption that the transverse steel yields before failure holds true for shear strengthened RC beams with EB FRP.

This paper is an effort to improve the perception of the researchers in the field on the possible effects of the existing transverse steel and the strengthening FRP shear reinforcement on one another by providing experimental evidence and experimental answers to the following questions are provided in this article as follows:

- Does $V_{frp}$ remain unchanged whether or not the RC beam has transverse steel reinforcement?
- Conversely, when using strengthening FRP in shear, does the contribution of steel to the shear resistance ($V_s$) have to be reconsidered by the codes and guidelines to correspond to steel stirrup tensile stresses below the yielding strength of steel?
- Finally, does a similar effect between transverse steel and FRP materials that was observed in beams shear strengthened with unanchored EB FRP exists between the transverse steel and FRP in RC beams strengthened with NSM, ETS, EB anchored FRP fabrics, and L-shaped FRP?

## Experimental Test Specimens

The tested specimens consisted of a full-scale RC T-beam under four-point loading with a web width of 152 mm and a flange depth of 102 mm. Full details of the tested specimens are provided elsewhere [4 and 7-10]. The experimental program involved 22 tests. The control specimens, which were not strengthened with carbon FRP (CFRP), were labelled NF (for **N**o **F**RP), whereas the specimens strengthened with moderate level of FRP strip reinforcement (strip width = 87.5 mm, strip spacing 175 mm) were labelled MF (for **M**oderate **F**RP reinforcement). The specimens strengthened with rather high level of FRP strip reinforcement (strip width = 87.5 mm, strip spacing 125 mm) were labelled HF (for **H**igh **F**RP reinforcement). The specimens retrofitted with a layer of EB CFRP fabric were labelled FF (for **F**abric **F**RP). Labels AT and MD correspond to the location of the FRP strips with respect to the location of steel stirrups, i.e., **At** the stirrup location and **Mid**dle of stirrups spacing. Series NR (**N**ot **R**einforced with transverse steel) consisted of specimens with no internal transverse steel reinforcement. Series HR (**H**eavily **R**einforced with transverse steel) and MR (**M**oderately **R**einforced with transverse steel) contained specimens with internal transverse steel stirrups spaced at s = d/2 and s = 3d/4 respectively, where d = 350 mm represents the effective depth of the cross section of the beam. The strengthened specimens are labelled based on their rehabilitation method, i.e., EB, NSM, ETS, and LS (L-Shaped) FRP methods. AG1 to AG4 correspond to different end-anchorage systems that have been used of specimens strengthened with EB method. Details of the anchorage systems can be found elsewhere [8]. Labels NE, PE and FE correspond to the embedment level of L-shaped FRP plates in the RC beams flanges, i.e. **N**o **E**mbedment, **P**artially **E**mbedded, and **F**ully **E**mbedded, respectively.

## Interaction of Internal Steel Reinforcement with Strengthening FRP

Experimental tests have revealed that the total shear contribution of steel ($V_s$) and FRP in a shear-strengthened specimen reinforced with internal transverse steel and EB FRP is less than the summation of $V_s$ and $V_{frp}$ on two separate specimens that have only transverse steel and only FRP as shear reinforcement, respectively. In the following sections, experimental results of beams strengthened with EB FRP method are provided to reveal whether or not the abovementioned effect is due to a diminishing effect of presence of FRP reinforcement on transverse reinforcement's contribution to the shear resistance or vice versa.

### Externally Bonded FRP

In this part of the study, 11 specimens including NS-NF, NS-EB-MF, NS-EB-HF, NS-EB-FF, HS-NF, HS-EB-MF-AT, HS-EB-MF-MD, HS-EB-HF, HS-EB-FF, MS-NF, MS-EB-FF are studied.

<u>Influence of the presence of EB FRP on steel shear reinforcement</u>

As it can be observed in Fig. 1, for all the internally reinforced specimens in shear in this study, the transverse steel yielded well before final failure (only results corresponded to the specimens with transverse steel are shown in Fig. 1). The light grey solid bars in Fig.1 (considering the left vertical axis) show the overall shear force applied to the beams (calculated based on the measured applied load) when the strain gauges on transverse steel that intercepted the shear cracks showed steel yielding. The solid dark bar shows how much more shear force was applied to the specimen before the specimen failed. Meanwhile, the chequered bars show the strain in the transverse steel intercepting the crack at the ultimate (readings are based on the right axis). It can be seen that all the mentioned stirrups exceeded the yielding strains (strains above 7000 $\mu\varepsilon$ are not reported in the figure).
This observation is in good agreement with existing code specifications and guidelines, which assume that the transverse steel yields at ultimate for RC beams strengthened in shear with EB FRP. Therefore, it can be concluded that at the ultimate state the contribution of internal steel stirrups to shear resistance was not affected by the addition of externally bonded FRP, i.e., no adverse effect of FRP on $V_s$.

Influence of the presence of steel on the shear reinforcement on EB FRP

Based on the outcomes reached in the previous section, $V_s$ in the strengthened specimens was considered the same as $V_s$ in the unstrengthened specimens (MS-NF and HS-NF). In particular, the presence of heavily reinforced transverse steel resulted in a significant decrease in the contribution of FRP to shear resistance for specimens NS-EB-MF, NS-EB-HF, and NS-EB-FF from 53.3, 69.3, and 38.7 kN to 14.5, 21.7, and 18.4 kN respectively in their corresponding transverse steel reinforced specimens. This corroborates the findings of previous research studies [e.g., 1-2] on the adverse effects of transverse steel on $V_{frp}$.

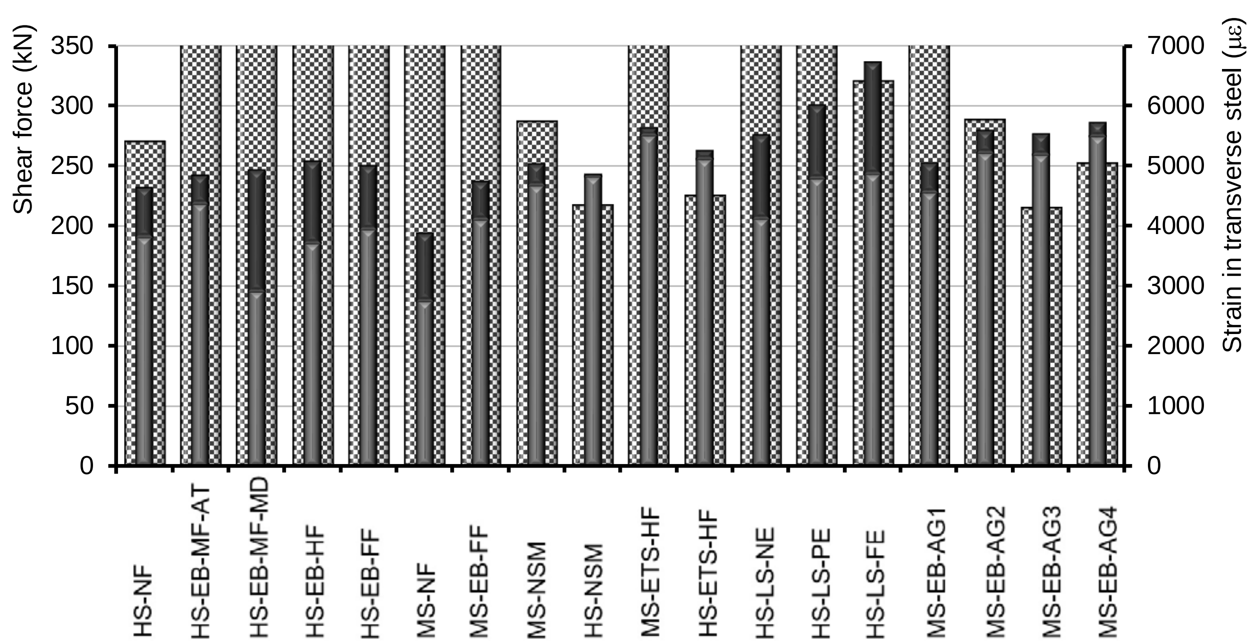


Fig.1: Response of the tested specimens with transverse steel at ultimate

**Near-Surface Mounted FRP**

In this part of the study specimens NS-NF, MS-NF, HS-NF, NS-NSM, MS-NSM, and HS-NSM are analysed. For specimen details, please see [10]. Fig. 1 shows that when comparing $V_{frp}$ in NS-NSM and MS-NSM, the FRP shear contribution slightly increased instead of decreasing in the presence of steel stirrups (i.e., 56.9 kN for MS NSM versus 49.8 kN for NS NSM). In other words, the presence of steel stirrups did not diminish the NSM FRP's shear contribution. It seems that unlike in the EB FRP method, the highly stressed areas around NSM FRP do not significantly overlap/interact with the highly stressed areas around the existing steel stirrups. This is mainly due to the fact that the NSM FRP rods is generally located a distance away from the location of steel stirrups to avoid possible damage to the steel stirrups during groove cutting for NSM FRP. Therefore, the bond quality between NSM FRP and concrete is not compromised by the presence of the steel stirrup. Note that, as shown in Fig. 1, in the specimens with steel stirrups (MS-NF, HS-NF, MS-NSM, and HS-NSM), shear failure occurred after the steel stirrups intersecting the principal crack had yielded (i.e., the steel contribution to shear resistance was not affected by the presence of the strengthening FRP). Therefore, similar equations can be used to calculate the shear contribution of steel for both unstrengthened and strengthened specimens. Hence, no interaction between transverse steel and NSM FRP, with respect to their contribution to the shear resistance in each other's presence, was observed. It should be noted that the specimen HS-NSM failed due in flexure and was not able to reach it maximum shear resistance.

**Embedded-Through Section FRP**

In this part of the study specimens NS-ETS-HF, MS-ETS-HF, and HS-ETS-HF with their corresponding control specimens are considered. Fig. 1 shows that the resistance due to FRP in the specimen strengthened with ETS FRP with no transverse reinforcement (NS-ETS-HF) has not significantly changed in the specimen that was moderately reinforced with transverse steel and was strengthened with ETS method (99.5 kN versus 87.1 kN, respectively). Similar to what experienced for the specimens strengthened with NSM FRP, it seems that the effect of transverse steel in inhibiting the effectiveness of FRP is less pronounced in the ETS method, if it exists at all, in comparison to that experienced for the EB method. Note that specimen HS-ETS-HF failed in flexure.

This is in agreement with the hypothesis of the effect of cracking pattern on the bond force [3]. As mentioned earlier for the specimens strengthened with NSM FRP, the cracking pattern is more spread on the surface of beams strengthened with EB FRP than in the beams strengthened with ETS FRP rod. This is due to the fact that while EB FRP is bonded to a highly stressed concrete surface interfering with the highly stressed concrete around transverse steel. Whereas the location of the ETS FRP is chosen with a certain distance to transverse steel to avoid possible installation difficulties. Therefore, the stressed concrete around transverse steel and ETS FRP do not interfere. In addition, as it can be observed in Fig. 1; in all specimens that failed in shear, the transverse steel that intercepted the shear crack yielded prior to RC beams failure.

**Anchored Externally-Bonded FRP and L-Shaped Externally-Bonded FRP plates**

Specimens MS-EB-FF, MS-EB-AG1, MS-EB-AG2, MS-EB-AG3, MS-EB-AG4, HS-LS-NE, HS-LS-PE, and HS-LS-FE are considered in this part of the study. The maximum value shown by the grey bars in Fig. 1 shows the applied shear force that led to yielding of the transverse steel in all the tested specimens in this study. The transverse steel that intercepted the major shear crack in MS-EB-AG1, MS-EB-AG2, MS-EB-AG3, MS-EB-AG4, HS-LS-PE, and HS-LS-FE yielded in a greater shear force compared to that in their corresponding unanchored specimens (HS-LS-PE and MS-EB-FF). It can be concluded that CFRP strengthening methods eased the strains in the transverse steel. It should be noted that for the specimens with transverse steel, shear failure occurred after the transverse steel intersecting the shear crack had yielded. Therefore, no adverse effect due to presence of FRP on the contribution of the transverse steel reinforcement was observed.

# Conclusions

This paper investigates the results of experimental studies that were conducted by the authors on 22 RC T-beams strengthened in shear using different FRP strengthening techniques. The focus of this study is to analyse a possible interaction between the existing transverse shear steel reinforcement and strengthening FRP for different FRP rehabilitation techniques in shear. The following conclusions can be drawn:

- For all the test specimens with transverse steel reinforcement, the steel yielded before the specimen failed. The presence of externally bonded FRP for shear retrofit did not cause a significant decrease in transverse steel strain. Overall, the contribution of steel stirrups to shear resistance was not adversely affected by the addition of FRP;

- Knowing the fact that shear contribution of transverse steel is considered based on yielding of transverses steel at the ultimate, the FRP shear contribution significantly decreases with the presence of transverse steel reinforcement as it was reported earlier;
- On the other hand, unlike the EB shear strengthening method, the presence of transverse steel shear reinforcement did not have a significant effect on the shear contribution of NSM and ETS FRP. Therefore, such effect should not be considered in the design models for NSM and ETS FRP;
- The presence of FRP reinforcement in beams with transverse steel eased the stresses in the steel stirrups. However, as mentioned earlier in all tested specimens the steel stirrups that intercepted the shear crack yielded well before failure.

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