ABSTRACT

The applications of fiber reinforced polymer (FRP) products are increasing in the construction sectors due to its versatile properties such as lightness, resilience to corrosion and ease of installation. They have been found to have almost unlimited usefulness in all segments of the construction industries such as FRP structural elements, bridge repair, cable-stayed bridge, structural strengthening, etc. The FRP products has attracted great attention due to its high specific stiffness, specific strength, non-corrodible characteristics and chemically inert properties. FRP beams made using pultrusion process consists of different layers of laminae. It is very important to determine the properties of each layer and panels (flange and web) for the optimal design of FRP beams for specific applications. Young's modulus of elasticity and shear modulus of the beams are determined by different test methods such as tensile testing of coupons, three-point bending testing of coupons and beams, and four-point bending test of beams. Further, the stiffness of beams is evaluated from approximate classical and mechanics of laminated beam theories. In order to check the accuracy of the stiffness, Timoshenko's beam theory is used to determine the load-deflection response of the beam with predicted stiffness and compared with that obtained from experimental three-point bending test. It is observed that flexural responses obtained using stiffness predicted from four-point bending test and theories give the good agreement of results. Hence, for further parametric study on beams, mechanics of laminated beam theory is used to determine the flexural response of beams having different types of laminae.

Flexural response of the beams having imperfection in the geometry (i.e., one of the flange is not perpendicular to the web) is predicted under three-point bending. It is observed that due to imperfection in the flange, beam deflects in lateral direction which leads to failure of the web-flange junction. Further, the flexural response of FRP beams without imperfection and with different layups is predicted. The first mode of failure is examined and it is observed that FRP beams fail at junction of flange and web under loading. It is due to discontinuity of layers at the junction of I-beam as well as low shear and transverse compressive strength of web. Flexural stiffness and strength of beams increase with removing the imperfection from geometry of beams. Replacing the chopped strand mat with 45^{o} and 90^{o} unidirectional rovings increases the crushing strength of the beam. This failure load can be increased by installing different stiffening elements at compression web-flange junction under the loading. In this study, stiffening elements such as cover plate, web plate, bearing stiffener, longitudinal

stiffener and carbon fiber layer are used. In the beams having imperfection and stiffened with T-shaped bearing stiffener, failure of T-shaped bearing stiffener was seen due to the eccentric loading (because of imperfection in the flange) on stiffener. From flexural testing of beams with bearing stiffeners, it is observed that the short length bearing stiffeners are more effective than full depth bearing stiffeners. The flexural strength of beams with bearing stiffeners is significantly higher than beams without bearing stiffener and the failure of web-flange junction is also prevented for span-to-depth ratios (L/d) of 3, 5 and 7. Beams stiffened with T-shaped bearing stiffeners using bolted connection failed by failure of web-flange junction of stiffening element, while in the beams having bonded and bolted connection of bearing stiffeners, the failure of stiffeners was not observed.

In this research, the flexural characteristics of stiffened and unstiffened FRP I-beams are also determined analytically and numerically (ABAQUS); and verified with experimental investigation. There are no code provisions for designing of FRP beams with stiffening elements such as cover plate, web plate, bearing stiffener, longitudinal stiffener and carbon fiber layer. Hence, equation to calculate the deflection of beams with different stiffening elements is derived using Castigliano's theorem. In order to get the better understanding of failure of FRP beams, various formulae for beams without stiffening elements available in design manuals are incorporated in the analytical model for prediction of failure load and mode. Further, a failure criterion is recommended for prediction of failure load of beams with and without stiffening elements. The results obtained from analytical and finite element models give the good comparison of results with experimental investigation. Further, a parametric study is performed on beams having different flange width-to-thickness ratios (5 to 15), depth-to-thickness ratios (21 to 40), and length-to-depth ratios (3 to 11) with different sizes of stiffening elements. It is observed that failure load of beams increases up to certain width of bearing plate, later it becomes constant. Under flexural loading, bearing stiffeners of a beam is found to fail, if the width of bearing plate is less than the flange width of T-shaped bearing stiffener. Similarly, if the length of cover angle or carbon fiber layer provided is less than the width of bearing plate, then the failure load is equivalent to the beam with having bearing plate only. Carbon fiber angles are less effective than beam with cover angle for effective depth-to-thickness ratio more than 21.

Furthermore, FRP castellated beams are fabricated having hexagonal openings. It is noted that castellated beams have 53% higher depth than its parent beams (beams from which castellated beam is made) and 36% lesser load than parent beam. From numerical investigation, it is observed that with increase in the size of the openings, stiffness and strength of the beams decrease. For the same height of openings, the beams having circular openings has lower stiffness and higher strength than beams having hexagonal and sinusoidal openings.

This study reflects that eliminating the imperfection in the beams enhances the flexural strength and stiffness of the beams. Rovings provided in direction of loading in the web panels, increases the failure load of the beams. Even though stiffening elements are provided at web-flange junction, still the failure of web and/or flange panel of I-beams is observed but the failure load of stiffened beams is 3-4 times higher than beams without stiffening elements. Moreover, it is recommended that the length of bearing plate should be lesser than the width or length of the stiffening element. FRP castellated beams having circular openings have higher failure load but low service load than other beams having hexagonal and sinusoidal openings.