Available online at www.sciencedirect.com
SCIENCE DIRECT®
Cement & Concrete Composites 27 (2005) 962–963
Cement & Concrete Composites
www.elsevier.com/locate/cemconcomp

Correspondence

Response to discussion of the paper: "Flexural strengthening of RC continuous beams using CFRP laminates" [Ashour AF, El-Refaie SA, Garrity SW. Cement and Concrete Composites 2004;26:765–775]

The authors are grateful to Drs. Sowa, Wasniewski and Kaminska for their interest in the paper. In the discussion, reference is made to two main modes of debonding failure, namely modes P and Z. These appear to correspond to failure modes 3 (mode P) and 4 (mode Z) described by the authors. However, it should be noted that the pure bending conditions cited in the discussion for failure mode Z did not exist in the 2-span continuous beam tests reported in the paper.

Before addressing the other comments raised in the discussion, it is useful to re-state some of the main aims of the work reported in the paper, namely:

- To develop a simplified technique for estimating the flexural capacity of continuous RC beams strengthened with external CFRP laminates.
- To calculate the reserve capacity of beams tested if premature failure was prevented.
- To compare the longitudinal elastic shear stresses along the adhesive/concrete interface at beam failure with the limiting values suggested in Concrete Society Technical Report 55 [1].

The method of estimating the flexural capacity of strengthened RC beam sections described in Appendix A of the paper is based on the simple approach for reinforced concrete beam design presented in British Standard 8110 [2]. The authors consider it to be simpler and more readily understood by most practising engineers than the numerical non-linear approach referred to in the discussion. Furthermore, as can be seen from the list of assumptions in Appendix A, the authors did not intend the method to take account of premature modes of failure such as peeling or plate/sheet separation.

Hence, many of the comments raised in the discussion are not considered by the authors to be directly relevant to the paper. Nevertheless, the discussion raises a number of important issues on which the authors make the following comments:

(a) The non-linear sectional analysis described in the discussion appears to be based on normal strain failure criteria. Although limiting normal strain criteria can be useful in design (see (b) and (c), below), in the authors' opinion it is also necessary to consider the longitudinal shear stresses at the concrete/adhesive and adhesive/CFRP interfaces to avoid premature failure by peeling (failure mode 3 in the paper or mode P in the discussion). As a result it is necessary to carry out sectional analyses and a longitudinal analysis [3]. Reliance on sectional analysis alone should only be used where proven measures have been taken to avoid premature de-bonding failures.

(b) The authors agree that the use of a limiting tensile strain in the externally bonded CFRP would avoid a sudden brittle tensile failure. The authors are surprised, however, to note the predicted failure strain in the CFRP laminates of 8.73% quoted in the discussion for beam H6. As far as the authors are aware, this is considerably higher than the tensile strain capacity of any commercially available CFRP laminates. From Table 3 of the paper, it can be seen that the tensile failure strain for the CFRP sheets used to strengthen beam H6 is in the order of 1.6%.

DOI of original articles: 10.1016/j.cemconcomp.2005.02.004, 10.1016/j.cemconcomp.2003.07.002

0958-9465/$ - see front matter
doi:10.1016/j.cemconcomp.2005.07.001

(c) Similarly, limiting the tensile strain in the concrete adjacent to the CFRP would minimise the risk of a premature de-bonding failure described as failure mode 4 in the paper (mode Z in the discussion). Indeed, such an approach is recommended in Concrete Society Technical Report 55 [1].

(d) The authors do not agree with the conclusion presented in the discussion that excessive shear stresses at the CFRP/concrete interface are not the main cause of de-bonding (or peeling) failure. The view expressed in the discussion seems to be at variance with those expressed by many other researchers [4–9].

(e) The authors agree with the view expressed in the discussion that "*there is no obligation to excessively lengthen the CFRP plates or sheets over the tension region of continuous beams*". The lengths of CFRP sheet or plate used in the tests were selected to cover the entire negative or positive moment regions (see Section 4.3 of the paper) to investigate their effect on preventing peeling failure (mode 3).

(f) Finally, it is suggested that where the experimental results presented in the paper do not correlate well with the results predicted using the computational approach developed by Dr. Sowa et al., "*the results given by the authors … must be verified*". The authors wish to make it very clear that all the experimental work was undertaken in a well-established structural engineering laboratory supervised by two very experienced academic staff (Ashour and Garrity) with the support of technician staff with considerable experience in structural testing. Furthermore all the work was carried out using regularly calibrated, carefully maintained equipment and instrumentation. The authors presented all the results in the paper with the confidence that befits a team with experience and expertise in large-scale structural experimental work. Consequently, the authors are disappointed that Dr. Sowa et al. consider it necessary to question the validity of some of the results.

References

[1] Concrete Society. Design guidance for strengthening concrete structures using fibre composite materials. Concrete Society Technical Report No. 55; 2000. p. 71.

[2] British Standards Institution. Structural use of concrete: code of practice for design and construction. BS 8110, part 1. Milton Keynes, UK; 1997.

[3] El-Refaie SA, Ashour AF, Garrity SW. Flexural strength of continuous reinforced concrete beams with externally bonded CFRP reinforcement. In: Proceedings of the ACI fourth international conference on repair, rehabilitation and maintenance of concrete structures, and innovations in design and construction, SP 193-57, Seoul, Korea, 2000. p. 959–78.

[4] Arduini M, Tommaso AD, Nanni A. Brittle failure in FRP plate and sheet bonded beams. ACI Struct J 1997(July–August):363–71.

[5] Malek AM, Saadatmanesh H, Ehsani MR. Prediction of failure load of R/C beams strengthened with FRP plate due to stress concentration at the plate end. ACI Struct J 1998(March–April): 142–52.

[6] Maalej M, Bian Y. Interfacial shear stress concentration in FRP-strengthened beams. Compos Struct 2001;54:417–26.

[7] Mukhopadhyaya P, Swamy N. Interface shear stress: a new design criterion for plate debonding. J Compos Constr, ASCE 2001:35–43.

[8] Oehlers DJ, Moran JP. Premature failure of externally plated reinforced concrete beams. J Struct Eng, ASCE 1990;116(4): 978–95.

[9] Roberts TM. Approximate analysis of shear and normal stress concentrations in the adhesive layer of plated RC beams. Struct Eng 1989;67(12/20):229–33.

A.F. Ashour
S.A. El-Refaie
S.W. Garrity
University of Bradford
EDT1
School of Engineering
Design and Technology
Richmond Road
Bradford BD7 1DP
United Kingdom
Tel.: +44 1274 233 870; fax: +44 1274 234 124
E-mail address: a.f.ashour@bradford.ac.uk
(A.F. Ashour)

Available online 28 July 2005