CHAPTER 7
Summary and Conclusions

7.1 Summary

The aim of the present study is to develop and demonstrate the use of Fiber Reinforced Polymer (FRP) and Engineered Cementitious Composite (ECC) as effective and potential strengthening material for strengthening of masonry structures. Since masonry structures represent a large portion of the residential masonry building and historical monuments in the world, the strength and ductility of these brittle brick masonry structures are limited and susceptible to collapse without significant warning especially under earthquake loading situation. In recent earthquakes, it has been proved that many of these structures are highly vulnerable and as a result, there is a serious need for proposing appropriate retrofitting techniques for existing masonry structures. The conventional retrofitting/strengthening patterns are not showing durable performance and long life. Usage of FRP bars/fabrics and ECC sheets have shown the satisfactory results to give maximum strength along with high ductility and durable structures with little maintenance requirements. The overall investigation is based on the material characterizations of strengthening materials and its applications on the strengthening of masonry elements such as beams and walls.

This thesis focuses on the flexural behavior of the unstrengthened and strengthened masonry walls. Improvement in this behavioral characteristic by ductile strengthening materials (ECC) with suitable approach was the main objective of this research work.

In Chapter 3, the stress-strain characteristics and modulus of burnt clay and concrete bricks masonry have been presented. The mechanical properties such as compressive strength, tensile strength, and flexural strength of ECC made up of PVA and polyester fibers are presented. Further, the tensile properties of FRP sheet and bars used for strengthening purpose have been investigated.

In the first part of Chapter 4, the experimental investigations have been carried out for the flexural response of masonry beams strengthened in flexure and shear by bonding FRP sheets at soffit and U-wrapping, respectively. Flexural capacity, deformation, and crack patterns of tested control masonry beams and strengthened masonry beams are compared and discussed. Moreover, the effectiveness of types of CFRP bars (pultruded and hand-layup) on the flexural strength of masonry beams are discussed based on experimental results. In the second part, the effectiveness of precast ECC sheets for strengthening of masonry beams by bonding them on tension face as well as both on tension and compression faces like a sandwich beam have been presented. Two types of bonding materials i.e., epoxy and cement mortar for bonding the ECC sheets with masonry beam have been used. Four-point loading test was performed to evaluate the flexural behavior of the beam specimens.

The fifth Chapter investigates the flexural response of strengthened masonry walls with and without opening. These masonry walls were externally strengthened with different layers of NSM FRP strips and ECC sheets. The opening was provided in ECC strengthened masonry walls at the center with the opening ratio of 11.02%. The flexural response of these masonry walls was investigated using four-point static loading test.

Numerical modelling to simulate the flexural behavior of the ECC strengthened masonry beams and masonry walls with and without opening are presented in Chapter 6. A nonlinear finite element macro-modelling approach has been developed for parametric study which integrates the various parameters such as thickness of ECC sheet, width, length and opening size of the masonry walls. Further, the design charts for ECC strengthened masonry walls have been developed.

7.2 Conclusions

7.2.1 Material characterization

The following useful conclusions are drawn after investigating the material characterization of masonry and ECC.

- The compressive strength of masonry prism is influenced by the compressive strength of brick and mortar. It increases with the increase of compressive strength of both the bricks and mortar.
- The mechanical properties of poly-ECC and PVA-ECC were examined and compared. It concluded that Polyester fiber could be used in place of PVA fiber for making of ECC.
- The compressive, tensile, and flexural strengths of PVA-ECC are respectively found to be 1.14, 2, and 1.11 times of compressive, tensile and flexural strength of Poly-ECC.

7.2.2 Flexural response of masonry beams

The following useful conclusions are drawn after experimentally investigating the masonry beams strengthened with FRP and ECC.

- Masonry beams with ECC as bed joints exhibit ductile performance, and ductility has increased by 9 times of that of masonry beam with cement mortar as bed joint. Therefore, ECC could be used in replacement of cement mortar.
- Use of continuous CFRP/ GFRP wrapping for shear strengthening changes the mode of failure from undesirable shear failure to the most desirable flexural failures.
- Provision of FRP bars within ECC as bed joint can enhance the flexural strength of masonry beams.
- Epoxy is observed to be better bonding agent over cement mortar especially for sandwich beams with respect to the load capacity, flexural stiffness, and deformability.
- Load carrying capacity of epoxy bonded sandwich beam with ECC sheet is found to be about 5 times of that of unstrengthened masonry beam.

7.2.3 Flexural response of masonry walls

The following useful conclusions are drawn after investigating the flexural response of strengthened masonry walls with FRP and ECC.

- Flexural strengthened masonry walls with CFRP bars along with CFRP strips has demonstrated a drastic improvement in their load carrying capacity as well as deformation capacity.
- Load carrying capacity of flexural strengthened masonry walls with CFRP bars and strips has increased 5 times of that of the unstrengthened/ control masonry walls.
- Due to high flexural strength of flexurally strengthened masonry walls with NSM CFRP bars and strips failed in shear which could be avoided by adequate shear strengthening.
- Load carrying capacity of flexural strengthened masonry walls with precast ECC sheet is found to be about 5.4 times of that of control/unstrengthened masonry walls.
- ECC sheet is an effective strengthening and retrofitting technique for the masonry walls.

7.2.4 Numerical modelling

The following useful conclusions are drawn after numerical modelling of flexural behaviour of the masonry beams and wall strengthened with ECC.

- For tension strengthened masonry beams, the recommended thicknesses of ECC strips are 45 and 50 mm for epoxy and cement mortar as bonding agents, respectively.
- The numerical results are sensitive to the mesh element size of the concrete damage plasticity model. Accurate element mesh size of CDP model is essential for the finite element analysis.
- The developed design charts will help the designer to determine the necessary ECC reinforcement ratio as per required strength in the strengthened masonry walls.
- The location of opening plays the crucial role on the flexural response of ECC strengthened masonry wall with opening. When the opening is considered towards left top & left center of the masonry wall a notable decrease in strength as well as displacement is observed as compared with central opening case.
- It is recommended that the rectangular and square opening ratio up to 7% is decent without significantly compromising the flexural strength.

7.3 Recommendations

Based on the result and observation of this investigation, the following recommendations are made.

- It is recommended that the indigenous Polyester fiber can also be used for making of ECC.
- It is recommended that cement mortar can be replaced with ECC where the ductility of the structures is of more concern. However, skilled labor is required to develop and handle the ECC.
- The epoxy as adhesive has been recommended for bonding of ECC sheet with masonry structures.
- The continuous FRP wrapping for strengthening of masonry beams is recommended for avoiding the shear failure.
- It is observed that the ECC is very potential material for strengthening purpose. The precast ECC sheet is recommended for the strengthening of masonry walls.
- FRP and ECC can be effectively used as retrofitting and strengthening materials for existing masonry structures including historic monuments.

7.4 Future Scope of the Work

In the present study, an attempt has been made in the direction of strengthening of masonry elements using FRP and ECC. There is tremendous scope for research in the retrofitting and strengthening of masonry as well as concrete structures using precast ECC and FRP sheets. In this regard, some of the studies which can be taken up for future investigation are as follows:

- The comparative study of present experimental results with analytical predictions using theoretical models available in the literature.
- Structural applications of precast FRP and ECC sheets for flexural and shear strengthening of existing old structures.
- Applications of precast ECC sheet and FRP laminate angles for strengthening of RC columns.
- Applications of FRP and ECC sheets for strengthening of RC slabs.
- Numerical modelling of FRP and ECC strengthened masonry beams and columns for parametric study.
- Developing the design guidelines and codal provisions for ECC strengthened RC structures.
- Developing precast ECC pipes, tiles and other products for durable usages.
- Application of precast ECC and FRP sheets for shear wall structures.
- Further experimental investigations are required on large masonry walls with and without opening strengthened with ECC.