

ABSTRACT

Advanced composite materials are increasingly used in the strengthening of reinforced concrete (RC) structures. An updating procedure based on strain-based monitoring of FRP laminates is proposed here to predict the initiation of midspan debonding on FRP-strengthened beams.

INTRODUCTION

Advanced composite materials are increasingly used in the strengthening of reinforced concrete (RC) structures [1]. The use of externally bonded strips made of fibre-reinforced plastics (FRP) as strengthening method has gained widespread acceptance in recent years since it has many advantages over the traditional techniques, especially because of the high strength and modulus of elasticity, improved durability, and low weight of the composite material. Failure of FRP-strengthened RC beams may take a variety of forms including all those associated with conventional concrete beams. However, unfortunately, this strengthening method is often associated with a brittle and sudden failure caused by some form of FRP bond failure. This kind of failure is produced in the form of cover delamination, i.e., along the plane of the steel reinforcement, or FRP delamination, i.e., in the plane along the FRP-concrete interface. Furthermore, failure may be originated at the termination of the FRP material and propagate towards the midspan [2,3] or in the vicinity of flexural cracks in the RC beam and propagate towards the FRP termination [4, 5]. Hence, flexural cracking of the RC beam has a major influence on the overall response of the strengthened member, and it affects the distribution of the stresses in the various constituents of the strengthened member.

As a result, considerable numerical and experimental efforts should be made to capture these phenomena. An updating procedure based on strain-based monitoring of FRP laminates is proposed here to predict the initiation of midspan debonding on FRP-strengthened beams.

DIFFERENTIAL EQUATIONS

Considering first-order shear deformation theory, the axial and transverse displacement field can be expressed as:

$$u_C(x, z, t) = u_0(x, t) - z\phi(x, t) \quad (1)$$

$$u_{FRP}(x, z, t) = u_0(x, t) - z\phi(x, t) + s(x, t) \quad (2)$$

$$w(x, z, t) = w(x, t) \quad (3)$$

where u_C , u_{FRP} and w are respectively the axial displacements in RC beam and FRP plate and the transverse displacement at a material point, ϕ is the curvature-independent rotation of the beam cross-section about the Y-axis and s is the interface slip.

The linear constitutive model for the concrete beam and the FRP plate can be expressed as

$$\sigma_{xC} = E_C \varepsilon_{xC} \quad \tau_{xzC} = G_C \gamma_{xzC} \quad (4)$$

$$\tau_{xzFRP} = G_{FRP} \gamma_{xzFRP} \quad (5)$$

where the material constants, E and G , are referred to the concrete beam (C) or the external plate (FRP) depending on the material considered.

Applying Hamilton's principle, the governing equations of the FRP flexural strengthened RC beam are obtained and can be written as

$$\delta u_0 : I_0 \ddot{u}_0 - I_1 \ddot{\phi} + I_{0FRP} \ddot{s} - A_{11} u_{0,xx} + B_{11} \phi_{,xx} - A_{FRP} s_{,xx} = 0 \quad (6)$$

$$\delta w : I_0 \ddot{w} - A_{22} w_{,xx} + A_{22} \phi_{,x} = 0 \quad (7)$$

$$\delta \phi : I_2 \ddot{\phi} - I_1 \ddot{u}_0 - I_{1FRP} \ddot{s} + B_{11} u_{0,xx} - D_{11} \phi_{,xx} - A_{22} w_{,x} + A_{22} \phi + B_{FRP} s_{,xx} = 0 \quad (8)$$

$$\delta s : I_{0FRP} \ddot{s} + I_{0FRP} \ddot{u}_0 - I_{1FRP} \ddot{\phi} - A_{FRP} s_{,xx} - A_{FRP} u_{0,xx} + B_{FRP} \phi_{,xx} + \frac{G_{AD} s b_{AD}}{e_{AD}} = 0 \quad (9)$$

and associated force boundary equations can be expressed as

$$N = A_{11} u_{0,x} - B_{11} \phi_{,x} + A_{FRP} s_{,x} \quad (10)$$

$$V = A_{22} w_{,x} - A_{22} \phi \quad (11)$$

$$M = -B_{11} u_{0,x} + D_{11} \phi_{,x} - B_{FRP} s_{,x} \quad (12)$$

$$N^* = A_{FRP} s_{,x} + A_{FRP} u_{0,x} - B_{FRP} \phi_{,x} \quad (13)$$

where (\cdot) denotes temporal derivative. N , V , M and N^* are the stress resultants associated with the variables u_0 , w , ϕ and s , respectively.

A_{11} , B_{11} , D_{11} , A_{22} , A_{FRP} and B_{FRP} are the stiffness coefficients obtained from the material properties.

1.3. SPECTRAL ELEMENT

A spectral Timoshenko beam finite element formulation for the problem under consideration has been considered [6]. The generic displacement vector at any point and frequency becomes

$$\{\hat{u}(x, \omega_n)\} = \begin{pmatrix} \hat{u}_0(x, \omega_n) \\ \hat{w}(x, \omega_n) \\ \hat{\phi}(x, \omega_n) \\ \hat{s}(x, \omega_n) \end{pmatrix} = \begin{bmatrix} R_{11} & \dots & R_{18} \\ R_{21} & \dots & R_{28} \\ R_{31} & \dots & R_{38} \\ R_{41} & \dots & R_{48} \end{bmatrix} \begin{bmatrix} e^{-jk_1x} & 0 & \dots & 0 \\ 0 & e^{-jk_2x} & \dots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ 0 & \dots & \dots & e^{-jk_8x} \end{bmatrix} \{A(\omega_n)\} \quad (14)$$

where $k_{p+4} = -k_p$ ($p=1, \dots, 4$) are the wavenumbers.

$\{A\}_n$ is a vector of eight unknown constants to be determined. This vector can be calculated by imposing the nodal spectral displacements at the two nodes of the element.

The dynamic stiffness matrix is formulated by using the force boundary conditions at the nodes of the element.

4. RESULTS

Using the proposed approach the distribution of stresses and strains of strengthened beams has been obtained.

Static predictions, i.e., dynamic computations with the proposed method when frequency tends to zero, have been compared with the experimental results.

The response of the B6 RC beam strengthened by an externally bonded carbon FRP strip, which was tested in [7] has been taken for comparison. The beam was 2.3 m long x 0.2 m wide x 0.15 m deep and was reinforced longitudinally with two bars of 0.008 m diameter over compression side and two bars of 0.010 m diameter over tension side; transversally, stirrups of 0.006 m diameter at every 0.075 m were distributed along the beam. The carbon FRP plate used with the B6 specimen was 1.930 m long and 0.15 m wide and its thickness was 0.0012 m. The beam was subjected to two identical point loads, applied symmetrically at 0.3 m from the middle (four-point bending test), being simply supported on a pivot bearing on one side and a roller bearing on the other side, over a span of 2.1 m.

For our study, in order to capture the cracking evolution of the beam, the strengthened beam would be divided into several elements where the stiffness coefficients are kept uniform throughout the entire element. Therefore, the number of elements used in the spectral method would depend on the expected extension of the nonlinearity along the length of the strengthened beam as well as on the desired degree of precision to represent it. Finally, 43 spectral finite

elements were used, one for each one of the two non-strengthened beam portions in the vicinity of the supports, another one for the beam portion between the applied loads and 20 elements uniformly distributed at the beam portions located between the ends of the FRP plate and the loads.

Figure 1 shows the comparison of the spectral model prediction of the load-deflection response of the strengthened beam A-400-2, along with the experimental results. The local behaviour at the adhesive-concrete interface considering flexural cracking of the RC beam is shown in Figure 2 by using the interface-slip evolution under increasing load levels. According to the experimental results, the beam failed as a result of transverse curling of the plates at the midspan. In Figure 2, the maximum peak values of the interface slip are located where there is steel rebar yielding, since, in that case, a sudden increase in FRP strain rate occurs starting from that region. This demonstrates the ability of the proposed method to simulate intermediate debonding failure and, therefore, its feasibility to be used in a damage identification procedure from experimental results.

CONCLUSIONS

A model using spectral elements has been proposed to simulate in a unified way the static and dynamic behaviour of FRP flexural strengthened reinforced concrete beams. The two main characteristics of the proposed approach are its simplicity and its ability in accurate high-frequency modelling. This model can be taken as a starting point to implement a damage identification procedure for this kind of strengthening.

ACKNOWLEDGEMENTS

The writers acknowledge the support for the work reported in this paper from the Spanish Ministry of Education and Science (project BIA2007-67790).

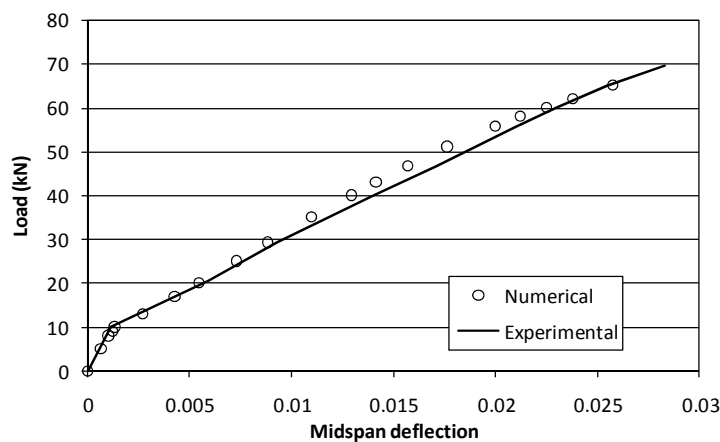


Figure 1. Load-displacement curve

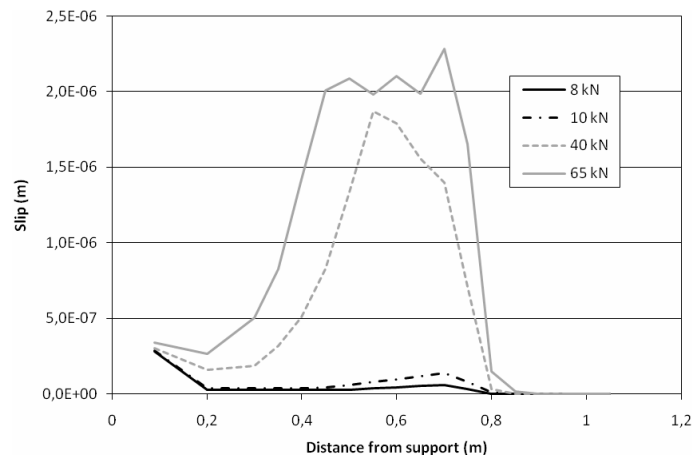


Figure 2. Interface slip evolution

REFERENCES

1. Bank LC. Composites for construction: Structural design with FRP materials, first ed. John Wiley and Sons 2006.
2. Yang ZJ, Chen JF, Proverbs D. Finite element modelling of concrete cover separation failure in FRP plated RC beams. *Constr. Build. Mater.* 2003; 17 (1): 3-13.
3. Pesic N, Pilakoutas K. Concrete beams with externally bonded flexural FRP-reinforcement: analytical investigation of debonding failure. *Compos. Part B-: Eng.* 2003; 34(4): 327-338.
4. Sebastian WM. Significance of midspan debonding failure in FRP-plated concrete beams. *J. Struct. Eng. ASCE* 2001; 127(7): 792-798.
5. Yao J, Teng JG, Lam L. Experimental study on intermediate crack debonding in FRP-strengthened RC flexural members. *Adv. Struct. Eng.* 2005; 8 (4): 365-396.
6. Gopalakrishnan S, Ghakraborty A, Roy Mahapatra D. Spectral finite element method, first ed. Springer, London 2008.
7. Rahimi A, Hutchinson A. Concrete Beams Strengthened with Externally Bonded FRP Plates. *J. Compos. Constr.* 2001; 5(1): 44-56.