CHAPTER 2

Literature Review

2.1 General

Brick masonry is still used as a construction material in most of the countries because of its good heat insulation properties, high compressive strength, easy availability, good soundness, durability, and the low cost. Masonry structures are an assemblage of brick and mortar units which are found to be a large portion of the building stock throughout the world and they are most vulnerable during the high intensity of earthquakes or high wind pressure. Generally, masonry structures are designed for the vertical load as the masonry is good in compression. When the masonry structures are subjected to lateral load during an earthquake and high wind pressure, the walls develop flexural and shear stresses [49]. Therefore, there is a great need for strengthening of existing masonry structures in the flexural and shear.

Numerous strengthening materials such as metallic or polymeric grid, engineer cementitious composite (ECC), textile-reinforced mortars (TRM), and fiber-reinforced polymer (FRP) are used for strengthening purpose nevertheless FRP and ECC have gained increasing popularity in the construction field because of its valuable properties such as high tensile strength, and non-corrodible characteristics. Various researchers have investigated the strengthening of masonry beams, columns, and walls using the conventional materials such as steel, concrete, etc. Some of the studies have investigated the strengthening of masonry structures using FRP. However, investigations of strengthening of masonry beams, columns, and walls using ECC sheet are very limited.

In this chapter review of some of the notable publications related to the strengthening of masonry beams, columns and walls with FRP and ECC have been presented. This review is divided mainly into following four distinct sections (Sections 2.2, 2.3, 2.4, and 2.5). Sections 2.2, 2.3, and 2.4 describe the strengthening of masonry beams, columns, and walls with both the FRP and ECC, respectively whereas Section 2.5 elaborates the standard/ design guidelines/ codes of masonry structures.

2.2 Strengthening of Masonry Beams using FRP and ECC

In the first century of A.D., Romans started constructing the low-rise unreinforced masonry (URM) buildings in which some of the buildings were four or more stories high. URM beams were utilized in order to allow for window and door openings on the face and within the interior masonry walls of the buildings (Fig. 2.1). In masonry construction, different kinds of beams are available i.e., floor beams, roof beams, bond beams, and grade beams. Masonry beams are located at the floor level or roof level and may have multiple functions such as tying the structure around its perimeter. They transfer the diaphragm action of the roof to the shear wall and span over the opening in the walls supporting the gravity loads coming from above (Fig. 2.2).

Fig. 2.1 Early multistory load-bearing masonry structure [3]

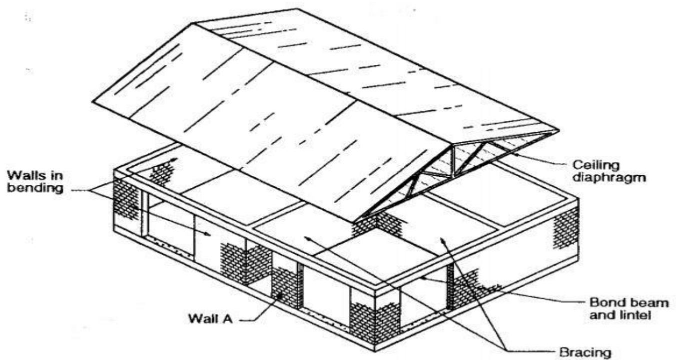

Fig. 2.2 Lateral load resisting structural system of a single-storey masonry structure [3]

It is a well-known fact that existing ancient unreinforced masonry structures (URM) do not meet the requirement of recent building codes and are prone to failure when subjected to excessive lateral loads such as the wind and seismic loads [50]. Moreover, most of those masonry structural members such as beams, columns, and walls are deteriorated and need urgent retrofitting. As a remedy, FRP is being used in the construction industries in order to rehabilitate, retrofit and strengthen the existing masonry structural members. Even though researchers have started conducting tests on FRP strengthened concrete beams during the past decade, literature regarding FRP strengthened masonry beams is very limited. Triantafillou [51] investigated the flexural behavior of URM beams strengthened with FRP laminates. A total of 6 specimens of size 120 × 400 × 900 mm (width × depth × length) were constructed to examine the out-of-plane response of the beams. Four specimens were strengthened with unidirectional carbon fiber reinforced polymer (CFRP) laminates of 1 mm thick and 50 mm wide and remaining two were tested as control specimens. Author [51] reported that flexural strength of strengthened specimens has increased approximately by ten times of that of control beam and specimens failed by crushing of masonry in compression zone which indicate the flexural failure. Kiss et al. [52] studied the flexural response of URM beams strengthened with FRP strips subjected to four-point bending. URM beams of size 206 × 95 × 492 mm (width × depth × length) were constructed which consist of seven brick units in a layer. These masonry beams were strengthened with four different types of FRP, i.e., chopped glass fiber with epoxy resin, chopped glass fiber with polyester resin, glass fabric cloth with epoxy resin and glass fabric cloth with polyester resin. Authors [52] observed that significant nonlinearity occurred due to delamination of FRP strips which gives a degree of ductility, despite the brittleness of both the masonry and FRP. Authors [52] reported that the FRP could be used to provide a mechanism for inelastic deformation as well as to increase the strength of masonry structures. Bajpai and Duthinh [53] carried out an experimental study on out-of-plane response of flexural strengthened concrete masonry beams strengthened with externally FRP bars which were placed parallel to the mortar bed joints. Four beams of two different types; one is narrow beam of size 400 × 200 × 2850 mm (width × depth × length) and another one is wide beam of size 800 × 200 × 2850 mm (width × depth × length) were made and tested for four-point bending test. Authors [53] reported that externally bonded FRP bars provide an efficient method of strengthened masonry beams against out-of-plane bending. Hao et al. [54] investigated the flexural response of concrete masonry beams strengthened with CFRP sheet. Eight fully grouted masonry deep beams were constructed of size 190 × 990 × 2590 mm (width × depth × length) and tested as simply supported beams under three-point loading. Authors [54] observed that adequate anchorage is necessary to postpone deboning between CFRP sheet and the substrate. Galal and Enginsal [55] investigated the flexural behavior of masonry beams that are internally reinforced using glass fiber reinforced polymer (GFRP) bars. Seven reinforced concrete masonry beams having spans of 4 and 2.4 m were made and tested under four-point loading. Out of seven, two specimens were reinforced with conventional steel bars and remaining five were internally reinforced using GFRP bars with different reinforcement ratio. Authors [55] concluded that the flexural capacity and stiffness of the reinforced masonry beams significantly improved as the internal GFRP reinforcement ratio is increased.

Another strengthening material, i.e., ECC has attracted great attention due to its ductile behavior. There are few literatures available on the strengthening of masonry beams using ECC. Kyriakides and Billington [56], Kyriakides et al. [57] have reported that ECC is an effective material for strengthening of masonry structures. Kyriakides and Billington [56] have studied the flexural response of masonry beams strengthened with 13 mm thick ECC sheet. The ECC sheet was bonded to masonry beams with screw anchors (Stitch dowels). Authors [56] found that the flexural strength of strengthened masonry beams has increased by 20-25 times of that of control masonry beams. In another study, Kyriakides et al. [57] investigated the flexural strength of masonry beams retrofitted with ECC layer. The masonry beams of size 96 × 94 × 602 mm (width × depth × length) containing nine brick units with eight mortar joints, each of approximately 10 mm thick were made. These beams were strengthened with 13 mm thick layer of ECC in the tension face with three sets of experiments. In the first set, ECC was troweled onto to the tension surface without mild steel reinforcement while in the second and third sets, a mild steel welded wire fabric (WWF) representing 0.125 % and 1.0 %, respectively, was inserted with ECC layer prior to troweling as shown in Fig. 2.3. Authors [57] observed that the first and second set of the specimens failed due to an opening in mortar-brick interface while the third set of specimens failed in shear due to the high percentage of reinforcement.

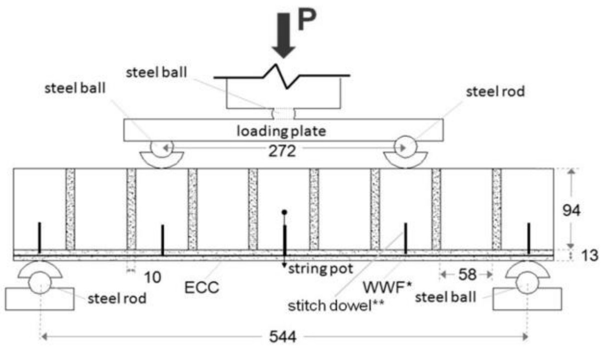

Fig. 2.3 Four-point bending test set-up of ECC strengthened masonry beams [57]

2.3 Strengthening of Masonry Columns using FRP and ECC

2.3.1 Experimental research work

Masonry column is one of the load bearing elements of masonry structures and required special attentions for strengthening or retrofitting. This section summarizes the previous research on axial load behavior of strengthened masonry columns with FRP and ECC. The summary focusses primarily on the effect of FRP and ECC on masonry columns strength and ductility. Numerous experimental studies have been conducted by various researchers [58-67] on strengthening of masonry columns with FRP in axial. Shrive et al. [58] investigated the axial strength of strengthened masonry columns of three different cross-sections and two different types of masonry units. The square columns were strengthened with CFRP sheet by wrapping after casting a circular concrete jacket around the columns. The modified circular columns have shown the significant enhancement in axial strength as compared to square columns after strengthening. This technique of concrete jacketing before wrapping to the masonry column may not be practically feasible as it will add dead load to the existing structure. Moreover, the FRP advantages of its light weight cannot be effectively exploited. After this study, researchers have started rounding off the edges of the rectangular columns before FRP wrapping to take full advantages of FRP. Bieker et al. [59] have investigated the axial compression strength of strengthened masonry columns made with two different types of bricks i.e., solid bricks and vertical coring bricks. The masonry columns of size 240 × 240 × 500 mm (width × depth × height) were strengthened with CFRP and GFRP sheet. Authors [59] observed that the load carrying capacity of both types of masonry column has increased, however, load carrying capacity of solid brick masonry columns was much higher as compared to vertical core brick columns. In India, mostly solid brick masonry columns are constructed. Krevaikas and Triantafillou [60] investigated the axial strength behavior of short masonry columns confined with FRP jackets. A total of 42 clay brick rectangular masonry columns of three different sizes as 115 x 115 mm, 172.5 x 115 mm, and 230 x 115 mm (width × depth) were tested. The corners of all the specimens were made round edges with radius of 10 mm or 20 mm. Masonry columns were strengthened with different numbers of layers of unidirectional GFRP and CFRP sheets. Authors [60] observed that the increasing the corner radius or decreasing the cross-section aspect ratio is advantageous to the strength and strain capacity of rectangular masonry columns; the strength and deformability increase with the average confining stress. Corradi et al. [61] studied the axial compression strength of 24 clay solid brick columns confined with CFRP. The parameters included different strengthening system, masonry types (square and octagonal cross-section), and curvature radius of the corners. Authors [61] observe that failure of masonry columns occurs at the edges which split the composite material and a significantly increase the stiffness and load carrying capacity.

Aiello et al. [62-64] in the year (2007 to 2009) have investigated the axial behavior of FRP wrapped masonry columns. In 2007, Aiello et al. [62] studied the mechanical behavior of FRP confined circular masonry columns built with calcareous blocks. In 2008 and 2009, Aiello et al. [63-64] investigated the axial strength behavior of FRP strengthened rectangular masonry columns and compared with analytical results obtained from CNR DT200-2004 [65]. A total number of 33 rectangular masonry column of size 250 × 250 × 500 mm (width × depth × height) made with limestone brick were tested. The parameter includes the different strengthening patterns, amount of reinforcement, cross-section aspect ratio, curvature radius of corners, and material of bricks. Overall 30 columns (18 full core and 12 hollow core) of limestone bricks and 3 full core columns made of clay brick were tested with strengthening by GFRP. Hence, the major investigation was done on limestone masonry columns and very fewer specimens were of clay brick masonry columns. Authors [64] concluded that the significant increase in peak load and ultimate axial deformation were observed in all types of specimens. Alecci et al. [66] reviewed the results of experimental tests carried out on wrapped and unwrapped masonry column specimens with CFRP and reported that it is necessary to consider the residual strength of the inner pillar after the first damage occurred.

The maximum strength obtained by various methods such as experimental, analytical, and by using coefficients proposed by other researchers for CFRP wrapped specimens. Researchers concluded that the final strength of confined masonry columns with FRP does not depend on the initial strength but on the residual strength of the specimens [2]. Ludovico et al. [67] have investigated the axial compression response of the masonry columns made up of tuff and clay brick masonry. Masonry columns were strengthened by wrapping with one ply of different types of fibers such as carbon, glass, and basalt. Authors [67] reported that the overall efficiency of FRP wrapping on clay brick masonry is more significant in comparison to tuff brick specimens. Witzany et al. [68] carried out an experimental study on the strengthening of masonry columns with CFRP and GFRP fabric. The study demonstrated a prominent effect of FRP on the reduction of characteristic tensile cracks and thus a significant increase in the load carrying capacity. In 2012, Galal et al. [69] have reported that most of the research effort in retrofitting of masonry structural elements with FRP were directed to walls, so less work has been conducted on retrofitting of masonry columns. It is same for the case of solid clay burnt brick masonry column also.

More recently, Lignola et al. [70] summarized the previous literature studies on strengthening of masonry columns and introduced a theoretical approach for determining the strength increase due to FRP confinement which is based on the Mohr-Coulomb strength criterion. Witzany and Zigler [71] carried out an experimental study on enhancing the displacement and ultimate strength of masonry columns strengthened with high strength FRP. The parametric study includes the effectiveness of different reinforcing methods, height, number, and distance of FRP strips. Authors [71] reported that the effectiveness of CFRP wrapping on masonry columns depend on the extent of damage to individual columns and must be assessed separately for each case of masonry failure. Fossetti and Minafo [72] investigated the compressive behavior of clay brick masonry columns strengthened with FRP. The masonry columns of size 230 × 230 × 960 (width × depth × height) were made up by assembling two brick units per course and connected with mortar joint having a thickness of 10 mm. The columns strengthened with FRP wrapping after making the round edge corner of radius 25 mm. Uniaxial compression test was performed on the strengthened masonry columns up to the ultimate failure. Authors [72] concluded that the strength has increased significantly, however, a brittle and sudden failure occurred due to stress concentration at the corners. In 2017, Alotaibi and Galal [73] carried out an experimental study on the axial compressive behavior of masonry columns confined by CFRP to enhance the axial compressive strength and ductility. A total of 19 fully grouted concrete masonry columns of size 185 × 185 × 470 mm (width × depth × height) were constructed. The corners of the columns were made round edges in three sets varied with the radius of 0, 10 and 30 mm before CFRP confinement. Authors [73] presented that the ultimate axial compressive strain and load carrying capacity of strengthened masonry columns has increased by up to 281% and 79%, respectively compared to control columns.

The literature review on retrofitting and strengthening of masonry columns with FRP shows that more research work is required to be carried out. Furthermore, ECC material could be used to study the enhancement of axial compressive strength of masonry columns strengthened with ECC. To the writers' knowledge, application of ECC as an external strengthening for masonry columns have not yet been investigated. Although application of ECC for the strengthening of masonry walls are available which have been presented later in Section 2.4.

2.3.2 Analytical research work

In this section, the main categories of empirically based confinement models for masonry columns available in literature are outlined. The basic concepts for masonry columns confined with FRP are adopted from the confinement of RC columns. The equations proposed in codes, even for reinforced concrete, are those based on plain concrete sample tests; and many strengthening design codes lack of design equations for masonry confinement [70]. The effect of confinement on the strength is calculated as sum of the strength of unconfined element and additional strength due to confinement. The analytical models developed or modified by various researchers have been discussed in the following sub-sections.

Analytical model by Richart et al. [74]

The first models proposed by Richart et al. [74] at research level in the beginning of last century were based on solid mechanics. Authors [74] proposed a linear relationship (Eq. 2.1) between normalized lateral confining pressure f_l/f_{md} and normalized confined strength f_{mcd}/f_{md} needing the evaluation of the k´ constant.

$$\frac{f_{mcd}}{f_{md}} = 1 + k' \frac{f_1}{f_{md}} \tag{2.1}$$

where f_{md} is the compressive strength of unconfined column

f_{mcd} = Compressive strength of confined column

f_l = Lateral confining pressure

k´ = Dimensionless confinement coefficient

Richart et al. [74] have considered the value of confinement coefficient (k´) as 4.1 for confinement by steel spiral. Further, researchers calibrated Eq. 2.1 with the experimental results and proposed the different value of k´ for FRP confinement of concrete members.

Toutanji and Deng [75] have found the value of k´ as function of confining stress f_l and unconfined concrete compressive strength f_{md}, as follows

$$k' = 3.5\left(\frac{f_l}{f_{md}}\right)^{-0.15} \tag{2.2}$$

The lateral confining pressure (f_l) is calculated from the lateral pressure (f) as given in Eq. 2.3

$$f_l = k_e f \tag{2.3}$$

where, k_e, is effectiveness coefficient and its value depend upon the shape of the cross-section and transverse and longitudinal distribution of reinforcement.

The above empirical model for confinement of concrete members has been considered as basic by the researchers to develop a model for predicting the strength of masonry columns confined by FRP. Many researchers have modified Eq. 2.2 by replacing 3.5 and -0.15 by other values for concrete members.

In 2004, Borri and Grazini [76] and Corradi et al. [61] in 2007 calibrated Eq. 2.2 as follows.

$$k' = 2.4\left(\frac{f_l}{f_{md}}\right)^{-0.17} \tag{2.4}$$

Alecci et al. [66] in 2009 have carried out an experimental investigation on cylindrical masonry columns and proposed the analytical model for confined masonry columns; which is also based on Eq. 2.1 with the value of k´ = 3.68.

Analytical model by Krevaikas and Triantafillou [60]

Krevaikas and Triantafillou [60] in 2005 proposed an analytical model for strength of FRP confined masonry. The basis of this model is the concept and expressions of the confined concrete as given in Eq. 2.5.

$$f_{MC} = f_{MO}\left(\alpha + k_1\left(\frac{\sigma_{lu}}{f_{MO}}\right)\right) \qquad \leq f_{MO} \tag{2.5}$$

where,

f_{MC} = Compressive strength of confined masonry,

f_{MO} = Compressive strength of unconfined masonry,

α and k_1 are empirical constants and

σ_{lu} = Confining stress at failure

For finding the empirical constants i.e., α and k_1, the graph is plotted based on the experimental results in between (f_{MC}/f_{MO}) versus (σ_{lu}/f_{MO}) and values of α and k_1 are 0.6 and 1.65, respectively. Hence, the analytical model has been finalized as follows:

$$f_{MC} = f_{MO} \quad \text{if } \left(\sigma_{lu} / f_{MO} \right) \leq 0.24 \tag{2.6}$$

$$f_{MC} = f_{MO} \left(0.6 + 1.65 \left(\frac{\sigma_{lu}}{f_{MO}} \right) \right) \quad \text{if } \left(\sigma_{lu} / f_{MO} \right) > 0.24 \tag{2.7}$$

Authors [60] have suggested that further experimental verification to account for different types of masonry materials other than those used in their experiments should be carried out.

Analytical model by Aiello et al. [64] for limestone masonry

The analytical model proposed by Krevaikas and Triantafillou [60] has been modified by Aiello et al. [64] for limestone masonry. Authors [64] have reported the values of α and k_1 as 1 for limestone masonry and obtained value has been substituted in the Krevaikas and Triantafillou [60] model in Eq. 2.5. The analytical model for limestone masonry is as follow

$$f_{MC} = f_{MO} \left(1 + \left(\frac{\sigma_{lu}}{f_{MO}} \right) \right) \tag{2.8}$$

Authors [64] have reported that this equation (Eq. 2.8) is able to represent the tested condition even if different strengthening schemes and corner radius were experienced.

Analytical model by Ludovico et al. [67] for clay brick and tuff masonry

In 2010, Ludovico et al. [67] carried out experimental investigations on clay brick and tuff brick masonry columns confined with FRP (discussed in Section 2.3 of this chapter) and proposed the refined equations for prediction of strength gains of confined masonry columns.

$$f_{MC} = f_{MO} \left(1 + k' \left(\frac{f_{leff}}{f_{MO}} \right) \right) \tag{2.9}$$

where, k´ =1.09 $\left(f_{leff} / f_{MO} \right)^{-0.24}$ for tuff masonry, and

k´ = 1.53 $\left(f_{leff} / f_{MO} \right)^{-0.10}$ for clay brick masonry

It can be seen that the developed models for tuff and clay brick masonry are modification of Krevaikas and Triantafillou [60] model.

Analytical Model by Rao and Pavan [77] for clay brick masonry

Recently, Rao and Pavan [77] carried out experimental study on clay brick masonry prism confined with FRP subjected to monotonic axial compression for different inclinations of the loading axis to the bed joint. Authors [77] have also studied the analytical models developed by other researchers and proposed the modified equations against two types of loading i.e., (i) Masonry with loading axis normal to bed joint (90°) (ii) Masonry with loading axis at various inclinations to bed joint (0, 30, 45, 60 and 90°). The analytical models for clay brick masonry is as follow.

For masonry with loading axis normal to bed joint (90°)

$$\frac{f_{MC}}{f_{MO}} = 1 + 1.53\left(\frac{f_{1,eff}}{f_{MO}}\right)^{0.92} \tag{2.10}$$

For masonry with loading axis at various inclinations to bed joint (0, 30, 45, 60 and 90°)

$$\frac{f_{MC}}{f_{MO}} = 1 + 4.96\left(\frac{f_{1,eff}}{f_{MO}}\right)^{0.87} \tag{2.11}$$

where,

f_{MC} = Compressive strength of confined masonry,

f_{MO} = Compressive strength of unconfined masonry,

$f_{l,eff}$ = Effective confining pressure

All the above developed models of masonry columns confined with FRP are based on the concept of calculation of confined strength of concrete columns. The developed analytical models by the researchers are based upon their experimental results. All these analytical models developed by the researches are based on FRP confinement of masonry column with round edges. Hence, more and more research works are required for developing the analytical models of FRP confinement of masonry columns without making the round edges.

2.4 Strengthening of Masonry Walls using FRP and ECC

2.4.1 Experimental research work

Walls are the prominent structural element of masonry structures. The walls are primarily designed to withstand gravity loads as masonry is good in compression. Since masonry is weak in tension, the walls are most vulnerable to the seismic lateral loads. Lateral load is generated due to earthquake and the wind pressure, which produce flexural stresses. These flexural stresses are out of plane in nature. Moreover, flexural stresses can also be developed due to some eccentricity of the vertical compressive load. Consequently, the development of affordable and effective strengthening techniques for masonry walls is an urgent need. FRP composites may provide viable solutions for the strengthening of masonry walls subjected to out-of-plane loads caused by high wind pressures or earthquakes. Numerous experimental studies have been conducted by various researchers [78-89] on strengthening of masonry walls with FRP under out-of-plane loading. In the year 1994, Saadatmanesh and Schwegler [78-79] were the first researchers to study the use of FRP for strengthening of masonry structures. Since then, FRP has been widely used for strengthening and retrofitting of structural masonry elements such as walls, vaults, arches, and columns [80]. In 1996, Ehsani and Saadatmanesh [81] investigated the flexural response of brick masonry walls retrofitted with FRP and found significant increases in load carrying capacity of the walls. Further in 1997, Ehsani et al. [82] investigated the shear behaviour of masonry wall strengthened with FRP. In 1999, same group of researchers along with Velazques-Dimas [83] tested three masonry walls strengthened with GFRP strips subjected to out-of-plane loading. The researchers observed that masonry walls and FRP strips failed in a brittle manner, however, this strengthening technique is capable of dissipating some energy. Papanicolaou et al. [84] carried out an experimental study on clay brick masonry walls strengthened with FRP, by applying out-of-plane cyclic loading and reported that FRP is an extremely promising solution for the strengthening of URM walls subjected to out-of-plane bending. Cheng and Mccomb [85] investigated the out-of-plane impact behavior of URM walls externally strengthened with CFRP composites. The walls strengthened with continuous woven sheets performed better than the unidirectional sheet. Valluzzi et al. [86] carried out an experimental study to find the performance of FRP and textile-reinforced mortar (TRM) strengthening schemes for masonry panels against out-of-plane loads. Twenty-seven specimens of size 120 × 390 × 1310 mm were constructed and strengthened with different types of FRP. The specimens were tested for four-point monotonic bending tests, aimed at reproducing the failure condition of infill masonry walls under out-of-plane actions. Authors [85] reported that application of FRP is very effective in improving the out-of-plane response of hollow block masonry walls. Bernat-Maso et al. [87] carried out an experimental study on FRP-strengthened masonry walls subjected to eccentric compressive load. The second order bending effects will be developed due to an eccentric load. Authors [87] observed that all the strengthened walls collapsed due to a compressive/shear failure mode located in the masonry near the end of the wall.

Elsanadedy et al. [88] conducted an experimental study on use of externally bonded FRP composite on URM walls for upgrading the out-of-plane flexural resistance. A total of six hollow concrete blocks walls of dimension 1650 × 1650 mm were constructed and strengthened with GFRP sheet in different schemes. Authors [88] reported that the effectiveness of FRP material in enhancing the load and deformation capacity of URM walls decreases with the increases of FRP reinforcement ratio.

Gattesco and Boem [89] studied the out-of-plane effectiveness of a modern strengthening technique applied to masonry walls. The technique consists of a mortar coating reinforced with GFRP meshes on both wall faces. Masonry walls of size 3000 mm (height) and 1000 mm (width) were constructed with three different masonry types: solid brick (250 mm thick), rubble stone and cobblestones (400 mm thick, both). Four-point bending tests were performed by applying two forces at the thirds of the height in the perpendicular direction to the wall surface. Authors [89] observed that the strengthened specimens are able to resist out-of-plane bending moments almost five times greater than that of control specimens.

Besides that, near surface mounted (NSM) FRP reinforcements have got a wide application for retrofitting and strengthening of masonry structures. In the NSM method, grooves are first cut into structural elements such as beams, columns, and walls and FRP bars is bonded therein with an epoxy adhesive/ or cement grout. Numerous experimental studies have been conducted on the strengthening of structural elements with NSM techniques. Hamid [90] have investigated the effectiveness of NSM FRP rods as a strengthening system for masonry structures. A number of studies on the strengthening of masonry walls with NSM techniques have been reported by Tumialan and Nanni [91], Tumialan et al. [92], Rizkalla et al. [31], Korany and Drysdale [93], Galati et al. [94]. Authors have concluded that the NSM technique is most promising strengthening technique for structural elements. Test results produced by Tumialan and Nanni [91] revealed that the load carrying capacity of strengthened masonry walls with NSM FRP bars shows an increase of 4-14 times of the control specimen with an increase in shear capacity as well. According to Rizkalla et al. [31], NSM FRP systems are three times more effective than externally bonded FRP systems. Two types of debonding failure generally occurred with NSM FRP bars, i.e., debonding due to the cracking of concrete surrounding the epoxy adhesive and debonding due to splitting of the epoxy cover [31]. High tensile stresses can lead to the splitting of the epoxy cover at the FRP-epoxy interface. The crack nearby the epoxy adhesive can occur when the tensile stresses at the masonry-epoxy interface reach the tensile strength of the masonry. However, the tensile stresses can be reduced by using adhesives of high tensile strength, increasing the thickness of the epoxy cover, and by widening the grooves [95].

Galati et al. [94] worked on strengthening of URM walls using NSM FRP bars. Fifteen URM walls were constructed and tested with different percentage and types of FRP reinforcement. This study included the effect of the dimension of the grooves, bars shape, and type of bonding material on the flexural capacity of URM walls. Different types of failure are observed such as flexural failure either due to crushing of masonry or rupture in FRP, debonding of FRP reinforcement, and shear failure in case of over-reinforced specimens. Subsequently, the flexural capacity of strengthened walls has increased up to 14 times that of URM control specimens. Turco et al. [96] studied the flexural and shear strengthening of concrete masonry walls with rectangular and circular FRP bars and concluded that the smooth circular FRP bars are appropriate for shear strengthening, while rectangular FRP bars are good for flexural strengthening. Galal and Sasanian [97] have assessed the out-of-plane flexural performance of masonry walls reinforced with GFRP bars and observed that the compression failure occurred at the section of the bed joint that has shear reinforcement. Authors [97] reported that the shear reinforcement could result in weakening of the bond at the block-mortar interface. Mahmood and Ingham [98] investigated the influence of various retrofit interventions on the shear strength of wallettes. They have shown that the presence of overlapped CFRP plates wallettes resulted in lower bond strength at the interface between the two plates and contributed to low shear strength resulting from premature debonding of CFRP. Authors [98] also recommended the usage of NSM CFRP on both faces of wallette as it is effective and also suggested various retrofit interventions based on the mechanical characteristic to be improved. Griffith et al. [99] reported that NSM reinforcement can be an efficient retrofit technique for increasing the vertical bending capacity of URM walls. In this paper, they have shown that NSM reinforcement increases the strength of the corresponding unreinforced wall by 20 times. Dizhur et al. [100] have investigated the flexural performance of masonry walls retrofitted with NSM CFRP strips and reported that the use of vertically orientated CFRP strips significantly increase the flexural strength, i.e., of the order of 3.05 to 6.21 times of that of the control walls. Mendola et al. [101] studied the flexural behavior of unreinforced and CFRP reinforced masonry walls by means of experimental investigation and numerical modeling. Authors [101] stated that the failure mechanism does not depend on the percentage of reinforcement. Al-Jaberi et al. [102] studied the strengthened masonry walls with NSM FRP bars for out- of-plane cyclic loading. Authors observed that the cementitious bonding material had more sudden failure in comparison with epoxy filler.

Significant progress has been observed in the last few years regarding the experimental study of the flexural response of masonry walls strengthened with FRP. However, strengthening of masonry walls with ECC has deserved very few investigations. Recent investigations have demonstrated the great advantages of ECC for strengthening and retrofitting purpose. The use of ECC for the strengthening of masonry structures has attracted great attention due to ductile behavior. Billington et al. [103], Maalej et al [104], Lin et al. [105], and Lin et al. [106] shows that the use of ECC is effective for the strengthening of masonry structures. Billington et al. [103] carried out an experimental study on masonry infilled non-ductile concrete frame retrofitted with different schemes. The four infilled frame specimens were constructed. Three specimens out of four were retrofitted with ECC layer of thickness 13 mm. The infill frames were tested for in-plane cyclic loading and it was demonstrated that ECC retrofit significantly enhance the performance of infill masonry walls. Maalej et al. [104] studied the out-of-plane resistance of URM wall panels strengthened with ECC. A total of 18 masonry wall panels of size 1000 × 1000 × 100 mm were constructed with solid clay bricks. The test specimens were divided into three series, and each series consists of two control specimens (except series #3, having only one unreinforced masonry wall) and four strengthened masonry walls. Series #1 & 2 specimens were tested for quassi-static loading while Series #3 specimens were tested for impact loading. The strengthened masonry walls have shown the increase in load carrying capacity and deflection capacity ranging from 6.5-22 times and from 4.2-15.9 times that of control specimens, respectively. Recently, Lin et al. [105] carried out an experimental investigation on in-plane behavior of concrete masonry wallets strengthened with ECC shotcrete mix. Twenty-six concrete masonry wallets of dimension 1180 × 1200 × 140 mm (height × length × thickness) were constructed and strengthened with ECC shotcrete of thickness 10-15 mm. Authors [105] concluded the in-plane shear strength of the strengthened masonry wallettes has significantly improved. In another study by Lin et al. [106], the flexural response of clay brick masonry wall strengthened with ECC shotcrete was investigated. Five masonry walls of size approximately 4100 × 1150 × 230 mm (height × length ×

thickness) were constructed and strengthened with 30 mm thick ECC on the tension surface. Authors [106] observed that the flexural strength of strengthened masonry walls has increased in between 646-1267 % of that of control wall.

The literature review on retrofitting and strengthening of masonry walls with FRP and ECC shows that more research work on burnt-clay brick walls subjected to flexural load is required to be carried out. The efficiency of strengthening with precast ECC sheet needs to be evaluated for masonry walls in the Indian scenario.

2.4.2 Numerical modelling

In the last decade, considerable numerical research has been conducted on predicting the performance of masonry walls subjected to different loading scenarios [107-109]. Depending on the level of simplicity and accuracy required, it is possible to use the following three modeling strategies [110] (Fig. 2.4).

(i) Detailed micro-modeling: bricks and mortar in the joints were represented by continuum elements whereas the brick-mortar interface was represented by discontinuous elements;

(ii) Simplified micro-modeling: bricks were represented by continuum elements whereas the behavior of the mortar joints and brick-mortar interface was lumped in discontinuous elements;

(iii) Macro-modeling: bricks, mortar, and brick-mortar interface were smeared out in a homogeneous continuum.

For small-scale structures where the more accurate response of masonry components is required, the micro-modelling is the most appropriate method to predict the actual behavior of masonry [111-112]. Although micro-modelling approaches are more realistic for masonry behavior, modelling becomes complicated due to high computational cost. Lourenco et al. [113] studied the nonlinear finite element micro-modelling approach to simulate the individual components, viz. brick and mortar. Authors [113] reported that micro-modelling approach has shown the promising and accurate strategies for modelling of masonry structures. Ghaderi et al. [114] proposed the advanced micro-modelling strategy for unreinforced masonry walls strengthened with FRP. The units and mortar joints were represented by continuum elements and cohesive elements were used to simulate the interaction between units and mortar. Authors [114] concluded that the micro-modelling approach is an effective tool for numerical modelling of FRP strengthened masonry walls.

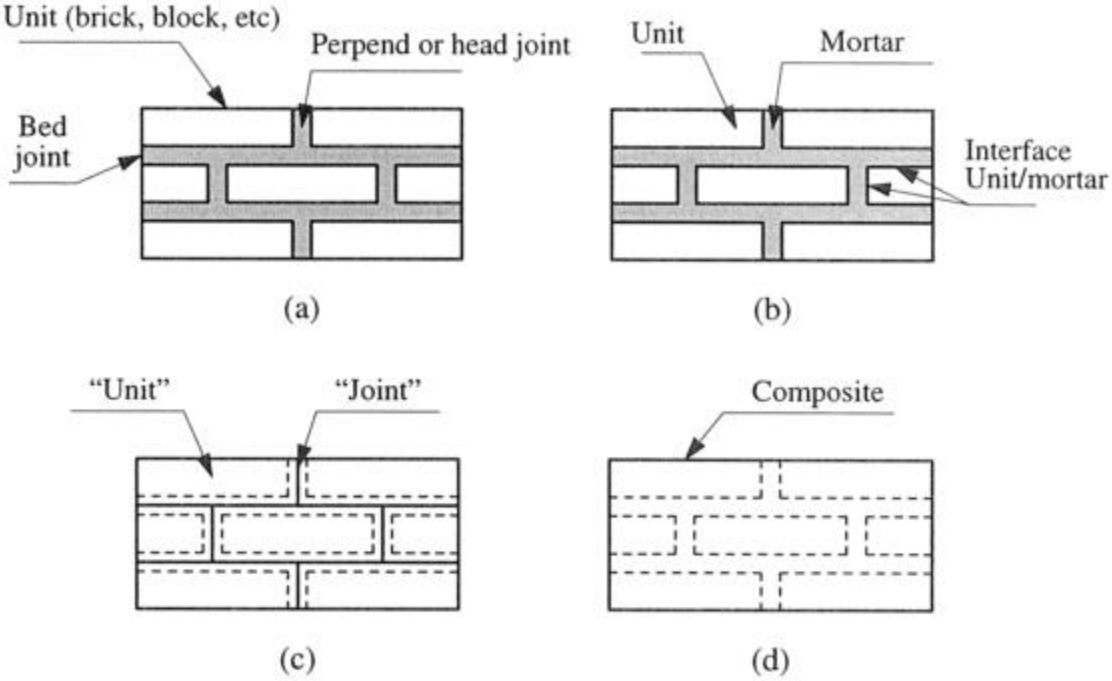

Fig. 2.4 Modelling strategies for masonry structure (a) masonry sample; (b) detailed micro-modeling; (c) simplified micro-modelling; (d) macro-modelling [110]

Kyriakides et al. [115] proposed the nonlinear finite element micro-modelling approach to simulate the small masonry beams strengthened with a thin layer of ECC. The study concluded that both a detailed and simplified micro-modelling approach is able to capture the experimental performance of the ECC strengthened masonry beams. On the contrary, the macro-modelling approaches with homogenization-based technique ignoring brick-mortar interaction have been successfully used for predicting the behavior of masonry walls [116-120]. ElGawady et al. [116] developed the numerical model to simulate the shear strength of unreinforced masonry walls strengthened with FRP and compared with the different models developed by other researchers. The model was explicitly developed to predict the shear strength of masonry walls strengthened with FRP. Masonry, epoxy, and FRP have been considered as different layers with isotropic homogeneous elastic materials in the developed model. The comparisons between the different models have been presented in the paper and shown that the developed model is more conservative than the other existing models. Kabir and Kalali [117] have presented the macro-modeling approach for the analysis of the behavior of unreinforced and FRP strengthened perforated brick masonry walls. The numerical simulations were validated with experimental data and parametric study has been conducted to determine the effects of different strengthening configurations with FRP and brick walls with openings (e.g. door, window) having different aspect ratios and positions. Authors [117] observed that the original failure mode of the solid brick walls changed from flexural to mixed failure modes due to the opening. The maximum strength decreased by 53%. In 2016, Noor-E-Khuda et al. [119] described a generalized finite element macro-modelling method to determine the out-of-plane response of unreinforced masonry and reinforced masonry. Masonry was modelled as a layer with macroscopic orthotropic properties and reinforcing bars were modelled as distinct layers of the shell element. The model was successfully validated with the experimental results of seven masonry walls comprising of unreinforced masonry, internally reinforced masonry, confined masonry and externally surface reinforced masonry walls. The developed model has shown the impressive tool for determining the response of strengthened masonry walls. Recently in 2017, Wang et al. [120] have proposed the extensive numerical model for investigating the effect of textile reinforced mortars (TRM) composites on the nonlinear response and failure modes of masonry walls. A macro-modelling approach based on smeared crack theory, with the assumption of having homogenized layer of mortar with distributed reinforcements was followed. The modelling strategy has shown the accurate predictions in comparison to experimental results for the non-linear response of TRM strengthened masonry panels. Authors [120] reported that the macro-modelling strategy is found to be practical in large-scale simulations and to be able to consider all failure mechanisms in strengthened masonry panels in a direct or indirect manner.

According to the review of existing literature on numerical modelling, most of the research works have focused on the simulation of FRP strengthened masonry walls. Hence, there is need to develop the numerical model for investigating out-of-plane response of masonry beams and walls strengthened with ECC sheets.

2.5 Masonry Codes

Until 1950’s there were no engineering method for design of masonry buildings. The thickness of walls was based on Rule-of-Thumb tables given in building codes and regulations [121]. As a result, walls made of very thick and masonry structures were found to be very uneconomical. Thereafter, the intensive experimental and theoretical researches on masonry was conducted in advanced countries and the masonry codes were established. The review of masonry codes from numbers of countries has been presented in the following sub-sections.

2.5.1 Codes for design of masonry structures

- ***Indian standard-code of practice for structural use of unreinforced masonry (IS: 1905-1987) [122]***

  IS 1905, Indian standard code on unreinforced masonry design was first published in 1960 and later on revised in 1969, 1980, and 1987. This code provides a recommendations of structural design aspect of unreinforced non-load bearing and load bearing walls, constructed with burnt clay brick, stones masonry, sand-lime bricks, and lime based brick. Allowable stress design with several empirical formulae is adopted throughout the code.

- ***Eurocode 6 (BS EN 1996) [123-126]***

  This code was published by European committee for standardization and is to be used with the National Application Document (NAD) of member countries. Eurocode 6 consists of four parts. Part 1 (BS EN 1996-1-1) [123] is for general rules for reinforced and unreinforced masonry; Part 2 (BS EN 1996-1-2) [124] discuss about structural fire design; Part 3 (BS EN 1996-2) [125] talks about selection and execution of masonry; and Part 4 (BS EN 1996-3) [126] discusses the simplified calculation methods for unreinforced masonry structure. All these documents are based upon limit state design method. Seismic design requirement of masonry structure is not covered in Eurocode 6, however provision related to such requirement are given in Eurocode 8 [127].

- ***International building code 2000 [128]***

  The international building code 2000 has been developed to meet the need for a modern, up-to-date building code addressing the design and installation of building systems through requirements emphasizing performance. This code covers the construction, design, materials and quality of masonry in the separate chapter. The Empirical design, strength design and working stress method design have been presented in this code. Masonry seismic design requirements have also been discussed in this code.

- ***Building code requirements for masonry structures (ACI 530-02/ASCE 5-02/TMS 402-02) [129]***

  This code is developed by the joint effort of masonry society, the structural engineering institute of the American society of Civil Engineers, and American Concrete Institute. The code covers the design and construction of masonry structures with minimum construction requirement for masonry in structures. This code discusses about materials, analysis and design, details and development of reinforcement, seismic design requirement, strength and serviceability, flexural and axial loads, walls, columns, and autoclaved aerated concrete masonry. An empirical and prescriptive design methods applicable to buildings meeting specific location and construction criteria are also included.

- ***New Zealand Standard – Code of practice for the design of concrete masonry structures (NZS 4230: Part 1:1990) [130]***

  This code was first introduced in 1985 as a provisional standard NZS 4230P:1985 and later on revised in 1990 and 2004. This code recognizes for material design and detailing of concrete masonry for structural applications in New Zealand. The code is based on limit state design approach and contains comprehensive details of structural seismic design that were equally applicable for construction using other structural materials.

- ***Canadian standards association (CSA) standards, design of masonry structures (S304.1-04) [131]***

  This code was first produced in 1994 and then revised in 2004. This code provides a requirement for the structural design of unreinforced, reinforced, and prefabricated masonry structures. This standard is in accordance with the limit state design of the national building code of Canada. This code also provides the requirements of the structural design of masonry beams, walls and columns. In addition, it includes the empirical design of unreinforced masonry.

2.5.2 Codes for repair / strengthening / retrofitting of masonry structures

There are few codes or standards available for strengthening/retrofitting of masonry structures.

- ***IS 13828:1993, Improving earthquake resistance of low strength masonry buildings – guidelines [132]***

  This standard covers the design and construction for improving earthquake resistance of building of low-strength masonry. This code is applicable to all seismic zones. This code discusses the techniques of making lintel band and roof band in masonry buildings.

- ***IS 13935:2009, Seismic evaluation, repair and strengthening of masonry buildings-guidelines [23]***

  This code provides the material selection and techniques to be used for repair and seismic strengthening of damages building during earthquakes. It also includes the damage ability assessment and retrofitting for the upgrading of seismic resistance of existing masonry buildings covered under IS 4326 [133] and IS 13828 [132]. In this code, the guidelines of material selection for repair work such as cement, epoxy mortar, epoxy resins, quick setting cement mortar, steel along with special techniques such as shotcrete, mechanical anchorage etc. are provided. Seismic strengthening techniques for inserting new walls, modification of roofs or floors, strengthening existing walls, random rubble masonry walls, masonry arches, and strengthening of the foundation have been given in details.

- ***FEMA 547: 2006: Techniques for the seismic rehabilitation of existing building [134]***

  This code covers the techniques used for seismic rehabilitation of existing building. This document is intended to describe the various techniques for seismic rehabilitation of existing unreinforced and reinforced masonry building. The techniques covered in this document are addition or enhancement of cross-walls, the addition of steel moment frame, concrete overlay to masonry walls, the addition of concrete or masonry shear wall, and the addition of veneer ties in URM wall. This document has included the strengthening techniques using fiber reinforced polymers overlay to masonry wall. It has been mentioned that the inadequate in-plane wall strength and out-of-plane bending capacity can be improved using FRP overlay.

2.5.3 Codes and design guidelines for FRP strengthened masonry structures

The design guidelines for strengthening and retrofitting of masonry structure using FRP materials are limited due to great variability of masonry properties. There are only two design guidelines available for FRP strengthening system applied on masonry structures i.e., CNR-DT200 2004 [65]; ACI 440M 2004 [135]. Moreover, specific consideration has to be taken into account for historical masonry structures to prevent any aesthetics modification of the structures.

2.5.4 Codes, standard and design guidelines for ECC materials

In 2008, Japan society of Civil Engineers (JSCE) has published “Recommendation for design and construction of high-performance fiber reinforced cement composite (HPFRCC) with multiple fine cracks” [136] which is the only design guidelines available for analysis, design, and construction using ECC materials. It provides basic stress-strain models and some analysis steps for flexure and shear. However, unified or full-length design approach is not available. Other countries including India are engaged in research activities to explore the application of ECC for bringing out standard design guidelines for ECC structures.

2.6 Concluding Remarks

The literature review pertaining to the strengthening of masonry beams, columns and walls with FRP and ECC are discussed. The below are the concluding remarks drawn on the basis of literature review.

- Little research has been done on structural response of masonry beams and walls strengthened with ECC.
- Structural response of masonry columns strengthened with precast FRP and ECC systems have not yet been investigated.
- Lack of strengthening system that would be adaptable to rectangular masonry columns without making their sharp edge corners to be round.
- Structural behavior of ECC strengthened masonry walls with openings is yet to be studied.
- Design charts for masonry walls strengthened with ECC is not available.