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Predictions of the maximum plate end stresses of FRP strengthened beams: Part II

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The authors are to be complimented for presenting an interesting paper on the emerging area of the strengthening of reinforced concrete structural elements using fibre-reinforced plastic (FRP) materials. The combined experimental and analytical parametric study conducted by them has led to a better understanding of the behaviour of concrete beams strengthened with externally bonded FRP plates.

(*a*) In all of the authors' specimens, the plates were terminated very close to the supports in a region of high shear and negligible moment. The authors have described the debonding failure mechanism on p. 346 as a 'shear-bond type of failure' in which 'the vertical shear force acting on the section presses down the longitudinal reinforcement and causes the destruction of the bond between the concrete and the steel, leading to the splitting of the concrete along the level of the reinforcement'. The effect of which is described on p. 344 as the 'premature separation of the plate from the beam at one end with the concrete cover still attached'. We would like to agree totally with the authors on this mechanism of debonding which occurs when the plates are terminated in a region of high vertical shear and low moment. This mechanism requires the formation of diagonal shear cracks and depends on the dowel action of the tension reinforcement, and the shear load at which this occurs can be taken as the strength of the reinforced concrete beams without stirrups.[1] This is confirmed by tests[1] that have shown that stirrups do not increase the shear load at which debonding occurs, simply because it is the formation of the diagonal cracks that cause debonding and stirrups are only effective after diagonal cracking. This mechanism explains why Swamy's technique of using angle plates[2] is so effective because they inhibit diagonal cracking and increase the dowel action.

(*b*) With regard to Fig. 4 in the original paper, it is not clear to us how the shear stress can be at a maximum at the plate end. One would have thought that the shear stress would be zero at the end of the plate where there is a free edge as shown by tests by Jones *et al.*[2] where the bond stress was zero at the plate end and reached a peak at a distance of 100 or 200 mm from the plate end.

(*c*) We find it very difficult to understand the significance of the analyses and the results tabulated in Table 3 in the original paper. The magnitudes of the stresses in Table 3 appear to be very high, bearing in mind that the debonding failure plane occurred in the concrete. The tensile strength of the concrete used was probably about 4 N/mm^2 yet the theoretical stresses given range from about 2 to 4 times this value. Furthermore, if the principal stresses were derived from Table 3 and compared with the tensile strength of the concrete then this factor would be much higher. However, if these are only representative stresses then should the principal stresses in each group be the same instead of having the very wide variations shown?

(*d*) It is worth comparing specimen A1b, which had a glue thickness of 1 mm, with A1c, which had a glue thickness of 2 mm. The results of the theoretical analyses in Table 3 suggest that doubling the glue thickness will increase the strength by 50% or more; however, the experimental results in Table 2 show a reduction in strength of 7%, that is there is virtually no change. A similar comparison of specimens A2b and A2c shows that doubling the glue thickness has only changed the strength by 2%. These experimental results suggest that the glue thickness does not have any significant effect on debonding. This is probably because the debonding plane occurs at the level of the tension reinforcement and not along the glue line.

We would like to thank the authors once again for a very interesting paper which we believe has clarified many issues in plated beam construction.

Reply by the authors

We would like to thank Dr Doric Oehlers and Mr Mohamed Ali for their interest in the above paper and their contribution to the discussion of it. We make the following comments on the four points raised in the discussion paper:

(*a*) This mechanism is highly dependent upon the shear span to beam depth ratio and we have shown elsewhere that as this ratio increases to greater than 6 the failure mechanism is completely different as the plate will tend to become detached from the beam near the externally applied load, forming a 'shear step' failure at this position.

(*b*) The diagram shown in Fig. 4 of the paper was intended to be a representation/simplification of what is known to be a complex stress regime. We agree with the observations that the discussers make regarding the shear stresses at this position being zero; indeed they must be. However, there is some uncertainty regarding the horizontal length over which the shear stress falls from its peak value to zero. It has been suggested from detailed theoretical and experimental study of adhesively bonded joints that such a length is of the order of the adhesive thickness. It was pointed out that the experimental work on steel plate bonded systems of Jones *et al.*[2] seems to indicate that the shear stress reaches a peak some 100–200 mm from the plate end. Reports are therefore somewhat conflicting. The equation of Roberts[3] used in the paper is intended to give the peak stress value only, wherever this occurs, not its variation with distance from the plate end.

(*c*) The review of previous work presented in the paper has shown that there remains doubt as to the actual values of stresses which cause plates to separate from strengthened reinforced concrete beams. Various suggestions have been made regarding the calculation and limitation of the plate end stresses to prevent such failure of steel-plated beams, but no comparable analyses have been carried out or reported for FRP-strengthened beams. It may be supposed that, since the plane of failure occurs within the concrete, the phenomenon is irrespective of the plating material. We have investigated whether the proposed calculation and design methods for steel plated beams are applicable to FRP-plated beams using the appropriate geometric and material parameters; the use of the suggested equations of Roberts is presented in the paper. Clearly, when failure occurs within the concrete at the plate ends the maximum stress levels within the adhesive must be closely related to the tensile/shear strength of the concrete to initiate such failure, as pointed out by Dr Oehlers. The theoretical results obtained by the use of the equations of Roberts are well in excess of this likely figure, suggesting that the equations are not directly applicable to FRP-plated systems, as stated in the discussion section of the paper (see p. 350), and that further study is required in this area to obtain more appropriate design methods. Therefore, although the *absolute* values obtained using the equations of Roberts appear inappropriate, the *relative* values obtained by substituting the geometric and material values of the experimental parameter study have indicated how these parameters affect the stress levels sustained before failure occurs (as discussed in the paper). From this point of view, and for demonstrating that the design equations seem inappropriate, presenting the results of the analysis was considered worthwhile.

(*d*) In all experimental tests, adhesive thickness, whether associated with 1, 2·3 or 4·5 m long beams (these are the length of beams being tested at the University of Surrey), has apparently little effect upon either the longitudinal plate strains or the concrete compression strain responses. The differences observed with the theoretical analysis is a part of the inaccuracies associated with the 1 m long beams stated in point (*c*).

References

1. Oehlers D. J. Reinforced concrete beams with plates glued to their soffits. *Journal of Structural Engineering of the ASCE*, 1992, **118**, No. 8, 2033–2038.
2. Jones R., Swamy R. N. and Charif A. Plate separation and anchorage of reinforced concrete beams strengthened by epoxy-bonded steel plates. *Structural Engineer*, 1998, **66**, No. 5, 85–94.
3. Roberts T. M. and Haji-Kazemi H. A theoretical study of the behaviour of reinforced concrete beams strengthened by externally bonded steel plates. *Proceedings of the ICE*, 1989, **87**, part 2, 39–55.