Available online at www.sciencedirect.com
SCIENCE DIRECT®
Cement & Concrete Composites 27 (2005) 958–961
Cement & Concrete Composites
www.elsevier.com/locate/cemconcomp

Discussion

Flexural strengthening of RC continuous beams using CFRP laminates [Cement & Concrete Composites 26 (2004) 765–775]

Lukasz Sowa *, Tomasz Wasniewski, Maria E. Kaminska

Department of Concrete Structures, Technical University of Lodz, al. Politechniki 6, 90-924 Lodz, Poland

First of all we must say that presented by the authors tests are very interesting and provide many important observations. However, it seems that the results of the tests can be interpreted in a different way.

Authors of the paper concluded that shear stresses calculated along the adhesive level using elastic theory should not exceed 0.80 N/mm^2 to avoid debonding failure of CFRP laminates. Meanwhile our tests of the beams strengthened for flexure with CFRP composites [1], shows two main modes of debonding failure.

The first one called "Z" started in the pure bending region close to the vertical crack and moved in direction to one of the supports. The plate debonded on the long segment including the pure bending region as well as the support region. The shear stresses were close to zero and the reason of the failure by debonding was vertical pressure of the concrete cover on the plate, which starts to debond from the steel reinforcement close to the vertical crack. The strains of the CFRP composites depend on the ductility of it, and in case of stiff plates are approximately few per mills and dozen per mills in case of slender sheets.

Second mode of failure is called "P" and was located in the support region, close to the end of the CFRP laminate. The plate debonded on the short segment including the support region only and did not reach the place where loading point was located. Composite plates debonded with concrete cover. Process started during steel yielding at the non-strengthened cross-section of the beam. Also in this case the shear stresses in adhesive are not the cause of the CFRP debonding. Fig. 1 presents both modes for single span beam strengthened for flexure with CFRP plates.

The similar conclusions about the failure of the beams strengthened using CFRP are presented by authors in [2] and [3].

We can estimate the strains of the beams tested by authors especially these which cannot be described by computational model presented by authors, i.e. beams H6, S5 and E4.

In the analysis transfer of the load over the some length of the beam was taken into account. The segment was assumed $a = 2 * 0.175$ m at the middle of the beam's height (Fig. 2a).

For numerical estimation of the strains in the critical cross-sections of the beams the non-linear model was used. The model takes into account non-linear σ–ε relationship for concrete in compression and experimental σ–ε relationship for reinforcing steel and CFRP composites. There is also a tension stiffening principle and assumption that cracks perpendicular to element axis are smeared over its length.

A rectangular cross-section of the beam with internal steel reinforcement and external CFRP composites was considered (Fig. 2b). The cross-section was divided over its depth into layers. Compressive and tensile steel reinforcement and CFRP laminates are treated as a separate layers with known position.

External load value was calculated based on the equilibrium condition of generalized forces in the cross-section. Load for which limit strain of one of the materials was reached was accepted as the load bearing capacity of the cross-section.

The beam H6 first failed over the middle support, where the CFRP composite broke. Presumably, first the CFRP debonded with average computational strains $\varepsilon_t = 8.73‰$ steel reinforcement.

DOI of original article: 10.1016/j.cemconcomp.2003.07.002
* Corresponding author. Fax: +48 42 631 35 84.
E-mail addresses: lukasz_sowa@interia.pl (L. Sowa), twasn@poczta.onet.pl (T. Wasniewski), markamin@p.lodz.pl (M.E. Kaminska).

0958-9465/$ - see front matter
doi:10.1016/j.cemconcomp.2005.02.004

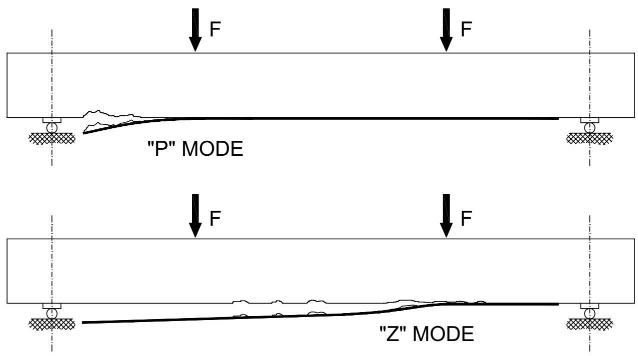

Fig. 1. Failure modes of the beams strengthened for flexure with CFRP plates.

Due to internal forces redistribution, the continuation of loading was possible. The load was taken over by high reinforced spans. Debonding strains of the CFRP sheet in the middle of the span were approximately 3‰, so they were lower than expected. The cause of failure was not for sure the deformation of cross-section by the end of composite plate, because reinforcement steel did not yield there.

In the beam with signature S5 the failure was caused by debonding of the composite with average strains of the CFRP only 2‰ (point M_h in Fig. 4). In our opinion the composite plates debonded in the compression region near the middle support and the cause of

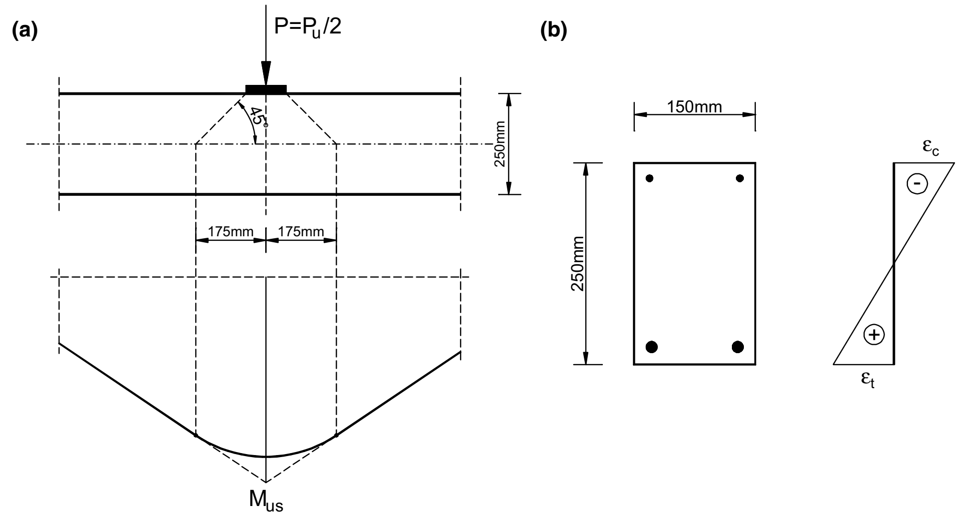

Fig. 2. Analytical model assumptions. (a) Load transfer; (b) strains notation.

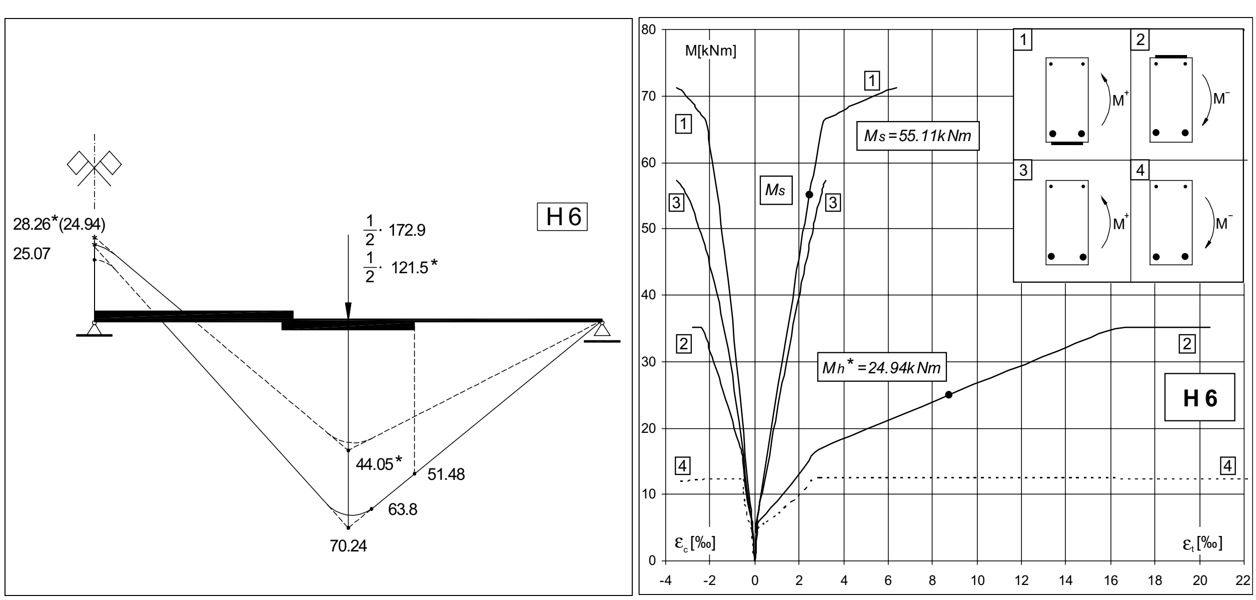

Fig. 3. Experimental bending moment diagram and computational bending moment–strain relationships for beam H6.

debonding was the contraflexure of fairly stiff layer of the composite.

Debonding of the CFRP composite occurred in the beam E4 when its strains reached value $\varepsilon_t = 6.5‰$, just after that tensile steel reinforcement reached yielding strength. Fig. 5 presents that mechanism.

For comparison in Figs. 3–5 calculated relationships bending moment–strains for non-strengthened cross-sections are also presented.

Following the experimental results given by authors in their article, the failure mode "Z" occurs also in the beams E2 and E3. Calculated in the same way as above strains are respectively $\varepsilon_t = 6.5‰$ and $5.9‰$. Those beams E2, E3 and E4 were strengthened using the same type of CFRP plates with the same ductility, so approximately constant value of debonding strains is evident. This prove that analytical model is correct.

In the beams strengthened with CFRP sheets there were different composite reinforcement ratios. Using 2, 4 or 6 layers of sheet leads to different ductility of the CFRP reinforcement. Computational values of debonding strains in failure mode "Z" are presented in Fig. 6. As we can see, transverse ductility of the composite very clearly influences debonding strains.

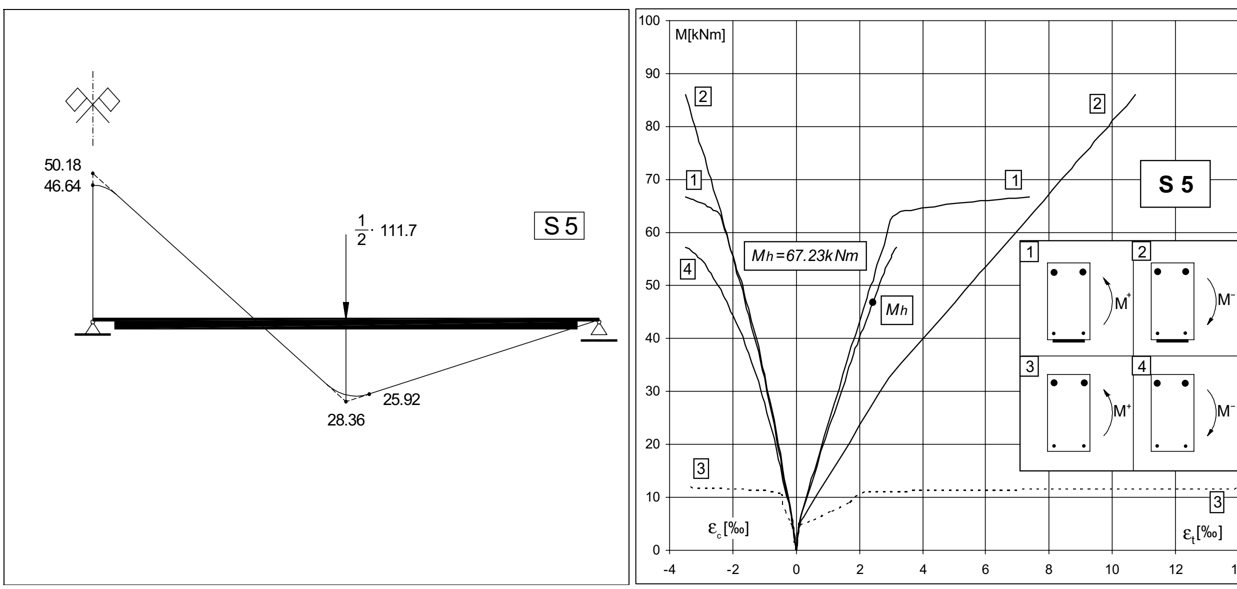

Fig. 4. Experimental bending moment diagram and computational bending moment–strain relationships for beam S5.

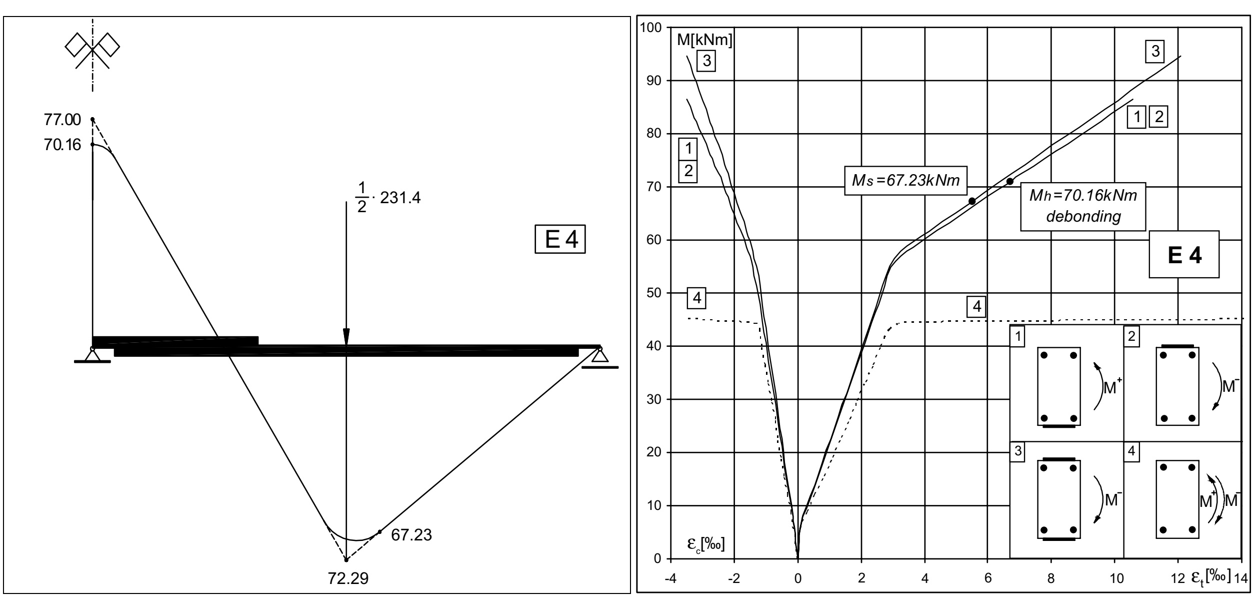

Fig. 5. Experimental bending moment diagram and computational bending moment–strain relationships for beam E4.

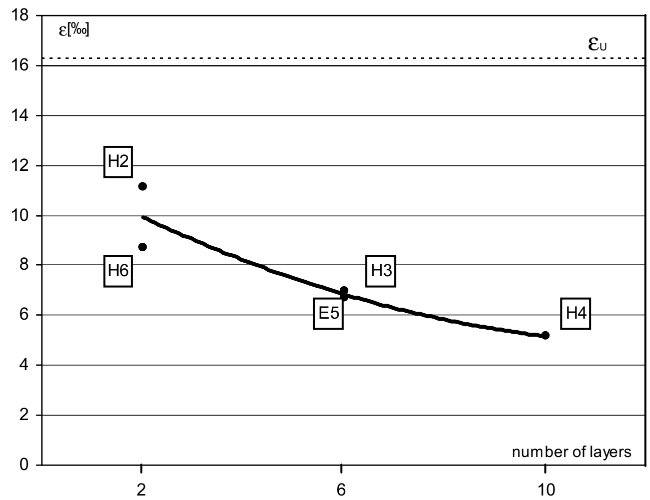

Fig. 6. Computational values of debonding strains versus number of composite layers.

Presented analysis of the load state is not possible for the beam S4, because experimental value of the bending moment is about 30% higher than computational capacity of the cross-section. It seems that results given by the authors in article must be verified.

Above considerations leads to the following conclusions:

- Estimating of load bearing capacity of the beam strengthened with CFRP composites should take into account analysis of normal strains in the critical cross-sections of the beam.
- In general shear stresses in the contact surface of the CFRP composite and concrete are not the main reason of CFRP plates or sheets debonding.
- Estimating of the flexural capacity of the strengthened cross-sections of the beam should take into account that forces in the composite are limited by limit strain $\varepsilon_{t,lim}$.
- There is no obligation to excessive lengthen the CFRP plates or sheets over the tension region of the continuous beams.

References

[1] Kaminska ME, Kotynia R. Effect of different parameters on strengthening ratio of RC beams strengthened with CFRP plates. In: Proceeding of the International Conference Composite in Construction CCC 2001, Porto 2001. p. 529–34.

[2] Grace NF. Strengthening of negative moment region of reinforced concrete beams using carbon fiber-reinforced polymer strips. ACI Struct J 2001(May–June):347–58.

[3] Stallings JM, Porter NM. Experimental investigation of lap splices in externally bonded carbon fiber-reinforced plastic plates. ACI Struct J 2001(January–February):3–10.