Chapter 4

Flexural Study of Beams: Experimental Investigation

4.1 Introduction

FRP beams are still lagging to replace steel beams in construction due to the deficiency of design guidelines of FRP beams. There are still some issues such as failure of flange-web joint and crushing of web that hinders the use of FRP I-sections in civil engineering applications such as frame structures of buildings. European code (Clarke, 1996) and Italian code (CNR DT-205, 2007) have drafted few guidelines of FRP beams for predicting the critical local and lateral-torsional buckling load of beams. However, no design recommendations are available with regard to FRP I-beams with different stiffening elements such as stiffeners, cover plates, carbon layer, etc. A lot of research has been conducted on strengthening of steel and concrete beams with CFRP laminates (Miller, 2001; Hollaway and Cadei, 2002; Ahmed, 2004), but the failure characteristics of FRP beams with stiffening elements have not been presented in detail. In order to assist the engineers for using FRP beams in civil engineering applications, it is necessary to evaluate the response of FRP beams with different stiffening elements. Without stiffening elements, failure of web-flange junction is a major problem in FRP I-beams under concentrated load.

It is manifested from available literature that stiffening elements can increase the failure load of the FRP I-sections. But the detailed study on the effect of type of connections of stiffening elements such as bonded or bolted on the flexural behavior of FRP I-sections is missing. Alongwith, the effect of addition of stiffening elements on the flexural response of low length-to-depth ratios (L/d) of beams is also lacking in the literature. For beams having low L/d ratios, shear deformation is predominant and shear stresses in web panels are also high. Therefore, holes of bolted connection of stiffeners increase the chances of the failure of beam. Hence, to examine the behavior of FRP beams using theoretical or numerical analyses, it is important to assess the response of FRP beams with different stiffening elements for different L/d ratios.

In this chapter, the effect of type and stacking sequence of fabrics on the crushing strength of web panel of I-sections for different L/d ratios is reported. Detailed investigation is performed to study the effectiveness of each stiffening element in enhancing the strength and stiffness of the FRP I-beams. Based on the strength, stiffness and failure modes of beams obtained from three-point bending tests, size, shape and type of stiffening elements are recommended to prevent the local failure of the beam such as delamination of layers of fibers at web-flange junction. Fabrication and testing of FRP castellated I-beams is also presented in this chapter. The flexural response obtained from the experimental investigation will be used to check the accuracy of analytical and numerical models presented in the preceding chapters of this thesis.

4.2 Description of specimens

In this chapter, the flexural behavior of stiffened and unstiffened beams is presented. Beams are stiffened with different types of stiffening elements such as cover plate, cover angle, web plate, bearing stiffeners and carbon fiber layers. The specimen ID of stiffened and unstiffened beams is described in Table 4.1. The first numeric term of each specimen ID represents the L/d ratio and the first letter in each specimen ID such as ‘A’, ‘B’ or ‘C’ represent the type of beam, i.e., ‘PULT-A’, ‘PULT-B’ and ‘PULT-C’, respectively. Latter letters represent, whether the beam is provided with stiffening element or not. The specimen IDs having letters ‘BP’ after the numeric term, it represents beam is provided with bearing plate only. Moreover, the specimens IDs having letters ‘TS’, ‘AS’, ‘CA’, ‘CP’, ‘WP’ or ‘CL’ after numeric term, denotes beam is loaded by bearing plate and have stiffening element T-shaped stiffener, angle shaped stiffener, cover angle, cover plate, web plate or carbon layer at the mid-span under the loading, respectively. If the bearing stiffeners are also provided at supports then the specimen ID consists of suffix ‘AS’ at the end of the ID. The suffix AS stands for angle shaped bearing stiffener. In this study, majority of specimens are connected by bolts and adhesive (epoxy + hardener), while few specimens are connected by bolts only. In order to give short specimen ID, stiffeners which are connected by bolts only have letter ‘B’ in their specimen IDs, while the letter ‘B’ is missing in specimen IDs in which stiffeners are connected by bolts and adhesive. Similarly, majority of specimens have short stiffeners, therefore specimens having full depth bearing stiffeners have letter ‘F’ in their specimen ID and this letter ‘F’ is missing in specimen’s ID in which short stiffeners are provided.

Table 4.1 Description of the specimens.

Specimen ID	**L/d ratio**	**Length of bearing plate at midspan* (mm)**	**Stiffening element at midspan**	**Stiffening element at supports**	**Type of connection**
3B-BP125	3	125	No	No	No connection
3C-BP125	3	125	No	No	No connection
5B-BP125	5	125	No	No	No connection
5C-BP125	5	125	No	No	No connection
7A-BP40	7	40	No	No	No connection
7B-BP40	7	40	No	No	No connection
7C-BP40	7	40	No	No	No connection
7B-BP125	7	125	No	No	No connection
7C-BP125	7	125	No	No	No connection

7A-TS-F-B♣	7	40	T-shaped bearing stiffener (BS)	No	Bolted connection only
7A-AS-F-B	7	40	Angle shaped BS	No	Bolted connection only
7B-TS-F-B	7	125	T-shaped BS	No	Bolted connection only
7C-TS-F-B	7	125	T-shaped BS	No	Bolted connection only
7B-TS-F	7	125	T-shaped BS	No	Bolted and adhesive connection
7C-TS-F	7	125	T-shaped BS	No	Bolted and adhesive connection
3B-TS-AS	3	125	T-shaped BS	Angle shaped BS	Bolted and adhesive connection
3C-TS-AS	3	125	T-shaped BS	Angle shaped BS	Bolted and adhesive connection
5B-TS-AS	5	125	T-shaped BS	Angle shaped BS	Bolted and adhesive connection
5C-TS-AS	5	125	T-shaped BS	Angle shaped BS	Bolted and adhesive connection
7B-TS-AS-F	7	125	T-shaped BS	Angle shaped BS	Bolted and adhesive connection
7C-TS-AS-F	7	125	T-shaped BS	Angle shaped BS	Bolted and adhesive connection
7B-TS-AS	7	125	T-shaped BS	Angle shaped BS	Bolted and adhesive connection
7C-TS-AS	7	125	T-shaped BS	Angle shaped BS	Bolted and adhesive connection
7C-CP	7	125	Cover plate	No	Bolted and adhesive connection
7C-WP-AS	7	125	Web plate	Angle shaped BS	Bolted and adhesive connection
7C-CA-AS	7	125	Cover angle	Angle shaped BS	Bolted and adhesive connection
7C-CL-AS	7	125	Carbon layer	Angle shaped BS	Bolted and adhesive connection
7HEX-45-BP♠	7	125	Splice plate	No	Bolted and adhesive connection
7HEX-60-BP♥	7	125	Splice plate	No	Bolted and adhesive connection

♣ ‘F’ denotes the full depth stiffener and ‘B’ denotes the bolted connection.

*All beams have bearing plate of size 50 x 50 x 6.5 mm (length x width x thickness) over supports, where length of bearing plate is along the length of the beam.

♠Castellated beams have hexagonal (HEX) opening edge 45^{o} w.r.t. to longitudinal axis of beam and ‘BP’ is bearing plate

♥Castellated beams have hexagonal (HEX) opening edge 60^{o} w.r.t. to longitudinal axis of beam and ‘BP’ is bearing plate

4.3 Experimental setup

FRP I-beams were tested in 3-point loading under displacement control mode with a displacement rate of 0.05 mm/sec. Beams were tested with simply supported boundary conditions and load was applied at mid-span of the beam. Fig. 4.1 shows the complete experimental test set-up of 3-point bending test of GFRP I-beam. The ends of beam were provided with torsional supports (see Fig. 4.1) to resist the translation in transverse directions and rotation about the longitudinal axis. Loading was continued till the complete failure of beams. In this study, one beam is tested for each category of beams stiffened with stiffening elements. Linear voltage displacement transducer (LVDTs) were installed to measure the lateral as well as vertical deflections of the beam. Lateral deflection (out-of-plane) was measured at the mid-span on compression flange and vertical deflection was measured at mid-span under the tension flange.

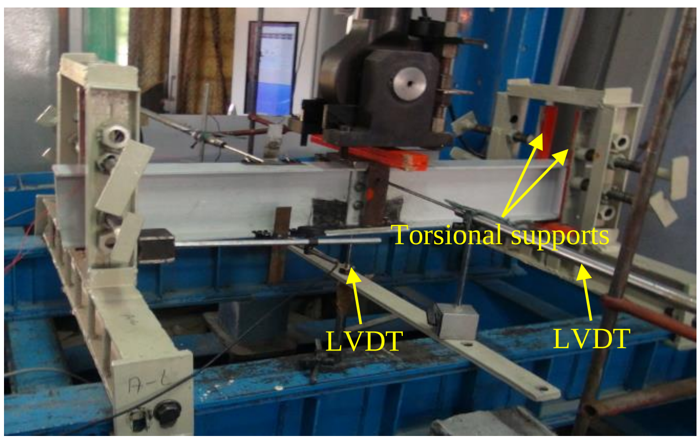
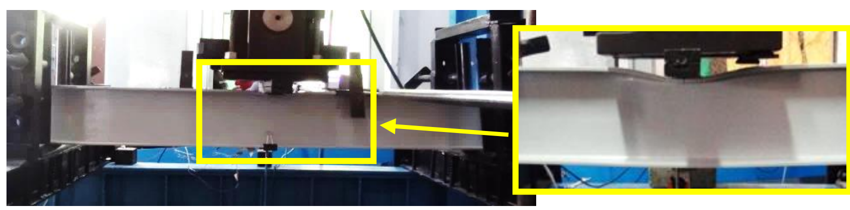


Fig. 4.1. Experimental set-up for 3-point bending test of GFRP I-beam.

4.4 Behavior of FRP I-beam under flexural loading

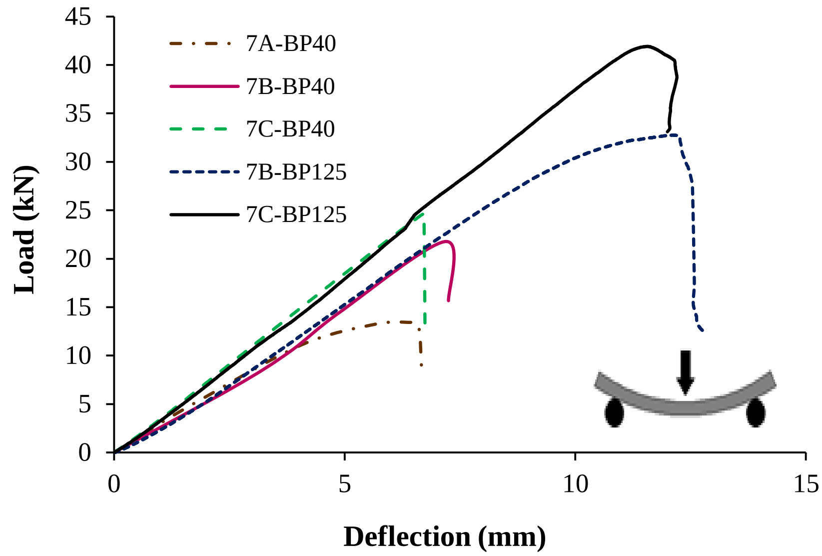
Bearing plate (BP) was positioned at top flange under the loading at the mid-span of the beam to distribute the load over the larger portion of the flange. Steel bearing plates were provided under the actuator (load) and over the supports. In this study, beams were tested with BP of sizes 40 x 75 x 35 mm and 125 x 75 x15 mm (length x width x thickness) and represented by BP40 and BP125, respectively. Length of the bearing plate was along the length of the beam and width was along the width of the beam. Deformed shape of beams with different sizes of bearing plate is shown in Fig. 4.2. During testing, it was observed that bearing plates did not deform under the loading, but the length of the bearing plate effected the failure load of the beams. In each test, cracking sound was heard due to crushing of the web. The crushing of web propagated along the depth of beam with the application of load. As the test proceeded, crushing of web was noticed. Failure load of the beam can be increased by stiffening the web-flange junction. Hence, full strength of the beam can be utilized only if the crushing of web panel of beam is prevented. The comparison of load-deflection responses of PULT-B and PULT-C beams with beam PULT-A having imperfection is shown in Fig. 4.3. It is observed that after removing the geometric imperfection in beams, slope of load-deflection curve of 7B-BP40 beam obtained is higher than that of 7A-BP40 beam. During testing of beams, lateral deflection was observed in beams having imperfection in the geometry (Fig. 4.3(b)), while the beams without imperfection lateral deflection was absent. It is worth noting that stiffness of the beam increases after removing imperfection from beams. It is also observed that length of bearing plate has greater influence on failure load of the junction of the FRP I-beam. Crushing strength of beam increases with increase in the length of bearing plate. Moreover, crushing strength of modified beams (7C-BP40 and 7C-BP125) is also higher than that of beam without imperfection (7B-BP40 and 7B-BP125), it is due to the addition of uni-directional roving in 45° and 90° to the longitudinal axis. In both beams, the width of the bearing plate is same, i.e., 75 mm but the thickness and length is different. The bending stiffness of the bearing plate is much higher than that of FRP beams, therefore while bending of beam, bearing plate was un-deformed. Hence, crushing strength of the beam depends on the length of the bearing plate, i.e., distribution of load on the length of beam. From Fig. 4.3, it is noted that the crushing strength of the beam with length of bearing plate 125 mm is higher than that of 40 mm, therefore further study is conducted on the beams with bearing plate of length 125 mm (BP125).



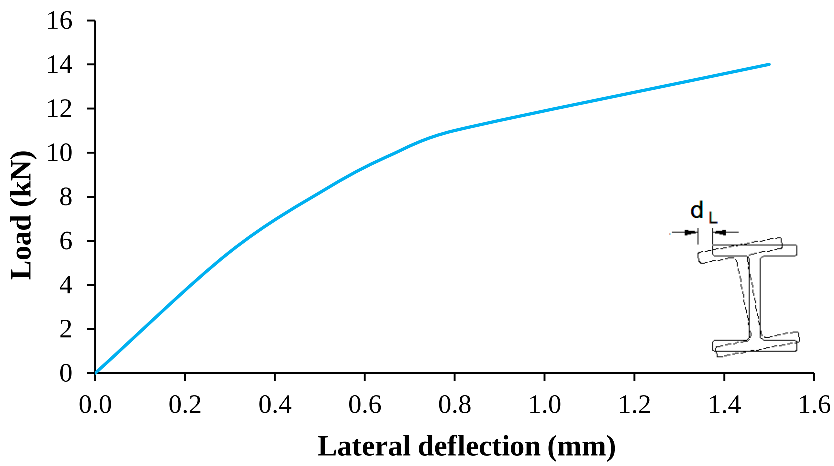
(a) Bearing plate of length 40 mm (7C-BP40)

(b) Bearing plate of length 125 mm (7C-BP125).

Fig. 4.2. Deformation of the beams under different lengths of bearing plates.



(a) Load vs vertical deflection



(b) Load vs lateral deflection of the beam PULT-A

Fig. 4.3. Flexural responses of beams with different lengths of bearing plates.

4.5 Effect of different stiffening elements

I-sections fail by local failure of flanges and web under highly stressed region. Web area of I-section over supports and under concentrated loads behaves like a short column. Therefore, when the compressive stress produced from reaction or concentrated load is higher than the compressive strength of the web, this leads to the failure at the web-flange junction. This phenomenon is called crushing of web. The high stressed region of the beam can be strengthened with stiffening elements to avoid the failure of web-flange junction. The local failure of the joint can be prevented by various strengthening techniques such as

1. Installing the bearing stiffener under the loading
2. Addition of cover plate
3. Increasing the thickness of web
4. Installation of cover angle under the loading

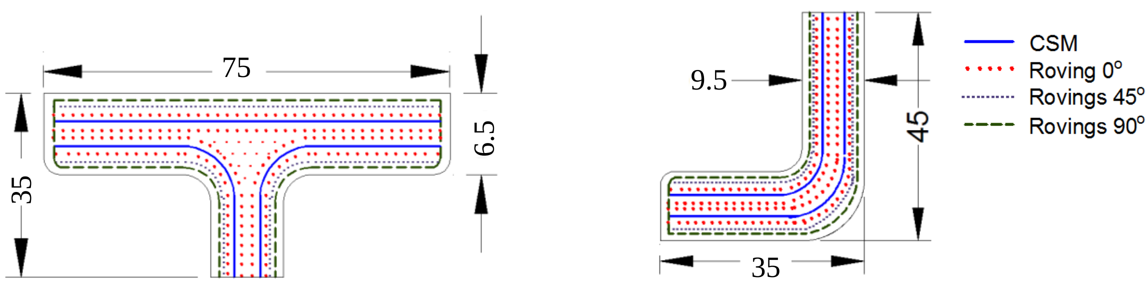
In all these methods, objective is to keep the bearing stress under the permissible limit which can be done by spreading the load over the larger area or transfer the stresses from the flange and web-flange junction to the web of beam, by providing longitudinal and/or vertical stiffeners. A very few studies have been conducted on FRP beams with these stiffening elements. Borowicz and Bank (2011) have performed the flexural study of FRP beams with different stiffening elements such as web plates, angles and bearing stiffeners. In the present study, firstly the strength and failure modes are predicted for beams having L/d ratio of 7 and strengthened in week zone with carbon layer, bearing stiffeners, cover plate, web plate, and cover angles. Based on the strength and failure mode of beams, a pioneering technique is determined, i.e., short bearing stiffener and its performance is predicted in beams having L/d ratios 3 and 5. In this study, stiffeners except carbon fiber layers were connected to web or flange of I-beam by using mild steel bolts of diameter 8 mm. The vertical spacing between the bolts is decided in such a way that the top horizontal row of bolts is at maximum distance away from the compression web-flange junction and vertical spacing between the bolts allows the tightening of bolts using wrench. The bottom horizontal row of bolts is symmetrical to the top horizontal row about the centroidal axis of the stiffening elements. Material properties of each stiffening elements are given in Table 3.9 (Chapter 3). The detailed discussion on experimental investigation of the flexural behavior of FRP I-beams with different stiffening elements is made in the following sections.

4.5.1 Beam with bearing stiffeners

In the previous section, it is observed that web gets crushed under the bearing plate as well as the joint of flange and web also fails due to high shear stress. Therefore, in order to resist the failure under the loading, stiffener must be provided under flange at the section of high stress concentration. T-shaped stiffeners (TS) were bolted over the web and the length of stiffeners was kept equal to the clear distance between the top and bottom flange of the beam. Failure mode of the beam was the rupture of fiber layers at web-flange junction under the loading. This failure is due to the gap between the stiffener and top flange, therefore load was not uniformly distributed over the stiffeners. During testing, initially flange deformed little under the gap, then one stiffener failed from its web-flange junction as shown in Fig. 4.4. The dimensions and layup of the TS stiffener is shown in Fig. 4.5. The T-shaped stiffener was formed by cutting a T-shaped from the web and flange portion of specimen PULT-C. The load vs deflection curves of beams with bearing stiffener under the loading is depicted in the Fig. 4.6. It is observed that the flexural stiffness of the beam PULT-A with T-shaped stiffener bearing stiffener (7A-TS-F-B) is higher than the beam with angle shaped stiffener (7A-AS-F-B). Since the beams had imperfection in the geometry, therefore increased in the failure strength of beams with stiffeners was not significant. The beam without imperfection, i.e., 7B-TS-F-B beam has high flexural stiffness and strength than 7A-TS-F-B and 7A-AS-F-B beams. But the purpose of providing the stiffener was not fulfilled in 7B-TS-F-B beam, because the beam failed by local failure of compression flange over the stiffener due to gap between stiffener and fillet of web-flange junction. Figure 4.6(b) shows that even though beams having imperfection are stiffened with bearing stiffener, still beams deflected laterally. In the beam 7B-TS-F-B, lateral deflection was not observed.

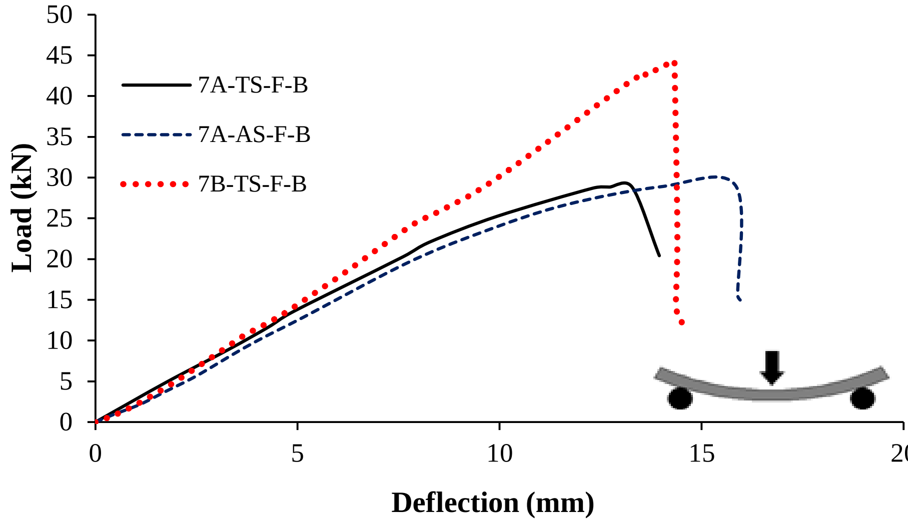
(a) Crushing flange (b) Failure of stiffener

Fig. 4.4. Failure mode of FRP I-beam (7B-TS-F-B beam) with T-shaped stiffener.

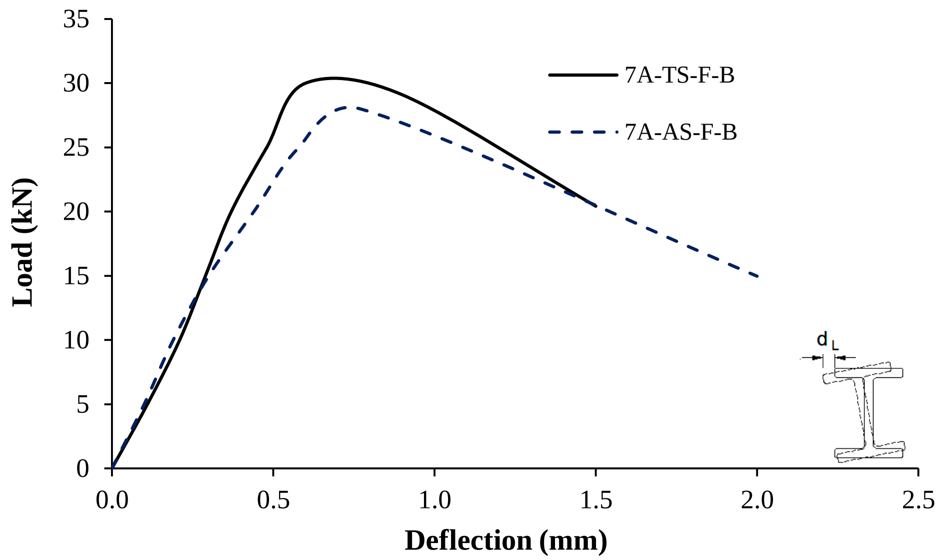


(a) T-shaped (TS) (b) Angle shaped (AS)

Fig. 4.5. Dimensions and layup of stiffeners.



(a) Vertical deflection



(b) Lateral deflection

Fig. 4.6. Load vs deflection responses of the beams with and without imperfection.

Further, in another beam the gap between the edge of stiffener and fillet of web-flange junction was filled with adhesive. The adhesive was made by mixing epoxy and hardener in proportion of 9:1 by the weight. Epoxy of grade ‘Resin 781’ and hardener of grade ‘Reactive Polyamide 67’ was used for making the paste. The surface of stiffeners and beam was made rough using sand paper for proper bonding of the stiffener with beam. Beams in which stiffeners were connected with bolts and adhesive failed by failure of the web-flange junction over the supports as shown in Fig. 4.7. After testing of beams, cracks were not seen at the junction of compression flange and web (see Fig. 4.7). It is due to the addition of adhesive in gap between stiffener and flange, therefore load is transferred fully from the flange to stiffener and web of I-beam, but beam failed over supports due to absence of bearing stiffeners. Even though, bearing plates were placed over the supports but beams failed due to high stress concentration at web-flange junction of the beam produced from bearing plate. Therefore, bearing stiffener is also necessary at support to resist the failure of joint. The responses of beam with and without adhesive, and bearing stiffener over the supports is shown in Fig. 4.8. It is noted that with addition of bearing stiffeners over the supports the flexural strength of the beam increases but the flexural modulus is unaffected.

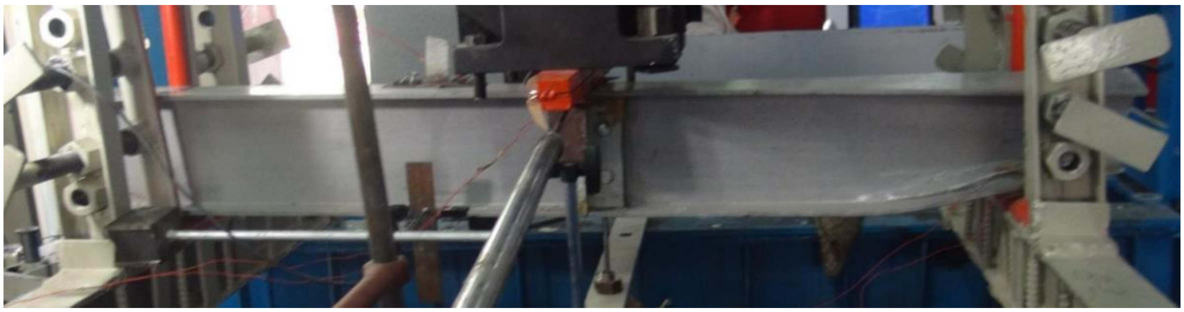


Fig. 4.7. Failure mode of the beam with bonded and bolted stiffener under three-point loading (7B-TS-F).

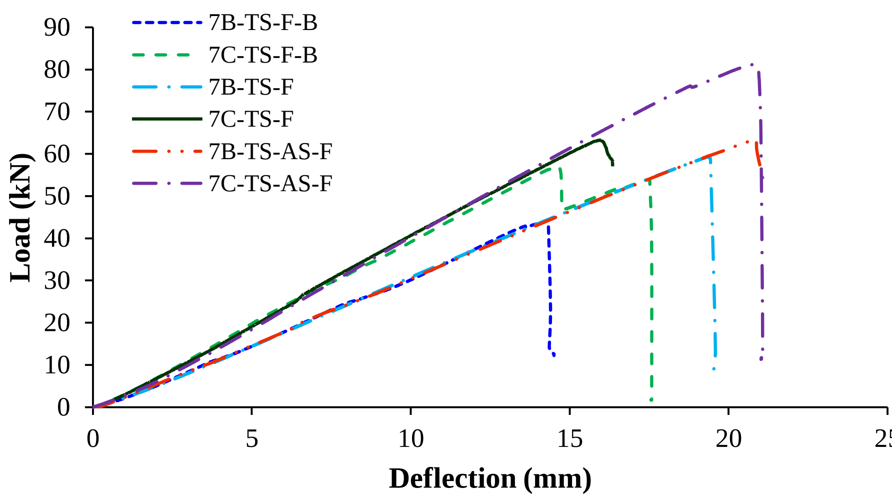


Fig. 4.8. Load vs deflection responses of beams with bonded and bolted connection.

In the further study, the effect of the addition of bearing stiffeners on the web-flange junction of the beam over the supports is investigated. T-shaped stiffeners were connected on web under the loading and angle shaped stiffeners were connected over the web at the location of supports using the adhesive and bolts. Failure mode of the beam with stiffeners under loading and over supports is shown in Figs. 4.9(a) and 4.9(b). During testing of beam 7B-TS-AS-F, first crack was seen at web-flange junction under the load and propagated towards the ends of the beam; another crack produced at the vicinity of bottom web-flange junction over the support and travelled towards the mid-span of the beam. Similarly, in 7C-TS-AS-F beam, initially crack was appeared at the support and further propagated towards the mid-span of the beam. Failure of both beams was very sudden and produced a sound similar to gunshot. The failure mode of the beams with bearing stiffener under the loading and over supports was delamination failure of web-flange junction as shown in the Figs. 4.9(a) and 4.9(b). The failure of web-flange junction under the load bearing stiffener is due to the transfer of stresses from the stiffener to junction of web-flange (in tension side) which leads to the delamination.

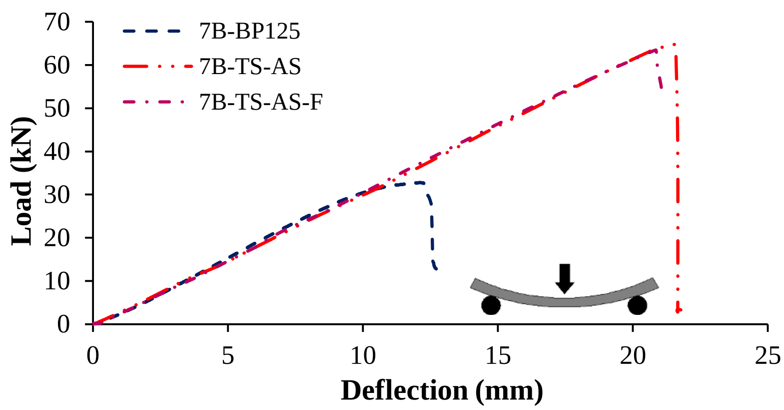
(a) T-shaped load bearing stiffener (7C-TS-AS-F beam)

(b) Angle shaped load bearing stiffener (7C-AS-AS-F beam)

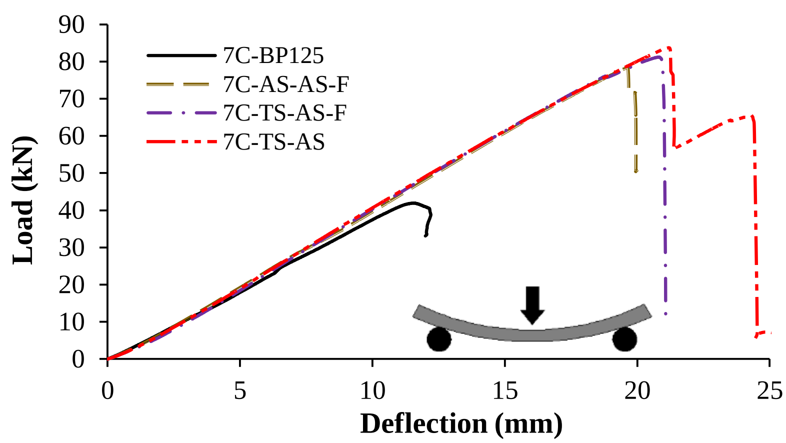
(c) Beam with short stiffeners (7C-TS-AS beam)

Fig. 4.9. Failure mode of the beams having bearing stiffeners under the loading and over supports.

In another beam, short stiffeners were provided, i.e., length of stiffener lesser than the clear distance between the top and bottom flange. The length of stiffener provided was 112 mm, which is 25 mm lesser than the distance between the flanges. A gap of 25 mm was left between the stiffener and tension flange as shown in Fig. 4.9(c). This beam is represented by 7C-TS-AS and the mode of failure of beam was crushing of web due to diagonal bearing stress produced from the bearing plate (see Fig. 4.9(c)). After crushing, delamination between the layers took place which leads to local crippling of flange under the bearing plate. This shows that stiffeners effectively transfer the load from flange to the web, without crushing the web-flange junction. Borowicz and Bank (2013) also investigated the flexural behavior of the FRP I-section beams with bearing stiffeners. They have discovered the 'V' shaped wedge type failure of web-flange junction. From this study, it is concluded that wedge type failure in FRP beams can be prevented by providing the short bearing stiffeners. The load vs deflection curves of beams with full depth and short stiffeners are depicted in Fig. 4.10. The increase in the ultimate load of the 7C-TS-AS beam w.r.t. 7C-TS-AS-F and 7C-AS-AS-F beams is 3% and 7%, respectively. Based on the above study, it is concluded that short T-shaped bearing stiffener is better than angle-shaped bearing stiffener (AS) under the loading and angle shaped short bearing stiffener is also required on beams at supports. The space between stiffener and flange or joint of flange-web, should be filled with adhesive for uniform distribution of load from flange to stiffener. Further the failure strength of the beams can be enhanced by increasing the thickness of web.



(a) Beam PULT-B



(b) Beam PULT-C

Fig. 4.10. Load vs deflection curves of beams with different sizes of stiffener.

4.5.2 Addition of cover plate

In this section, effect of addition of FRP cover plate on flexural strength of FRP I-beam (PULT-C) is studied. Sizes of FRP cover plate were 175 x 75 x 9.5 mm (length x width x thickness), where length and width of the plate is along the length and width of the beam, respectively. The layup of the plate was similar to the angle shape bearing stiffener as given in the Fig. 4.5(b). Beam was loaded by bearing plate over cover plate. The role of bearing plate was to distribute the load over larger area and cover plate provides the flexural and local crippling strength to compression flange. Cover plate was attached to the flange with mild steel bolt of 8 mm diameter. Mode of failure of beam under flexural loading was crushing of web (see Fig. 4.11). Response of the beam with cover and bearing plate under bending is illustrated in Fig. 4.12. It is noted that flexural strength and stiffness of the beam with cover plate is higher than beam without cover plate (7C-BP125). As expected, crushing of the web occurred like in beam with bearing plate only (7C-BP125) but failure load of 7C-CP beam w.r.t. 7C-BP125 beam is higher, i.e., 14%.

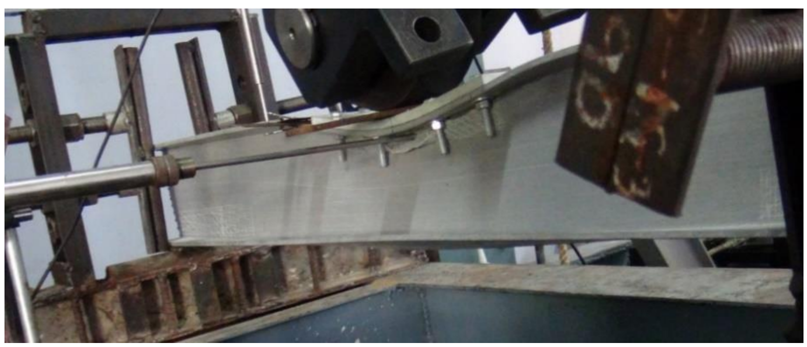


Fig. 4.11. Flexural behavior of the FRP I-beam with cover plate (7C-CP beam).

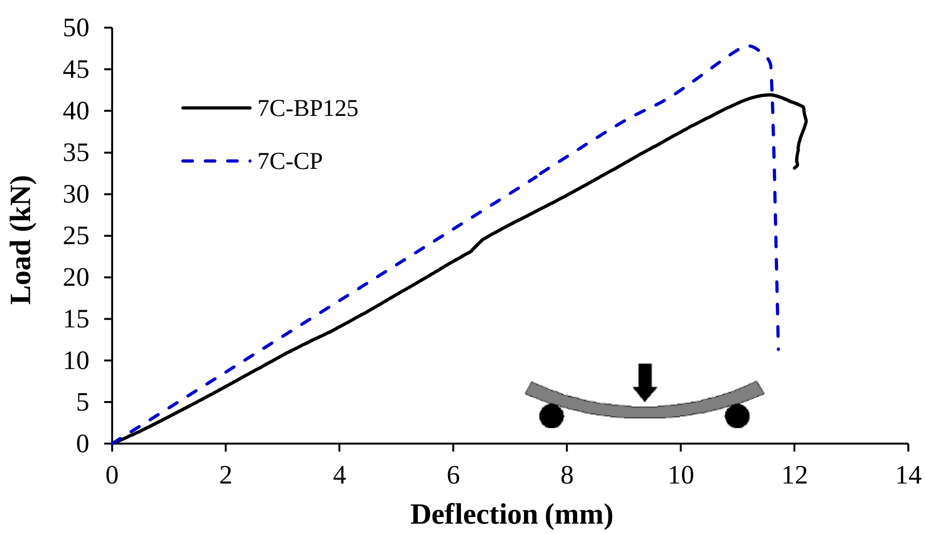


Fig. 4.12. Load vs deflection responses of beams with and without cover plate.

4.5.3 Increasing the thickness of web

In this section, FRP plates were provided on both sides of web under the web-flange junction below loading. The objective of providing the FRP plates was to strengthen the weaker zone, i.e., web-flange junction. Sizes of web plate were 125 x 137 x 9.5 mm (length x width x thickness), where length of plate was along the length of the beam and width of the plate was along the depth of the beam. The layup of the web plate was similar to the angle shape bearing stiffener as given in the Fig. 4.5(b). Length of the plate was kept more than the length of bearing plate, so as to resist the failure due to bearing stress. FRP plates were connected on both sides of web with bolts and adhesive. The space left due to fillet (web-flange junction) between the compression flange and the plate was filled with adhesive (see Fig. 4.13) for uniform distribution of the load from flange to web plate. Fig. 4.14 shows the comparison of load-deflection responses of the beams with and without FRP web plates. With the addition of FRP plates, there is little increase in the flexural stiffness of the beam w.r.t. the beam with bearing plate, but the enhancement of flexural strength is significantly high, i.e., 58%. Under the flexural loading, beam failed due to crushing of web at the end of web plate. After crushing sudden drop in load was observed and delamination at compression flange was noticed in experimental test. Fig. 4.13 provides the view of local failure of flange alongwith delamination in the compression flange and Fig. 4.14 shows that beam with web plate experienced a brittle failure with sudden loss in load carrying capacity without giving any warning.

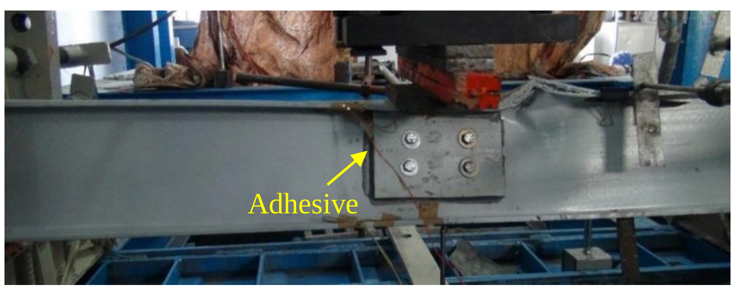


Fig. 4.13. Local failure of the compression flange of beam stiffened with FRP web plate. (7C-WP-AS beam)

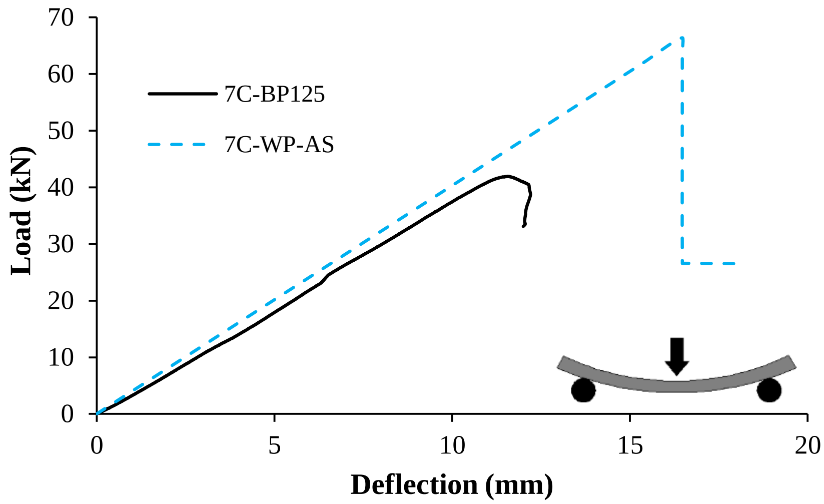
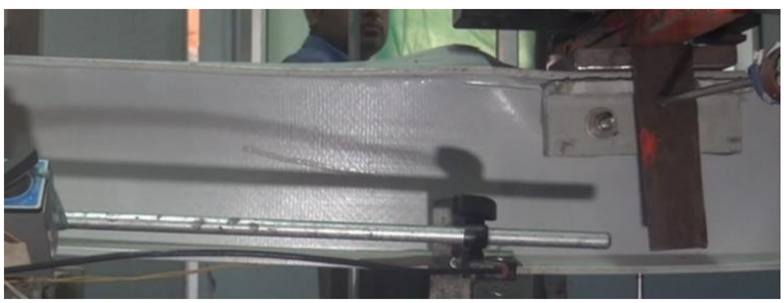


Fig. 4.14. Load vs deflection responses of beams with and without web plate.

4.5.4 Installation of cover angles under the loading

Cover angles at web-flange junction enhances the strength of joint as well as increases the flexural stiffness of I-beams without increasing the height of beam. Like glass fiber reinforced polymer (GFRP) cover angles, high stiff layers of fibers such as carbon fiber layer can also be placed at joint to increase the ultimate load carrying capacity of the beam. The major advantage of using carbon layers instead of GFRP cover angle is the reduction in the weight of beam as well as required strength can be achieved by placing layers in a specific direction. In this study, two layers of carbon fibers (0/90) were provided on each side of web-flange junction under the loading as shown in Fig. 4.15(a). Carbon fiber layer having orientation 0^o (along the length of the beam) was laid first under the compression flange and over web; then second layer was placed in 90^o. After casting, a polythene sheet was placed over the fiber layers and light loads were kept on that sheet for compression. Loads and polythene sheet was removed after 24 hours and other side of the beam was strengthened with same process. The role of 90^o layer is to enhance the crippling strength at junction, while the 0^o layer uniformly distributed the load on each fiber of 90^o layer. Properties of carbon fiber layers is given in Table 3.9 (Chapter 3). Length of layers was kept more than the length of bearing plate. Another beam was strengthened under the web-flange joint with cover angle of length equal to the length of vertical bearing stiffener. The layup of the cover angle is shown in the Fig. 4.15(b). From the three-point bending test, it is observed that beam strengthened with cover angle (7C-CA-AS) failed due to the delamination of fiber layers of compression flange. This failure is due to stress concentration produced from the change in geometry of the cross-section of the beam, i.e., at the end of the cover angle. While this failure mode is missing in the beam with carbon layer (7C-CL-AS), because the length of carbon fiber layers is higher than bearing length. The failure of 7C-CL-AS beam was due to delamination of carbon fiber layers. Failure load of 7C-CL-AS beam is 7% higher than 7C-CA-AS beam and it is 58% more than that of the beam with bearing plate (7C-BP125) only. The slope of load-deflection curve of 7C-CL-AS beam is also higher than the 7C-CA-AS beam (see Fig. 4.16), it states that beam with carbon fiber layers offers more stiffness. Moreover, the failure load of 7C-CA-AS beam is 47% higher than beam without any stiffening element, i.e., beam with bearing plate only (7C-BP125). The beam with cover angle has experienced lower ultimate load carrying capacity and stiffness than beam with carbon fiber layers, it is because bearing length produced on web by bearing plate is higher than length of cover angle. Therefore, diagonal bearing stress caused the crushing of web of I-section just after the cover angle. Even though, moment of inertia of carbon layer is half of the cover angle, but the overall stiffness and length of the carbon fiber layer is higher than that of cover angle leading to saving of material and weight of the beam.

(a) Beam with carbon fiber layers (7C-CL-AS beam)



(b) Beam with GFRP cover angle (7C-CA-AS beam)

Fig. 4.15. Deformation of the beam with cover angle under the loading.

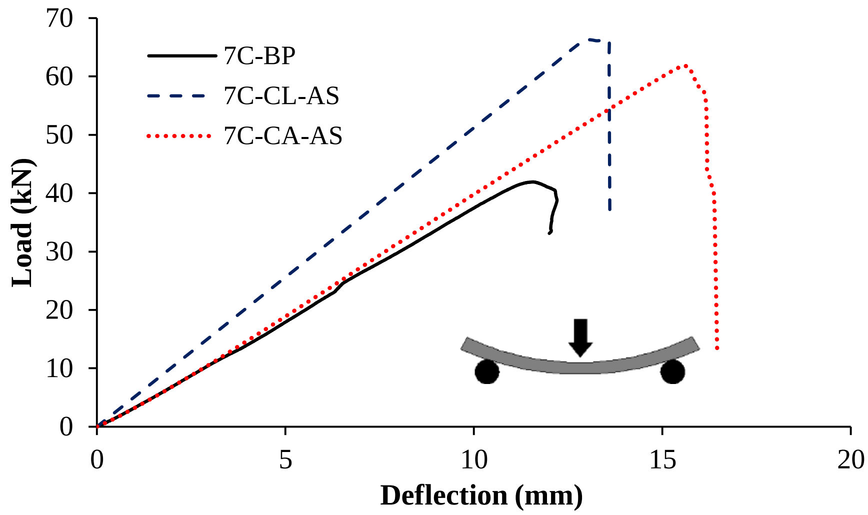


Fig. 4.16. Load vs deflection responses of beams with GFRP cover angle and carbon fiber layers.

4.6 Effect of stiffening elements for different length-to-depth ratios (L/d)

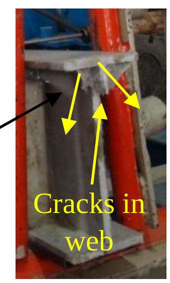
With decrease in the L/d ratio, shear deformation has predominant effect on the deformation of the beam. As it is observed from previous investigations that the short bearing stiffeners are effective in resisting the premature failure of the beam. Therefore, it is necessary to check the performance of the beam with bearing stiffener for low L/d ratio. Flexural behavior of the beams PULT-B and PULT-C having L/d ratios 3 and 5 is predicted by three-point bending test. The load vs deflection responses and failure modes of beams with and without bearing stiffeners are addressed in the following sections.

4.6.1 Beams having L/d ratio 5

Beams PULT-B and PULT-C without stiffening element and having L/d ratio 5 are represented by 5B-BP125 and 5C-BP125, respectively. Similarly, PULT-B and PULT-C beams with bearing stiffeners are represented by 5B-TS-AS and 5C-TS-AS, respectively. Fig. 4.17(a) demonstrates the failure modes of PULT-B beam with and without bearing stiffeners. From Fig. 4.17(a), it is observed that 5B-BP125 beam failed by crushing of the web which is expected, because bearing stiffener was not provided, while the beam 5B-TS-AS failed by tearing of layers of web (see Fig. 4.17(b)). Due to the bearing stress produced by bearing plate, a diagonal crack developed on the web and then travelled in longitudinal direction towards the end of the beam as shown in Fig. 4.17(c). Fig. 4.17(c) also shows that the web-flange junction is intact, but the web failed. This failure led to an immediate loss in the load carrying capacity. Fig. 4.18 depicts that with the addition of the bearing stiffener there is no increase in the stiffness of the beam, but the strength of the beam has increased by 79%. Flexural deformation of the 5C-TS-AS beam is completely different from the 5B-TS-AS beam. During testing, 5C-TS-AS beam experienced the local crushing of flange (see

Fig. 4.19) and failure of web-flange junction was not seen in this test. Same failure mode was observed in the beam having L/d ratio 7 (7C-TS-AS). The enhancement of load carrying capacity of PULT-C beam with bearing stiffener is around 95% and there is no increase in the stiffness of the beam (Fig. 4.20). In beam 5C-TS-AS, failure of tension flange-web junction is not observed due to short length bearing stiffener. Hence, it is stated that short bearing stiffeners are efficient to resist the delamination failure of tension flange-web junction in beams having L/d ratio 5.

(a) Beam 5B-BP125



(b) Beam 5B-TS-AS (c) Side view

Fig. 4.17. Flexural deformation of the beams having L/d ratio 5.

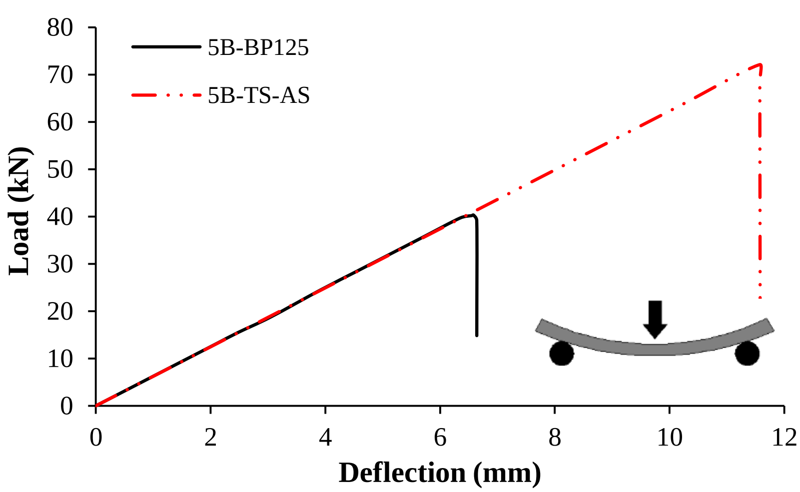


Fig. 4.18. Load vs deflection responses of PULT-B beams with and without bearing stiffener.

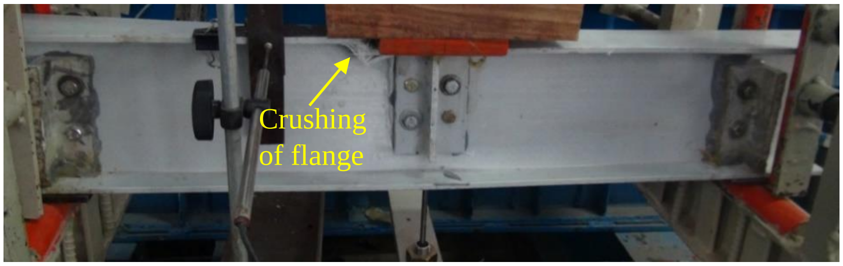


Fig. 4.19. Crushing of compression flange of the beam 5C-TS-AS under three-point bending.

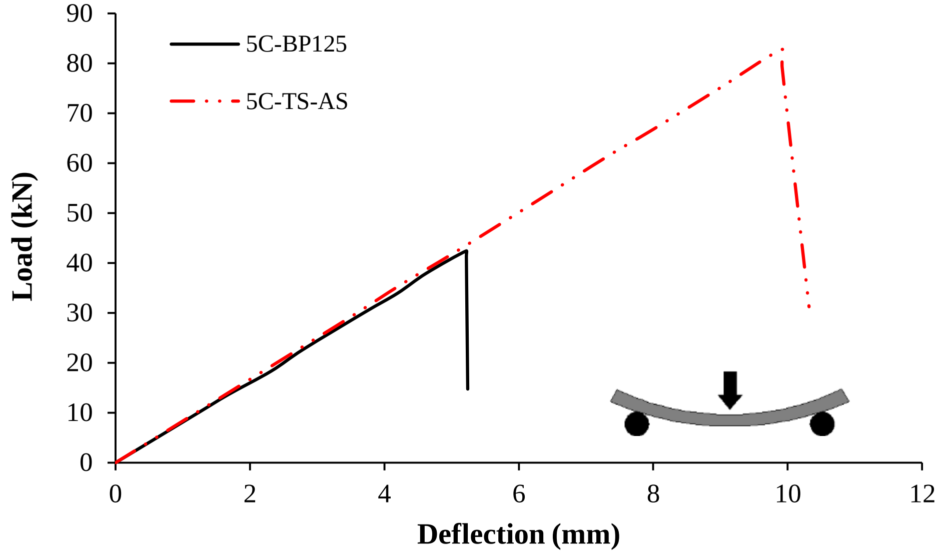
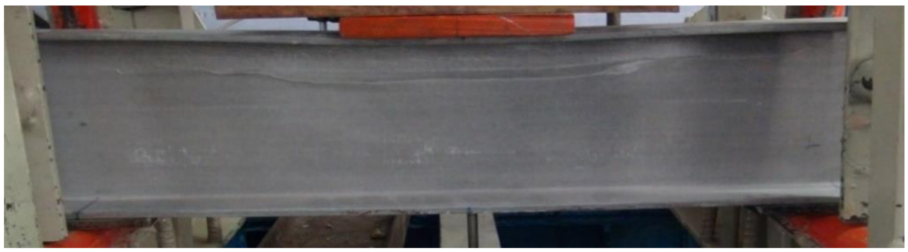


Fig. 4.20. Plot of load vs deflection responses of beams 5C-BP125 and 5C-TS-AS.

4.6.2 Beams having L/d ratio 3

Beams PULT-B and PULT-C without stiffening elements and having L/d ratio 3 is represented by 3B-BP125 and 3C-BP125, respectively. Similarly, PULT-B and PULT-C beams with bearing stiffeners is represented by 3B-TS-AS and 3C-TS-AS, respectively. Due to the absence of the bearing stiffeners, beam 3B-BP125 failed by crushing of web under flexural loading as shown in Fig. 4.21(a). Beam having bearing stiffeners (3B-TS-AS) failed due to diagonal stresses produced by bearing plate. Firstly, a diagonal crack developed, which proceeded towards the compression flange and traveled to the end of beam. Fig. 4.21(b) shows the failed cross-section of the 3B-TS-AS beam. Failure mode of the beam is the V-shaped wedge type failure. This mode of the failure is due to the low transverse strength of the panels of I-beam. The beam with bearing stiffener offers more stiffness than the beam without bearing stiffener (Fig. 4.22), while the load carrying capacity of the beam increased by 32%. The failure mode of 3C-TS-AS beam was crushing of web due to diagonal bearing stress, while the delamination of fibers of web-flange junction was not observed. After first failure, with further increment of displacement of the beam, cracks produced from the hole of bolted connection of the stiffener under loading as shown in the Fig. 4.23. In contrast to the strength gained by 3B-TS-AS beam, 3C-TS-AS beam has 85% higher strength than 3C-BP125 beam. Fig. 4.24 depicts the load vs deflection responses of 3C-BP125 and 3C-TS-AS beams. From Fig. 4.24, it is noted that there is little change in the stiffness of the beam with bearing stiffener while the gain in the strength is significantly high.



(a) Beam 3B-BP125

(b) 3B-TS-AS beams (c) side view of beam 3B-TS-AS

Fig. 4.21. Failure of beams under three-point bending test having L/d ratio 3.

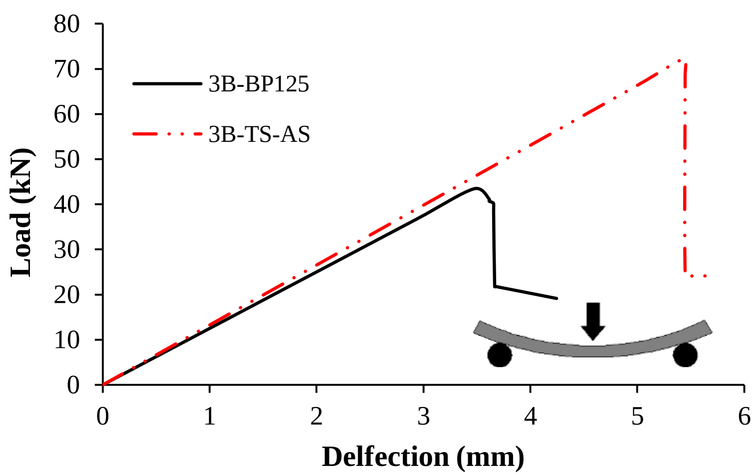
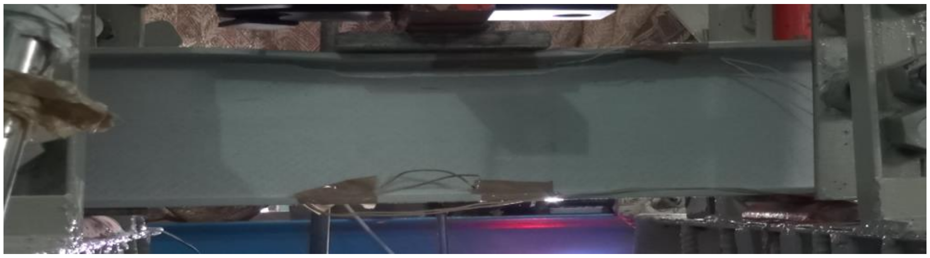
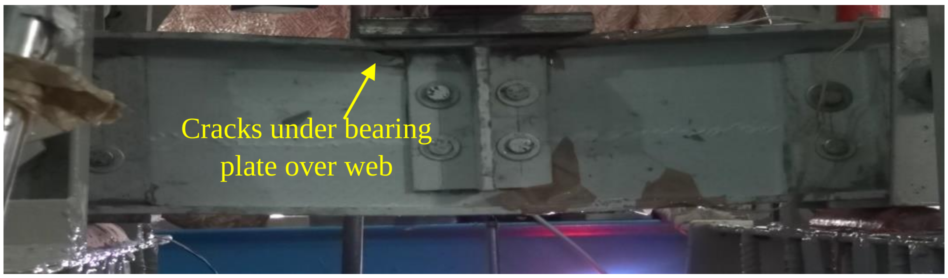


Fig. 4.22. Load vs deflection responses of the PULT-C beams with and without bearing stiffener.



(a) Beam 3C-BP125



(b) Beam 3C-TS-AS

Fig. 4.23. Flexural behavior of beams having L/d ratio 3.

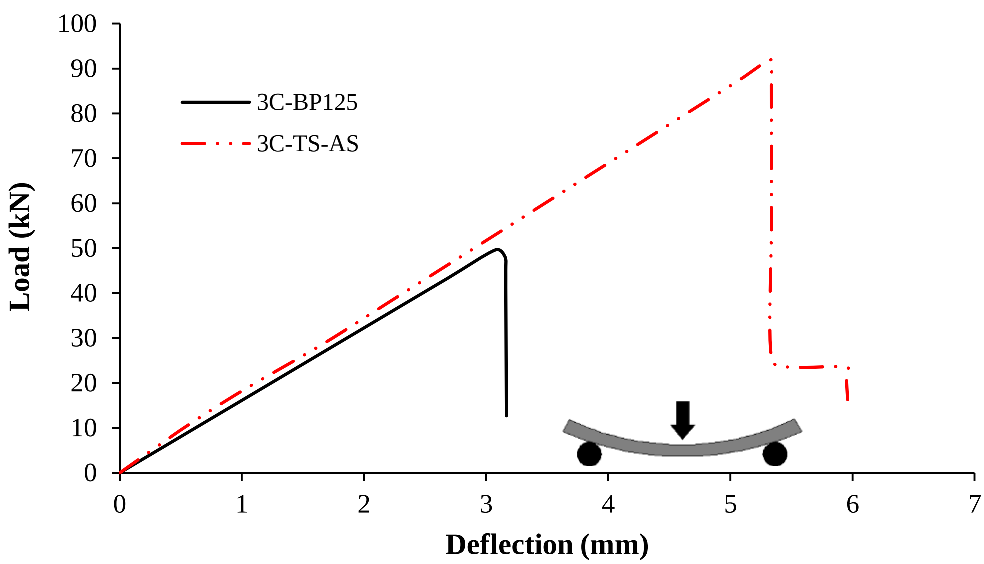


Fig. 4.24. Load vs deflection plot of the beams 'PULT-C' with and without bearing stiffener having L/d ratio 3.

4.7 Discussion

Imperfection in the cross-section of the beams increases the chances of lateral instability, i.e., lateral-torsional buckling of the beam, before reaching the full load carrying capacity of the beams. After removing the imperfection from PULT-A beams, load carrying capacity of the beam increased by 46%. The beam without imperfection (PULT-B) failed by deformation under loading, i.e., crushing of web and no lateral deflection of beam was observed. Crushing strength of the web of FRP I-section is increased by modifying the layup of the beam, i.e., replacing the chopped strand mat with unidirectional fabrics (rovings) in transverse direction to the length of beam. The increase in the failure load of the PULT-C beam having modified layup w.r.t. PULT-B beam is 12% and 20% for bearing plate of length of 40 and 125 mm, respectively. Crushing of the web is the local failure of the beam. Therefore, full load carrying capacity of the beam can be utilized only by stiffening the web-flange junction. Comparison of load-deflection responses of the PULT-C beam with different stiffening elements is presented in Fig. 4.25. It is observed (Fig. 4.25) that the beam with carbon fiber layer shows high stiffness than the beam with other stiffening elements. In addition, strength of the beam with carbon layer is lesser than beams with T-shaped bearing stiffener but higher than other stiffening elements. On the other hand, beam with cover plate has lower flexural strength than all stiffening elements but has higher stiffness than for other stiffening elements except beam with carbon fiber layers. Study of the load-deflection relationship from ductility point of view shows that beam having carbon layer (7C-CL-AS) offers little ductility due to delamination of the carbon fiber layers.

In this study, it is noted that beams stiffened with bearing stiffeners using bolted connection failed by the failure of the web-flange junction of the T-shaped bearing stiffeners due to the gap between the fillet of web-flange junction of I-beams and bearing stiffeners. On the other hand, beams stiffened using bolts and adhesive, neither the failure of stiffener nor the failure of bolts and/or interface of bolt and web of I-beams observed, because adhesive was filled in the clearance between the bolt and stiffening element and the web, as well as the gap between the fillet of web-flange junction and the stiffener. Hence, it is stated that the strengthening of beams with bearing stiffeners under loading is effective only, when it is connected with adhesive and bolted connection, otherwise stiffener may fail. Even though bearing stiffeners are provided under high stressed region, i.e., under loading, but beam still failed by delamination of the layers of the web-flange junction of the beam over the supports. Therefore, bearing stiffeners are also required at the location on the beam over supports to resist the failure of web-flange junction of I-beam. The mode of failure of the beams ($L/d = 7$) having full-length stiffener is the delamination at web-flange junction, while beams with short stiffeners failed by local crushing of web which leads to delamination of layers of compression flange near to the edge of bearing plate. Failure strength of the beam with short stiffeners can be further improved by adding carbon fiber layers at web-flange junction of I-beam. Hence, it is concluded that the short stiffeners are found to be helpful in preventing the delamination of web-flange junction (compression side) of beams PULT-B and PULT-C. Beams of PULT-B type having L/d ratio 3 and 5 (i.e., 3B-TS-AS and 5B-TS-AS beams) failed due to the bearing stress produced on web by the load bearing plate. On the other hand, 5C-TS-AS beam failed due to local failure of the compression flange and crushing of the web. The PULT-C beam has uni-directional fibers of orientation 45° to the longitudinal axis of the beam, therefore web of PULT-C beam exhibits higher strength than beam PULT-B to bear the bearing stress produced by the bearing plate. Hence longitudinal crack did not develop in the 5C-TS-AS beam as observed in 3B-TS-AS and 5B-TS-AS beams. Failure mode of the 3C-TS-AS beam is the local crushing of web under flexural loading. Hence, it is concluded that the stiffening technique incorporated in the beam 'PULT-C' is capable of resisting the failure of web-flange junction of I-beam.

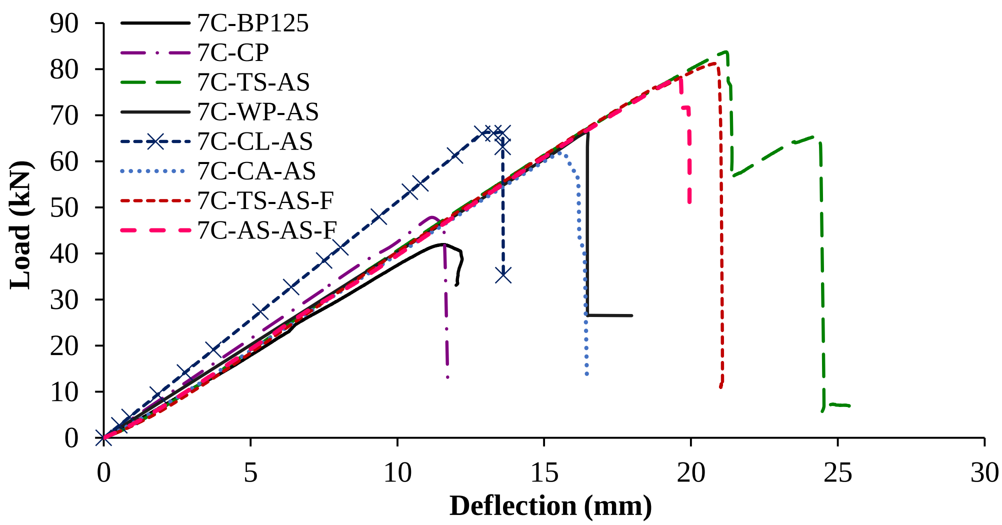


Fig. 4.25. Comparison of load vs deflection responses of beams with different stiffening elements.

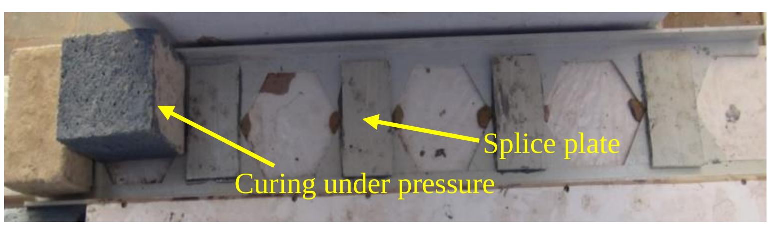
4.8. FRP castellated Beams

4.8.1 Fabrication

FRP castellated I-beam having hexagonal opening was formed by cutting the web of I-beam along the line of semi-hexagonals made along the length of the beam as shown in Fig. 4.26(a). Using a hand cutter (BOSCH GWS 600), a cut was made on the beam, which generates two T-sections. After completing the cutting process, two T-sections of original solid I-beam were then separated, shifted and placed together for connection (Fig. 4.26(b)). Like welding, here a high strength adhesive was used to connect both T-sections as depicted in Fig. 4.26(b). During curing of adhesive, T-sections were clamped together and a small pressure was applied on the web, to prevent the displacement T-sections (see Fig. 4.26(c)) during curing. After curing, FRP splice plates were connected both side on the connection of the T-sections with bolts and adhesive as shown in Fig. 4.26(c). Length of the splice plate (along the depth of beams) was equal to depth of opening and width of splice plate was equal to least distance between the edge of the openings along the longitudinal axis of the beam. Final castellated beam has hexagonal openings and higher depth than the parent beam (FRP beam from which castellated beam was made) and is depicted in Fig. 4.26(d). Due to hexagonal web holes, overall beam depth of castellated beam is higher than that of the parent beam. In particular, the depth of the parent and castellated beam is 150 and 230 mm, respectively.

(a) Cutting and separation of T-sections of the beam

(b) Assembling of the T-sections and filling the gap with adhesive



(c) Installation of splice plate over T-sections

(d) FRP castellated beam

Fig. 4.26. Fabrication process of FRP castellated beam.

4.8.2 Flexural response of castellated beams

Three-point bending test was performed to investigate the flexural response of the FRP castellated beams. Fig. 4.27 shows the deformation of castellated FRP I-beam under three-point loading. It is observed that beams failed by shear failure at the corner of the opening of compression and tension T-sections. Failure of web-flange junction was not seen in this investigation. After removing the splice plates, it was observed that epoxy used to attach both T-section was uncracked and there was no any failure of plies near the holes of splice plate. Comparison of load-deflection curves of the beams with and without openings is shown in Fig. 4.28. The beam having angle of opening edge 45^o and 60^o w.r.t. to longitudinal axis of beam is represented by 7HEX-45-BP and 7HEX-60-BP, respectively, while the parent beam without opening is represented by '7C-BP'. It is noted that castellated beams have lower service and failure loads than that of parent beam. This is attributed to the openings in the beam, opening reduces the stiffness of the beam. Premature failure, i.e., tearing of fiber layers at the corner of opening was observed. Therefore, full loading carrying capacity of the beam was not achieved. Hence, castellated beams exhibited lower strength than parent beam.

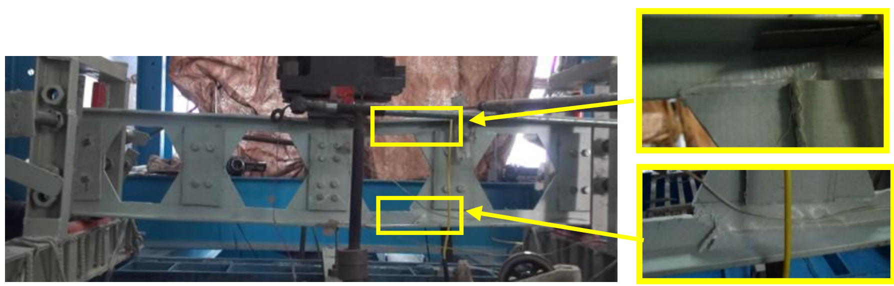


Fig. 4.27. Flexural deformation of the castellated beam under 3-point loading.

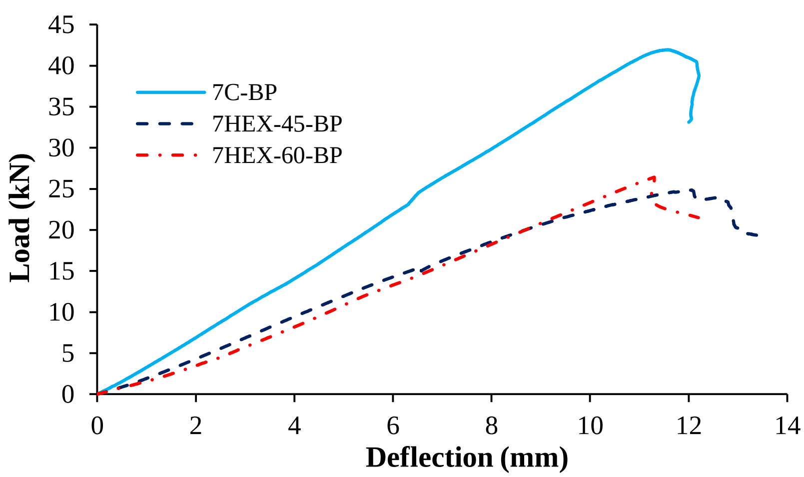


Fig. 4.28. Flexural responses of FRP castellated and parent (7C-BP) beams.

4.9 Conclusions

This chapter presents the experimental investigation on stiffened and unstiffened FRP I-beams of different layups and length-to-depth ratios. Failure modes and load carrying capacity of beam is predicted with different stiffening elements such as bearing stiffeners, cover plate and cover angle and carbon fiber layer. Fabrication and prediction of flexural responses of FRP castellated I-beams are also discussed. Based on this study, following concluding remarks can be made:

1. An FRP I-beam under flexural loading may fail by crippling of flange and crushing of web before it fails by lateral-torsional buckling. Crushing of GFRP I-beam can be prevented by installing stiffeners such as longitudinal and/or vertical stiffeners under the loading.

2. With addition of stiffening elements under the compression flange, stiffness of the beam does not increase, but the strength of the beam increases. Beams stiffened with short bearing stiffeners have higher load carrying capacity than beam stiffened with other stiffening elements.

3. Short length bearing stiffeners are more efficient than the full-length bearing stiffeners. The failure mode of beam with short bearing stiffeners is local failure (delamination) of flange and crushing of web under the edges of bearing plate.

4. Results of beams having L/d ratios 3 and 5, confirm that the short length bearing stiffeners are efficient in increasing the load carrying capacity of the beam. The layup of the beam 'PULT-C' is efficient in reducing failure of the web-flange junction with short bearing stiffeners for L/d ratios of 3 and 5.

5. Compression flange-web junction under loading is weaker portion in FRP I-beams, due to low shear and transverse compressive strength. Therefore, to enhance the strength of beam, compression flange should be strengthened with stiffening elements.

6. As expected, the strength and stiffness of castellated beam are lower than that of its parent beams. The failure mode of the castellated beams is the tearing/delamination of layers of fibers at the corner of openings.