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A rational approach towards the design of FRP-reinforced concrete beams

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ABSTRACT: Fibre Reinforced Polymers (FRP) bars offer a practical solution for various problems of traditional steel reinforcement not only because of the non-corrosive nature of FRP but also for their high tensile strength to weight ratio and wide range of material properties. However, the failure of FRP-reinforced concrete beams is, usually, different from that of conventional steel-reinforced concrete ones. Recently, the authors reported the major effect of the crack path geometry, the crack width and the dowel action of FRP bars on the behavior and strength of FRP-reinforced concrete beams. In addition, an analytical model was developed by the authors to trace the beam shear-flexure interaction up to the formation of a failure mechanism. The model results, while matching the results obtained experimentally, pointed at a significant over-estimation of the strength values obtained by most of the current design guidelines for FRP-reinforced concrete structures. This over-estimation, which is mainly due to the neglect of the above-mentioned parameters, reflects the inadequacy of the inherited design philosophies of steel reinforcement to represent the real behaviour of FRP. Herein, a parametric study, based on the previously developed model, is presented. Various parameters have been considered such as shear span, beam depth, the percentage of shear reinforcement and the contribution of shear reinforcement at failure. The study reveals guidelines to control the failure location as well as to achieve the desired beam strength and mode of failure. Furthermore, the present study is believed to be an approach towards comprehensive guidelines for the design of FRP-reinforced concrete beams.

1 INTRODUCTION

A series of studies carried out recently by Salib et al. (1999, 2001, 2002 & 2004) highlighted the significant influence of crack formation within shear span on the behaviour and strength of concrete beams reinforced and/or prestressed with FRP bars. The crack path geometry and crack width interact with the magnitude and direction of both shear and flexural stresses induced in both reinforcement and concrete. Since the shear failure of FRP bars takes place in a brittle mode and at a considerably low shear stress compared to that of the ductile failure of steel bars, the crack width and geometry are essential parameters that influence the beam behaviour and strength. An analytical modeling was developed by the authors, ‘Salib et al. Model’, taking into account the above-mentioned parameters in order to predict the beam strength and mode of failure. The model results were verified with the corresponding ones obtained experimentally. Thereafter, a comparison was held between the beam strength values obtained experimentally, predicted by the model, and calculated by various design guidelines/codes for FRP reinforced concrete structures. For the beams failed due to the dowel failure of FRP bars, it was, and it is still, observed that such guidelines over-estimate the beam strength significantly, mainly because of the neglect of such failure. In addition, the contribution of shear reinforcement calculated by the investigated design guidelines is based on assuming the number of stirrups crossing the crack equals the beam depth divided by the spacing of stirrups (i.e. the crack path is a straight line with a 45^O slope) where steel stirrups yield prior to beam failure. In fact, the number of stirrups depends on the actual progress of the crack through the beam span (i.e. crack path geometry). Furthermore, the shear displacement induced in the FRP bars crossing the crack may trigger a dowel failure of FRP prior to the yield of stirrups (Salib 2001).

However, all the previously mentioned parameters are part of the differences between using FRP or steel as flexural reinforcement. Yet, a major difference still lies within the design philosophy itself. The current design guidelines/codes for FRP-reinforced concrete structures adopt the same philosophy of the design codes for steel-reinforced concrete beams (e.g. ACI-318 & CSA-A23.3) where the beam strength is the minimum of two values; each is calculated in an independent step. The first value is the flexural strength corresponding to a pure flexural crack and the second value is the shear strength corresponding to a diagonal crack with a given slope. This design philosophy is not always applicable for FRP-reinforced concrete beams where FRP bars crossing a shear-flexural crack may experience a dowel failure prior to developing their tensile strength or that of the stirrups (i.e. reaching neither the flexural nor the shear capacity calculated independently), known as a pre-mature failure of beam. Even the few sophisticated methods available to calculate the shear strength for steel-reinforced concrete (e.g. CHBDC & CSA-A23.3), accounting for the effect of flexural reinforcement, do not consider the dowel failure of reinforcement. This is, probably, because of the ductile failure of steel bars in flexure and/or shear as well as the rare possibility for the dowel failure of flexural steel reinforcement to control the beam strength. Therefore, the Salib et al. Model has been utilized herein to investigate the influence of parameters such as shear reinforcement on the beam strength and failure conditions for FRP-reinforced concrete structures including the dowel failure of FRP bars.

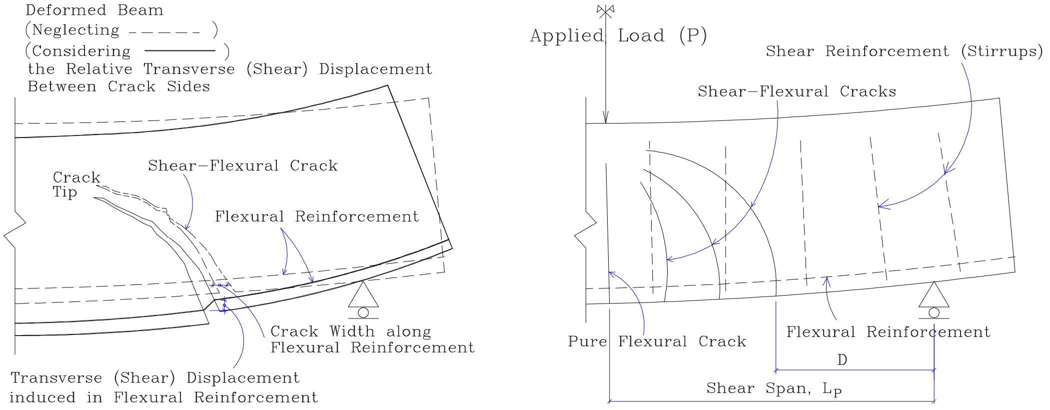
2 ANALYTICAL MODELING, ANALYSIS AND VERIFICATION

The procedure of analytical modeling (mathematical formulation), analysis and verification was described in details by the authors through different publications, especially by Salib (2001). However, this procedure can be summarized as follows (see Fig. 1):

- Modeling of crack path geometry for shear-flexural cracks (Salib et al. 1999)
- Modeling of crack width along flexural reinforcement (Salib & Abdel-Sayed 2004)
- Modeling of the relationship between crack width and the relative transverse (shear) displacement between crack sides while the crack progresses along its path (Salib et al. 2002)
- Modeling of the strength envelope between longitudinal (tensile) and transverse (shear) stresses induced in FRP flexural reinforcement (Park & Naaman 1999, Salib et al. 2002), i.e. dowel action/failure of FRP bars.
- Modeling of the relationship between longitudinal and transverse stresses/strains induced in both shear and flexural reinforcement crossing a crack as well as in the concrete portion above crack tip through the conditions of equilibrium/strain compatibility (Salib et al. 2002)
- Analysis and results; a pure flexural crack as well as some shear-flexural cracks are modeled within beam span. For each crack tip along each crack path, the load is applied incrementally and the strains/stresses induced in concrete and reinforcement are calculated taking into account the non-linearity of material properties. Thereafter, they are compared with their critical values to identify any possible failure in concrete or reinforcement. If a failure condition is satisfied, the corresponding applied load is considered the beam failure load for the crack tip under study. The analysis is repeated for each of the following crack tips along the crack path as well as for the remaining cracks and the beam is assumed to fail at the minimum failure load of all, i.e. beam strength, in the corresponding mode of failure (Salib et al. 2002).
- Verification; the results obtained from three different experimental programs, conducted by Abdel-Sayed et al. (1999), Park & Naaman (1999) and Salib (2001), were used to verify the model. The tested concrete beams were reinforced and/or prestressed in flexure with FRP bars and in shear with steel stirrups. Also, Wang and Belarbi (2005) showed that the results obtained from the Salib et al. Model were in good agreement with their experimental program for Fiber-Reinforced-Concrete (FRC) beams reinforced in flexure with FRP bars.

3 PARAMETRIC STUDY

A simple beam system has been adopted for the present study (Fig.1). The load has been applied either at mid-span or at two points symmetrical about mid-span.



(a) Deformed Beam (b) Investigated Prameters

Figure 1. Partial beam elevation for deformed shape and investigated parameters.

Among the investigated parameters is the ratio of the distance between crack starting point and nearest support , *D*, to the shear span, *Lp*. A pure flexural crack (i.e. at *D*=*Lp*) has been analyzed to determine the beam flexural strength, $P_{u,flex}$. In addition, a minimum of four shear-flexural cracks within shear span, *Lp*, have been traced along the crack path geometry by the model to predict the failure load, P_f, corresponding to the dowel failure of FRP flexural reinforcement crossing each crack. The minimum *D* (i.e. the closest crack to support) has been set as same as the beam depth, *d*. The investigated shear span to depth ratio, *Lp/d*, has a range between 2.0 and 5.5. The minimum *Lp/d* has been selected as 2.0 in order to maintain the shear span within the shallow beam limits. The studied range of the percentage of shear reinforcement, ρ_{sh}, covers beams without shear reinforcement (i.e. ρ_{sh} = 0.00%) as well as higher values (e.g. 0.09% ~ 0.56%). The ratio between failure load and beam flexural strength, $P_f/P_{u,flex}$, has been used as an index for optimum beam design. A value of one means the beam should fail in flexure, as well as in shear-flexure at the same applied load, i.e. the beam resources are utilized efficiently and uniformly along the beam span. Also, the ratio between the stress induced in the stirrups crossing the crack at failure and their yield stress, f_s/f_y, has been an indication for the maximum contribution of shear reinforcement at failure with respect to their yield strength. The relationship between $P_f/P_{u,flex}$ and *D/d* for different values of ρ_{sh} are shown in Figures 2, 4 and 6 for *Lp/d* equals 2, 4 and 5.5 respectively while Figures 3, 5 and 7 show the relationship between f_s/f_y and *D/d* for different ρ_{sh} and *Lp/d*. It should be noted that the values in the chart legend are the percentages of shear reinforcement.

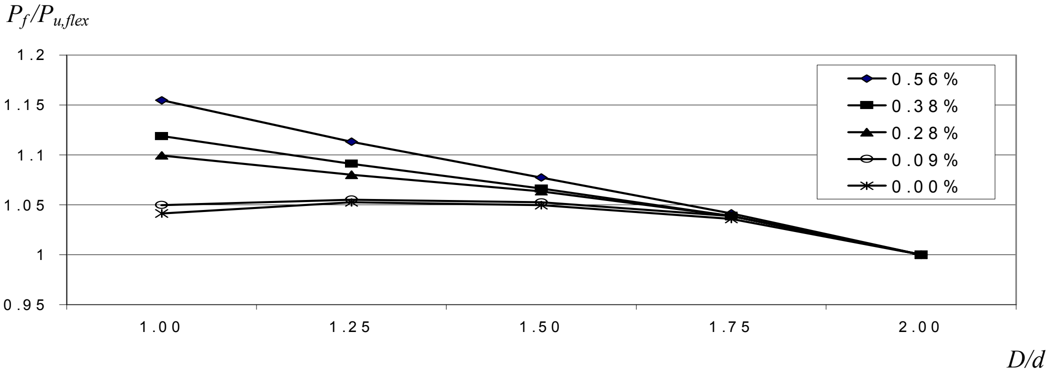


Figure 2: Relationship between $P_f/P_{u,flex}$ and *D/d* (for *Lp/d*=2).

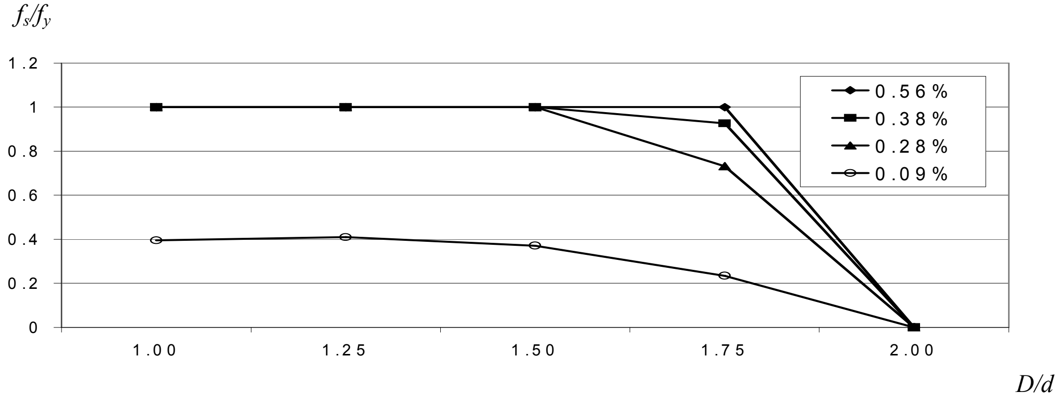


Figure 3: Relationship between f_s/f_y and D/d (for Lp/d=2).

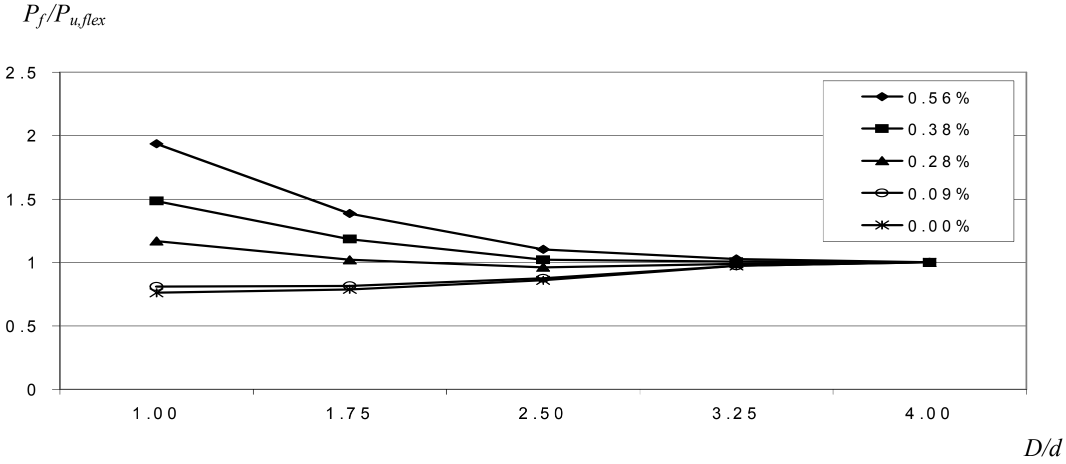


Figure 4: Relationship between $P_f/P_{u,flex}$ and D/d (for Lp/d=4).

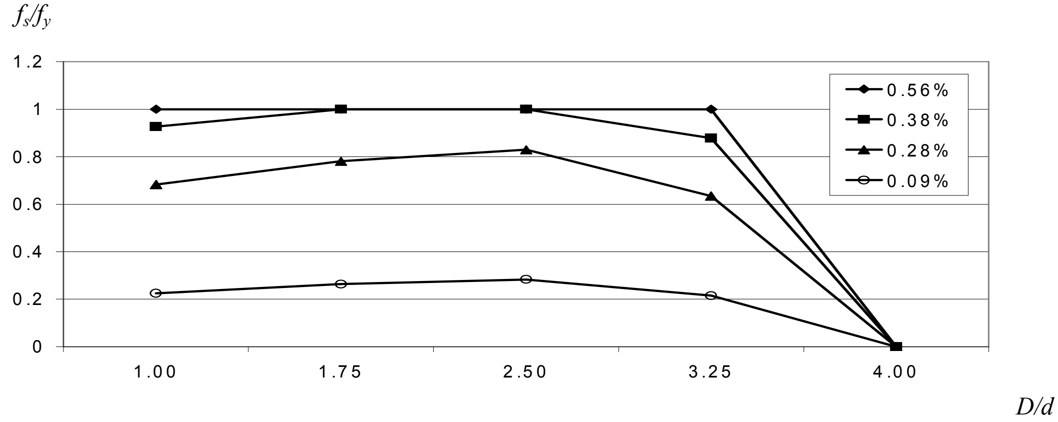


Figure 5: Relationship between f_s/f_y and D/d (for Lp/d=4).

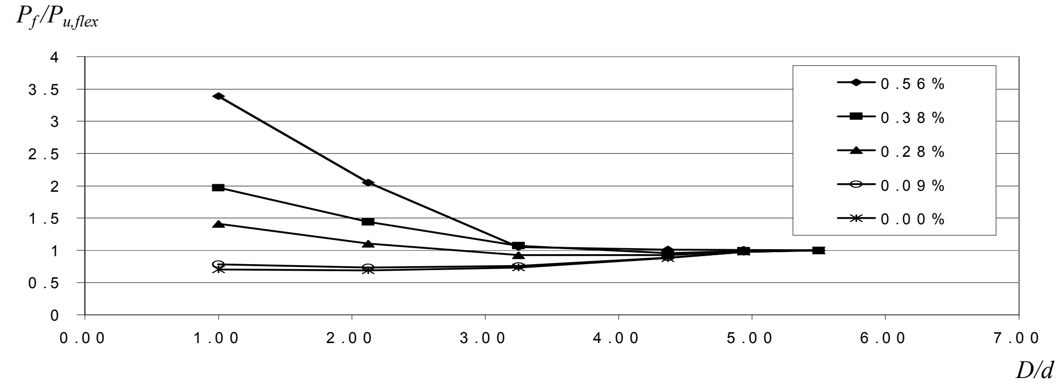


Figure 6: Relationship between $P_f/P_{u,flex}$ and *D/d* (for *Lp/d*=5.5).

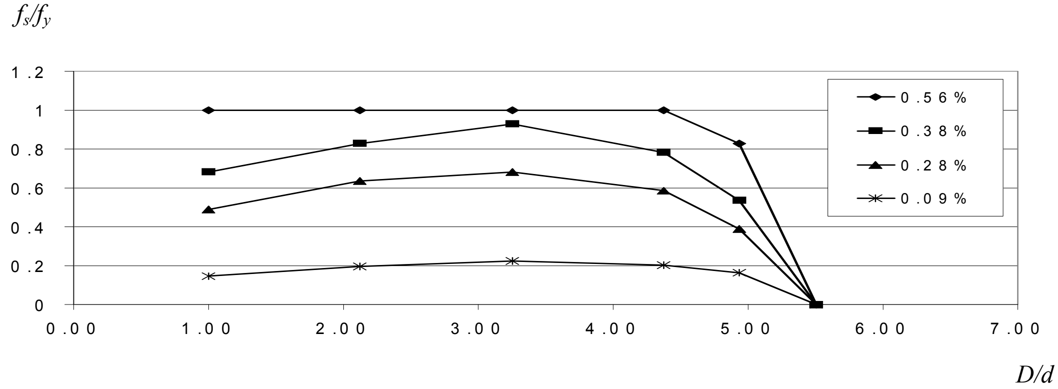


Figure 7: Relationship between f_s/f_y and *D/d* (for *Lp/d*=5.5).

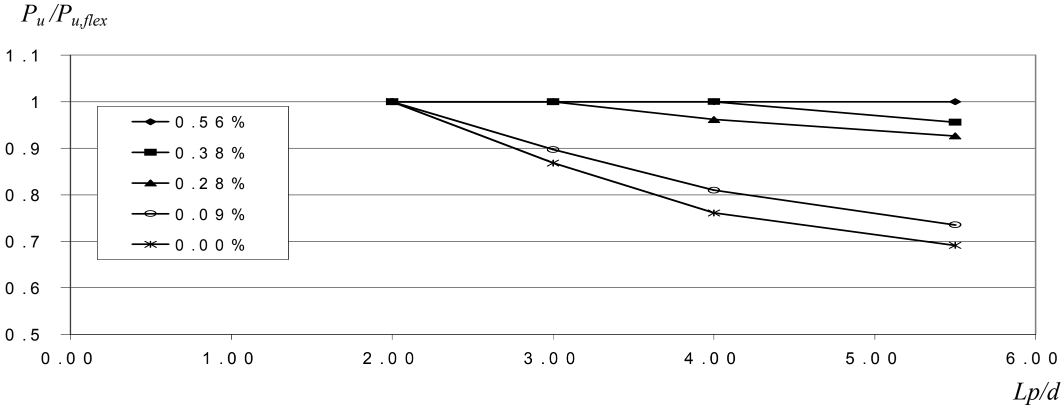


Figure. 8: Relationship between $P_u/P_{u,flex}$ and *Lp/d*.

It can be seen that for low values of *Lp/d*, the increase of *D/d* leads to a decrease of $P_f/P_{u,flex}$ from being above 1.0 to be equal 1.0 (at *D/d*=*Lp/d*) regardless the value of ρ_{sh} (Fig. 2). In case of higher values of *Lp/d* (Figs 4, 6), similar behavior is observed for high values of ρ_{sh} (0.28% and higher) while for beams provided with ρ_{sh} = 0.09% or less, $P_f/P_{u,flex}$ increases up to 1.0 when *D/d* approaches *Lp/d*. In other words, with respect to *Lp/d*, the minimum failure load of the beam, based on all of its investigated cracks (i.e. beam strength, P_u), is governed by the beam flexural strength for low *Lp/d* and by shear-flexural capacity (due to dowel failure of FRP bars and/or yield of stirrups) for higher *Lp/d*.

This behavior is emphasized when plotting the ratio $P_u/P_{u,flex}$ versus *Lp/d* (Fig. 8) where $P_u/P_{u,flex}$ =1.0 at *Lp/d*=2.0 and decreases gradually with the increase of *Lp/d*. However, the significant effect of ρ_{sh} is clearly seen where a value of 0.56% has been successful to upgrade the shear-flexural strength to $P_{u,flex}$ as well as to control the failure location within the pure flexural zone for all the studied values of Lp/d.

The ratio f_s/f_y is another demonstration for the influence of increasing ρ_{sh} on the efficiency of the shear reinforcement, as well as on improving the beam shear-flexural strength. First, it can be seen that for all the investigated cases, $f_s/f_y = 0.0$ at $D=Lp$ where the crack develops in a pure flexural zone and there is no crack component to induce any strains in the stirrups. Also, the number of stirrups crossing such crack is zero. Second, the maximum of f_s/f_y takes place within the middle zone of shear span. Third, f_s/f_y can reach a value of one only if ρ_{sh} equals a minimum of 0.56% or Lp/d does not exceed 2.0.

4 CONCLUSIONS

Based on the conducted study, the following conclusions can be reached:

The design philosophy for conventional steel-reinforced concrete beams is not always applicable when using FRP instead of steel bars since FRP bars crossing a shear-flexural crack may experience a dowel failure (causing a brittle pre-mature beam failure) prior to developing the design tensile capacity of such bars and/or that of the shear reinforcement.

The term ‘Shear Strength’ for FRP-reinforced concrete beams may be refereed to as ‘Shear-Flexural Strength’ since their shear strength depends, fundamentally, on the flexural behaviour and parameters such as crack width and crack geometry.

The overall beam strength is governed by the beam flexural capacity for low shear span to depth ratio, i.e. low Lp/d, and by the shear-flexural capacity (corresponding to the dowel failure of FRP bars and/or the yield of stirrups) for higher Lp/d.

In order to utilize the beam full flexural capacity prior to a dowel failure of FRP bars can take place, the minimum percentage of shear reinforcement as well as the maximum stirrups spacing has to satisfy specific limits. Theses limits have been observed, for the investigated beams, to be in the range of (0.5~0.6) % and (0.25~0.33) the beam depth respectively.

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