# Synopsis

Brick masonry with concrete elements is extensively used in the construction of multistorey buildings throughout the world. Moreover, most of the heritage structures are also constructed with brick masonry. However, the strength and ductility of these brick masonry structures are limited. Furthermore, strengthening and rehabilitation of deteriorated masonry structures have been a major issue in the last decades. The deterioration of these masonry structures might be due to ageing, corrosion, poor maintenance, poor initial design or construction and accidental situation like earthquakes. Many of the brick masonry structures collapsed during 2001 Bhuj (Gujarat) and 2005 North Kashmir earthquakes. Since the steel as strengthening material is corrodible and conventional strengthening patterns are not highly durable. Usage of non-corrodible, high strength and highly ductile materials for strengthening of brick masonry structures seems to be a potential solution for the above-mentioned problems. Therefore, it is essential to use such high-performance materials for constructing and strengthening of brick masonry structures. Use of Fiber Reinforced Polymer (FRP) bars/ fabrics and Engineered Cementitious Composite (ECC) have shown satisfactory results to give maximum strength along with ductility and durability with little maintenance requirements. ECC is an innovative cement-based composite construction material which uses polymeric fibers with very less fiber volume fraction, i.e., about 2%. This material shows unique strain hardening behavior in tension. ECC is also known as Ductile Fiber Reinforced Cementitious Composite (DFRCC) due to their ultra-high ductile behavior.

In this study, an attempt is made to use and demonstrate ECC and FRP as an effective and potential strengthening materials for masonry structures. This thesis presents the results of experimental investigation pertaining to the structural response of masonry elements (beams and walls) strengthened with FRP and ECC. Present study focuses on the flexural behavior of the unreinforced masonry walls. Improvement in behavioral characteristic of masonry walls by strengthening materials (FRP and ECC) with suitable approach has been presented in this research work.

This thesis is divided into seven chapters. In the first chapter, a brief introduction of masonry structures, conventional methods for strengthening, and general overview of FRP and ECC along with their applications in field of structural engineering are presented. A brief but complete review of the existing literature on the masonry elements such as beams, columns, and walls strengthened with FRP and ECC is presented in the second chapter. In the third chapter, material characterization of masonry and its constituents (brick and mortar) is presented along with the material behavior of strengthening materials i.e., ECC and FRP. Material characteristics of masonry such as compressive strength of masonry prisms, bricks, mortars as well as bond strength (i.e., flexural and shear bond strengths) of brick and mortar joint are determined experimentally. The compressive stress-strain curves of brick, mortar, and masonry have also been demonstrated in Chapter 3. Further, two types of polymeric fibers (i.e., polyvinyl alcohol (PVA) fibers and polyester (Poly) fibers) are introduced to produce ECC. The uniaxial compressive, uniaxial tensile, and four-point bending tests are carried out to evaluate compressive, tensile and flexural stress-strain responses of ECC. The experimental results have shown that PVA-ECC exhibits higher compressive, tensile and flexural strength in comparison to the Poly-ECC.

The fourth chapter deals with the flexural behavior of masonry beams strengthened in flexure and shear by bonding FRP sheets at soffit and U-wrapping, respectively. Masonry beams are made in different ways with cement mortar and ECC as a bed joint. Masonry beams of 150 x 230 mm cross-section and 1300 mm length are casted using locally available burnt clay bricks and cement mortar of proportions 1:3 (cement: sand) as bed joint. Further, 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) are discussed. Two types of bonding materials have been used, i.e., epoxy and cement mortar for bonding the ECC sheets with masonry beam. These masonry beams are tested for four-point bending and loaded monotonically up to failure. Flexural capacity, deformation, and crack patterns of tested control masonry beams and strengthened masonry beams are compared and discussed. The experimental results of masonry beams strengthened with FRP and ECC have shown significant improvement in flexural performance in terms of load as well as deformation capacity. Moreover, masonry beams with ECC as bed joints have shown a drastic improvement in their load carrying capacity and ductility in comparison to masonry beams with cement mortar as bed joint. Therefore, ECC could be used in replacement of cement mortar.

The fifth chapter describes the flexural response of unstrengthned and strengthened masonry walls with and without opening. Masonry walls of size 762 × 480 × 230 mm (length × width × thickness) are casted using locally available burnt clay bricks and cement mortar. These masonry walls are externally strengthened with different layers of near surface mounted (NSM) FRP strips and ECC sheets. These masonry walls are subjected to flexural static loading and loaded monotonically up to failure. Flexural performance of tested control masonry walls and strengthened masonry walls in terms of modes of failure and the load-deflection response is presented and discussed.

Numerical modelling to simulate the flexural response of ECC strengthened masonry beams and walls with and without opening along with parametric study to examine the effect of thickness of ECC sheet, width, length, and opening size of the masonry walls are discussed in Chapter 6. As experimentally it is not possible to make masonry beams & walls with all the parameters selected, therefor a finite element based numerical study is conducted to provide a design chart which is useful for determining the necessary ECC reinforcement ratio as per required strength. The results of finite element analysis using ABAQUS for masonry beams and masonry walls are validated with experimental results. For ECC strengthened masonry walls with different opening ratios, it is observed that the normalized flexural strength decreases with increase in opening ratio. For square opening, impact of opening percentage up to 7% is considerably low on its flexural strength. Moreover, the location of opening plays crucial role on the flexural response of ECC strengthened masonry wall with opening. When the opening is considered towards left top & left centre of the masonry wall a notable decrease in strength as well as ductility is observed as compared with central opening case. The summary, overall conclusions, and future scope of the work are presented in the last chapter (i.e., Chapter 7).

This study reflects that ECC and FRP are effective strengthening materials for brick masonry elements. Masonry beams with ECC as bed joint is found to be more effective as compared to masonry beam with cement mortar. Substantial increase in load carrying capacity of masonry beams is obtained by proposed U-wrapping system. In case of masonry walls, flexural load carrying capacity is increased significantly due to strengthening with precast ECC sheet. The numerically developed design charts for flexural strength of masonry walls will be helpful to the designers for determining the necessary ECC reinforcement ratio as far as performance-based design in concerned.