Chapter 7
Summary and Conclusions

7.1 Summary

The aim of the present study is to study the structural response of FRP beams with and without stiffening elements and cutouts under flexural loading. FRP is resistant to corrosion when exposed to harsh weather and chemicals. Moreover, it is also nonconductive to electricity and have impact resistant. The major advantages of FRP are its high strength-to-weight and high stiffness-to-weight ratios. Even though, FRP is used in construction since three decades, there are no sufficient guidelines available for using FRP beams as a flexural member in buildings and bridges. There are few codes available on FRP beams such as American code (ASCE, 2011), European code (Clarke, 1996), Italian code (CNR DT-205, 2007), and design manuals of FRP production industries (Pultrusions, 2013). These codes discuss the buckling of FRP beams but designing of beams with stiffening elements with guidelines to resist the local failure such as tearing of web-flange junction and crippling failure of web is missing. Hence, in this study flexural behavior of stiffened and unstiffened beams is investigated. Alongwith, design guidelines of castellated I-beams are described. Improvement in the flexural behavioral characteristic of FRP beams with suitable approach was the main objective of this research work. Design charts of FRP I-beams with and without stiffening elements are made using analytical and numerical models, which can be used to design the beam as a flexural member for buildings and bridges. Futhermore, flexural study of castellated beams with different shapes and sizes of cutouts is performed, and this study is helpful to design the FRP beam for industrial structures.

In this thesis, material characterization of pultruded beams are presented. Young's and shear moduli are evaluated from experimental tests and analytical methods such as mechanics of laminated beam theory and approximate classical lamination theory. Moreover, tensile, compressive, flexural and shear strengths are determined from the experimental investigation. Flexural response of FRP I-beam of different layups, depths and length-to-depth ratios is predicted from experimental investigation. Failure modes and load carrying capacity of beam are predicted with different stiffening elements such as bearing stiffeners, cover plate, cover angle and carbon fiber layer. Moreover, fabrication and testing of FRP castellated beams under three-point loading are presented. Different equations available in Italian, European, and American society codes for determination of flexural behavior in terms of local buckling, lateral-torsional buckling and failure of web-flange junction have been presented. Further, the equations are derived for determination of loaddeflection response of the beams with different shapes and sizes of stiffeners. In addition, a failure criterion is recommended for determination of the failure load of the beam due to failure of web-flange junction.

Numerical modeling of the FRP beams with and without openings, such as castellated beams using finite element software (i.e., ABAQUS) is presented. Further, the flexural responses obtained from analytical and numerical models are validated with experimental response. After validation, a parametric study is conducted to assess the potential role of stiffening elements in enhancing the service and ultimate loads of beam. The parametric studies include the effect of length of bearing plate, material properties and sizes of stiffeners on flexural response of beams for different flange width-to-thickness ratios, depth-to-thickness ratios, and length-to-depth ratios of the beam. A parametric study is also conducted on the FRP castellated beams with different shapes and sizes of openings. The design charts for FRP stiffened beams and beams with cutouts are presented.

7.2 Conclusions

The main following concluding remarks based on the results presented in the thesis are as follows:

1. The Young's and shear moduli determined from the mechanics of laminated beam theory and approximated laminated theory are in good agreement.
2. Beams having imperfection in the compression flange deflected in lateral direction which leads to failure of the web-flange junction. Flexural stiffness and strength of beams increase with removing the imperfection from geometry of beams.
3. An FRP I-beam under flexural load may fail by crippling of flange and crushing of web before it fail 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.
4. Mode of failure of the beam changes with modification of layup of the beam. With addition of uni-directional fabrics in 0^o and 90^o, crushing strength of web as well as failure load of web-flange junction of FRP I-beam increases.
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 carbon fiber layer, cover angle, web plate or bearing stiffeners.
6. With addition of stiffening elements under the compression flange, overall stiffness of beam does not increase however the strength of the beam increases. Beams stiffened with short bearing stiffeners has higher load carrying capacity than the beam stiffened with other stiffening elements.

7. Short length bearing stiffeners are more efficient than the full-length bearing stiffeners in enhancing the failure load of beams. For beams having L/d ratio 7, the failure mode of beam with short bearing stiffeners is crushing of web and local failure of flange due to delamination of layers of flange under the edges of bearing plate.

8. Results of beams having L/d ratios of 3 and 5 verify 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 resisting the failure of the web-flange junction with short bearing stiffeners for L/d ratios of 3 and 5.

9. Formulae available in codes give significantly higher or lower failure load than that obtained from experimental investigation. Delamination failure criterion gives the failure load closer to experimental results.

10. The failure load of beams increases up to certain length of bearing plate, thereafter it becomes constant. This effect is observed in beams having different width-to-thickness ratios, effective depth-to-thickness ratios, and length-to-depth ratios. Service load increases with increase in the length of bearing plate.

11. Failure load of beams increases with increase in longitudinal-to-transverse Young’s modulus ratio (E_1/E_2), while it decreases with increase in the longitudinal Young’s modulus-to-shear modulus ratio (E_1/G_{12}) of the beams. The service load decreases with increase in E_1/E_2 and E_1/G_{12} ratio of the beams.

12. Under flexural loading, bearing stiffeners of a beam fail, if the length of bearing plate is less than the flange width of T-shaped bearing stiffener. Similarly, if length of cover angle or carbon fiber angle provided is less than the length of bearing plate, then the failure load is equivalent to the beams having bearing plate only.

13. Stiffening elements such as cover plate is not effective in enhancing the strength as demonstrated by bearing stiffeners, cover angle and carbon fiber layer, hence the failure load is equivalent to beams having bearing plate only.

14. Beams strengthened with carbon fibers or cover angle produces diagonal stresses from the ends of angles, which lead to the pre-mature local buckling of web. Hence, the failure load of beams of depth-to-thickness ratio (h_w/t) of 40 is lesser than beams having h_w/t ratio equal to 30. Carbon fiber angles are less effective than beam with cover angle having h_w/t ratio more than 21.

15. The use of stiffening elements proves to be effective in many aspects such as increasing the stability, ultimate failure, and service loads of beams.

16. The FRP castellated beam having sinusoidal openings, i.e., radius of fillet 20 mm at the corner of hexagonal openings, has higher strength than that of castellated beams with hexagonal opening. FRP castellated beams having circular openings have higher failure load but low service load than other beams having hexagonal and sinusoidal openings.

7.3 Limitations and scope of the future work

In the present study, an attempt has been made to find the detailed structural response of FRP beams with stiffening elements and cutouts. This study is limited to the flexural response of glass fiber reinforced polymer I-beams. More study could be performed on beams having high stiff carbon fibers at web-flange junction and carbon fiber reinforced polymer beams. The results of this study is limited and/or applicable to predict the flexural response, failure and strength of glass fiber reinforced polymer (GFRP) beams with and without stiffening elements and/or cutouts in particular, and FRP beams in general. There is tremendous scope for research on FRP beams to deal with issues related to web-flange junction failure and development of design equations of castellated beams.

In this regard, some of the studies which can be taken up for future investigation are as follows:

- Flexural response of functionally graded FRP beams.
- Fabrication of FRP I-beams with glass fibers in web and carbon fibers in the flanges of beams for cost effective design.
- Response and failure characterization of castellated beams with different stiffening elements and laminates.
- Study of behavior of FRP framed structures.
- Study the effect of different types of connections in beams-column frame structures.