SHEAR BEHAVIOR OF CONCRETE-FILLED CFRP BOX BEAM

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1. INTRODUCTION

Carbon fiber reinforced polymer (CFRP) composite has emerged as a prosperous construction material in civil engineering because of its favorable durability and very high specific strength and stiffness. CFRP has been utilized in various retrofitting and rehabilitation activities, most commonly as a confining material for concrete structures. However, very few studies have focused on the use of CFRP as a primary structural element. Due to its anisotropic nature and high degree of orthotropy, design of CFRP structure is highly complex; and at the same time it offers a unique opportunity of tailoring its properties to achieve an efficient design.

Unlike the case of isotropic materials, the shear modulus and shear strength of CFRP are substantially low compared to flexural properties. This impedes the use of conventional design assumptions and theories for the design of CFRP box beams. This study explains the outcome of finite element analysis for investigating the shear response of a CFRP box beam filled with concrete under four point bending. An FEM model is developed that considers cracking and crushing of concrete; interface friction between concrete and CFRP; and failure index of CFRP based on three dimensional stress state. Predicted stiffness and failure location show a reasonable agreement with an experiment.

2. MATERIAL PROPERTIES

Materials treated in the analysis are concrete and CFRP. Strength, stiffness and Poisson’s ratio for concrete are obtained from the test data. A constitutive relation of concrete is selected such that it is capable of crushing in compression and cracking in tension. A confinement model of concrete as proposed by Samaan et al. (1998)[1] is utilized. CFRP is modeled as an orthotropic material with linear stress-strain relations for all six stress components. Mechanical properties are shown in Table 1; in-plane properties are obtained from the test and the rest is suitably assumed or computed referring to various literatures.

3. FINITE ELEMENT ANALYSIS

This study employed 8-node three-dimensional solid elements for both FRP and concrete. Details of the beam are shown in Fig. 1. Only one quarter of the beam was modeled utilizing the symmetry of the beam in two planes. An empty beam was analyzed first. Later, two analyses were performed for concrete-filled beams to investigate the interface behavior: one with perfect bond and the other with interface friction. The analysis scheme was non-linear with non-linear concrete model and had the ability to have progressive failure of CFRP. Tsai-Wu failure criterion[2] was employed for CFRP, in which failure can occur by a combination of different stress components. A sharp change in slope of moment-deflection curve was defined as the ultimate failure of beams.

Table 1: Material properties for CFRP

Properties from test		Assumed properties	
Tension1-1	1790	Tension 3-3	62
Comp. 1-1	-515	Comp. 3-3	-173
Tension 2-2	295	E_3	8500
Comp. 2-2	-173	Shear 2-3	25.0
E_1	110800	Shear 3-1	25.0
E_2	20900	G_{23}	2500
Shear 1-2	36.1	G_{31}	2500
G_{12}	3500	μ_{23}	0.460
μ_{12}	0.13	μ_{13}	0.432

Note: all stresses and moduli have a unit of N/mm^2.

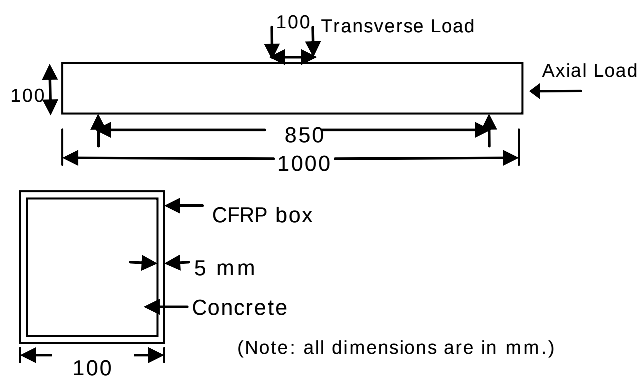

Fig. 1: Longitudinal and cross section of beams

4. RESULTS

Ultimate load capacities for empty and filled beam were observed as 82.04 kN and 119.26 kN respectively in the experiment, while they were observed as 57.00 kN and 107.80 kN respectively for empty and filled beam in the FE analysis. Failure location was observed near a loading plate in both empty and contact analysis case. Moreover, shear failure of web was observed in both cases. In-plane shear stress substantially contributed to the failure of beams.

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5. DISCUSSIONS

Analysis of the empty beam elucidated that the contribution of shear to the deflection of the beam was as high as 56% as shown in Fig. 2. Euler-Bernoulli beam theory was inapplicable for CFRP box beams despite a large span-depth ratio of 8.5. Stiffness of the concrete-filled beam was obtained more than 200% of that of the empty beam under perfect bond assumption, which was only around 120% in the experiment, as shown in Fig. 3. Moreover, the failure location was observed near the mid span while it was observed near the loading plate away from the mid span in the case of experiment. In the contact analysis, the stiffness of the filled beam was found about 115% of that of the empty beam as shown in Fig. 3. Ultimate failure location was observed similar to the experiment. The large variation of stiffness between perfect bond case and interface friction case could not be described by the flexural modulus of concrete alone. While concrete contributed for shear transfer in the former case, shear was mostly transferred through the web of the box beam in the latter case reducing the overall stiffness of the beam substantially.

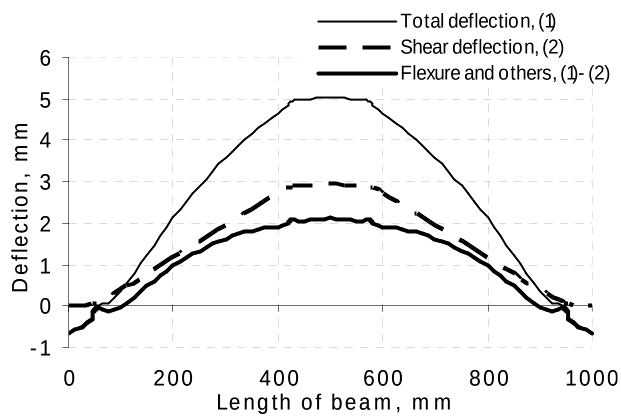

Fig. 2: Deflection of the empty beam at load of 46.5 kN

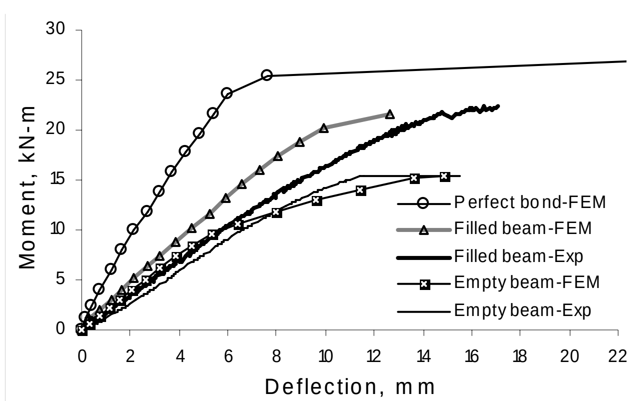

Fig. 3: Moment-deflection curves for CFRP box beams

Failure of the beams was found to be contributed by shear stress in addition to longitudinal stress. Failure at the flange near the loading plate occurred with interaction of longitudinal compressive stress and in-plane and interlaminar shear stresses. Compressive strength of FRP was not fully utilized at the time of failure: only about 40% in the empty beam and 70% in the filled beam. Contribution of in-plane shear stress to the failure of flange was about 45% for the empty beam. Thus, the ultimate load capacity of the beams would largely depend on the shear strength. In-plane shear strength of CFRP used in this analysis is suspected lower than the actual strength of experimental beams as indicated by the shear failure of web and the lower load capacity in the analysis.

6. CONCLUSIONS

Finite element analysis was performed to analyze empty and concrete-filled CFRP box beams. Shear contribution to the deflection of the empty beam was observed as high as 56%. Euler-Bernoulli beam theory was inapplicable to CFRP box beams despite a high span-depth ratio of 8.5. Classical lamination theory indicates that the shear modulus of FRP laminate can be substantially increased by adding off-axis lamina to the cross-ply lay-up. Modification of a material design to improve the shear modulus is highly recommended.

Failure location was observed at the top flange near the loading plate. Failure at the location mostly occurred with interaction of longitudinal compressive stress and in-plane and interlaminar shear stresses.

It could be concluded that slip occurred between concrete and CFRP in the experiment. Concrete contributed little to shear transfer. Shear deformation of CFRP significantly contributed to the deflection of the beams: not only in the empty beam, but also in the concrete-filled beam. Interfacial bond between concrete and CFRP was found of paramount importance for the design of beams. Stiffness and strength of beams could be substantially improved by having perfect bond between concrete and CFRP. In the absence of an adhesive or a mechanical bond, slippage occurred between concrete and CFRP. Bond is highly recommended for effective utilization of concrete and to make concrete and CFRP work together.

Discrepancies existed between experimental and analytical results for ultimate load capacity. They might be basically attributed to the assumed properties of CFRP. Further studies and verification of material properties are necessary for clarification of such results. In-depth studies of specific parameters are suggested for future works.

REFERENCES

1. Samaan, M., Mirmiran, A., and Shahawy, M. (1998). “Model of concrete confined by fiber composites.” Journal of Structural Engineering, ASCE, 124(9), 1025-1031.
2. Tsai, S. W., and Wu, E. M. (1971). “A general theory of strength for anisotropic materials.” Journal of Composite Materials, 5(1), 58-80.