2. Literature Review

2.1 Introduction

The use of Fiber Reinforced Polymers for strengthening and retrofitting of masonry structures has grown in recent years. The use of FRP for strengthening of reinforced concrete structures is well established. FRP systems were first applied to reinforced concrete columns for providing additional confinement in Japan in the 1980s \(^{31, 32, 33}\). As compared to concrete, less work has been done on masonry. Schwegler and Saadatmanesh \(^{34, 35}\) were the first researchers to analyze the use of FRP for strengthening of masonry structures.

This chapter presents the review of literature in the field of FRP strengthened masonry structures as under:

- Confinement of masonry columns with FRP
- Retrofitting of masonry walls using FRP

2.2 Confinement of Masonry Columns with FRP

Masonry column is one of the load bearing members in masonry structures and hence need special attention for strengthening or retrofitting. Confinement of column increases axial load carrying capacity of the column. This section summarizes the research done on strengthening of masonry columns with FRP. The work done has been divided in two categories as ‘Experimental Research Work’ and ‘Analytical Research Work’. The information has been compiled in the tabular formats wherever possible so as to get clear and complete understanding. This study aims at providing brief review of experimental and analytical research work on application of FRP on solid clay brick masonry columns for confinement. The literature review reveals that less research work has been done on masonry columns as compared to RCC columns and even on masonry walls.

2.2.1 Experimental Research Work

Experimental investigations of masonry columns with CFRP wrapping has been carried out by Shrive et al. \(^{36}\), 18 columns of three different cross sectional sizes and two different types of masonry units were tested. Strengthening was achieved by wrapping the square section columns directly with CFRP sheets or by wrapping columns after casting a circular concrete jacket around the column. Each column was initially loaded axially until cracking was
observed in the masonry. The columns were then wrapped with CFRP sheets over their height and retested under axial compression until failure occurred. The columns were of three different sizes and made up of two different shapes of masonry units, one of the types of bricks were regular with sharp corners and the other were of rounded corners termed as bullnose units. The cavity formed at the centre of the column in each case was filled with grout.

The modified circular columns showed significant enhancement in load carrying capacity as compared to square columns after strengthening. As the modified circular shape was obtained by concrete jacketing surrounding original square column, the contribution of CFRP wrap could not be quantified. Also, the technique of concrete jacketing to masonry column, proposed by researchers, may not be practically feasible. Another problem with such technique is that, it will add dead load to existing structure and hence, the very advantage of FRP being light weight can not be effectively utilized. However, it can be concluded from this experimental study that in case of square or rectangular columns, rounding off the edges of columns before FRP wrapping is essential to achieve higher confinement.

Bieker C et al. 37, carried out experimental evaluation of masonry columns strengthened with CFRP and GFRP. Solid bricks and vertical coring bricks were used for casting the masonry columns with calcium and calcium cement mortar. Uniaxial compression testing was carried out for all specimens and results were recorded. Experimental results showed increase in load carrying capacity of both types of masonry columns, however, increases in case of solid brick masonry was much higher as compared to vertical core brick masonry columns. In India, vertical core brick masonry is very rare as compared to solid brick masonry. The researchers have mentioned here, that more studies are necessary to analyse and complete these results.

Krevaikas and Triantafillou 38 carried out an experimental investigation on the behaviour of axially loaded short masonry columns confined with FRP jackets, followed by development of an analytical model for the prediction of confined strength and ultimate strain. Total 42 clay bricks masonry column specimens of three different dimensions as 115 x 115 mm, 172.5 x 115 mm and 230 x 115 mm were tested. Corners of all specimens were rounded at radius of 10 mm or 20 mm. Strengthening was done by using different number of layers (1, 2 and 3) of unidirectional CFRP sheets or GFRP sheets. There were total 17 categories with permutation and combination of column dimension, corner radius, number of layers of FRP and type of FRP such as CFRP or GFRP. More details on analytical model proposed are given in section 2.2.2 in this chapter.
In another series of experimentation Aiello et al. 39, 40 and 41 in the year 2007, 2008 and 2009 have studied the behaviour of FRP wrapped masonry columns. In 2007, Aiello et al. 39 studied mechanical behaviour of circular masonry columns built with calcareous blocks. In 2008 and 2009 Aiello et al. 40 and 41 have studied experimental behaviour of rectangular masonry columns and compared with analytical results obtained from Italian National Research Council guidelines (CNR DT200-2004) 42. Total 33 specimens of rectangular columns were tested. The parameters included different strengthening schemes, curvature radius of the corners, amount of FRP reinforcement, cross-section aspect ratio and material of masonry blocks. The strengthening scheme included internal and external application of FRP. Internal application was in the form of FRP bars inserted in the masonry column. In this category, variation was made in grade of reinforcement. Externally one or two FRP sheets/strips were wrapped. Corner radiuses were 10 mm and 20 mm. The masonry units used for columns were limestone and clay. Overall 18 full core columns and 12 hollow core columns of limestone and 3 full core columns of clay were tested with strengthening by GFRP. Hence, the major experimentation was on limestone masonry columns and very less specimens were of clay brick masonry columns.

Significant increase in peak load and ultimate axial deformation was reported for all the types of specimens. It has been observed that, in columns strengthened only with bars, the ultimate load was increased but brittle behaviour of unconfined masonry remained.

Uniaxial and triaxial tests on brick masonry columns with and without CFRP wrapping have been conducted by Alecci et al. 43. Cylindrical masonry column specimens of ¼ scaled dimensions were tested in triaxial compression device (Hoek cell). The failure was characterised by the rupture of the composite wrap in the central zone of the specimen height and by the cohesive debonding of the reinforcement in the bulk masonry for the length of a half perimeter.

For each CFRP wrapped specimen comparison between maximum loads obtained by various methods such as experimentally, analytically using CNR-DT200(2004), by using coefficients proposed by other researchers and upper and lower bounds has been presented. Researcher concludes that the upper and lower bounds determined in hypothesis that masonry is still undamaged or completely disintegrated when wrap breaks; are not useful. Another conclusion is that the final strength of the compressed masonry member confined with FRP does not depend on the initial strength but on the residual strength of the confined masonry.

Ludovico et al. 44 have carried out the experimental program to assess potential of confinement of masonry columns, made up of tuff masonry and clay brick masonry. Column
specimens were wrapped using one ply of different types of fibers and tested for axial compression. Along with Carbon and Glass FRP; Basalt FRP was used. The test results and their comparison helped to derive some conclusion in relation with performance of different FRPs. BFRP wrapping was more effective in terms of ultimate axial strain gain. Comparison of performance of tuff masonry and clay brick masonry showed that overall efficiency of FRP wrapping is more significant on clay brick masonry than on tuff.

In a more recent study, the application of steel fiber reinforced polymer (SRP) for masonry columns has been investigated by Borri et al. Total 23 masonry columns were tested out of which 10 were of square cross section of side 245 mm and 13 had octagonal shape with side of 100 mm. It has been reported by the researchers that octagonal masonry columns are quit common in Italy and the rest of Europe in many historical constructions such as churches, monasteries and porticoes. Two types of steel cords were used for strengthening the columns. All the fibers were made up of high-strength steel filaments covered with a layer of brass to prevent oxidation of the metallic cords. Type 1 cord was formed by winding four single high strength metallic filaments together and Type 2 was made by twisting five individual filaments together. The increase in strength and deformation capacity measured was significant demonstrating efficiency of SFP. Furthermore, comparison of experimental results has been done with analytical values obtained by using equations from CNR DT 200. However the performance of SFP can not be compared to other fibers like CFRP and GFRP from this experimental study.

In 2012, Khaled Galal et al. have reported that, most research efforts in retrofitting deficient masonry structural elements using FRP were directed to masonry walls, so less work has been conducted on retrofitting reinforced masonry columns. It is same for the case with solid clay brick masonry columns also.

Furthermore, whatever experimentation has been carried out on solid clay brick masonry columns, cannot be applied as it is in each case as the properties of bricks vary from region to region depending on the nature of available soil and technique adopted for moulding and burning, and the behaviour of masonry depends on its constituent materials bricks and mortar. Table 2.1 gives the compressive strength of clay bricks used by researchers.
Table 2.1: Compressive Strength of Bricks in Previous Research Works.

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Research Work</th>
<th>Compressive Strength of Bricks (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Borri et al (2011)</td>
<td>20.99</td>
</tr>
<tr>
<td>3</td>
<td>Aiello et al (2009)</td>
<td>23.29</td>
</tr>
<tr>
<td>5</td>
<td>Alecci et al (2009)</td>
<td>15.71</td>
</tr>
<tr>
<td>8</td>
<td>Krevaikas and Triantafillou (2005)</td>
<td>23.50</td>
</tr>
<tr>
<td>9</td>
<td>Bieker et al (2002)</td>
<td>20.00</td>
</tr>
</tbody>
</table>

It can be seen from Table 2.1 that brick compressive strength ranges between 15 to 23 MPa whereas the compressive strength of bricks in India is in the range of 7 to 10 MPa. Bureau of Indian Standards (BIS)\(^{48}\) has also presented the information about the compressive strength of bricks in various states of India; which is worth presenting here (Table 2.2)

Table 2.2: Compressive Strength of Bricks in Different Regions of India [from SP 20\(^{48}\)]

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>State of India</th>
<th>Compressive Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Delhi &amp; Punjab</td>
<td>7 to 10</td>
</tr>
<tr>
<td>2</td>
<td>Uttar Pradesh</td>
<td>10 to 20</td>
</tr>
<tr>
<td>3</td>
<td>Madhya Pradesh</td>
<td>3.5 to 5</td>
</tr>
<tr>
<td>4</td>
<td>Maharashtra</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>Gujarat</td>
<td>3 to 10</td>
</tr>
<tr>
<td>6</td>
<td>Rajasthan</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
<td>West Bengal</td>
<td>10 to 20</td>
</tr>
<tr>
<td>8</td>
<td>Andhra Pradesh</td>
<td>3</td>
</tr>
<tr>
<td>9</td>
<td>Assam</td>
<td>3.5</td>
</tr>
</tbody>
</table>

From Table No. 2.2, it can be seen that in majority of states compressive strength of bricks is in the range of 3 to 5 MPa.

Here, comparison of ‘compressive strength’ as one of the important property of bricks, has been presented just to highlight the fact, that the experimental results obtained in Germany, Italy or in Greece region cannot be applied directly in Indian scenario. Hence, experimental
investigations to assess the effectiveness of confinement of brick masonry columns by composite fiber wrap system has to be carried out using locally used materials.

In majority of experimental work, the FRP strengthening technique adopted is ‘Continuous wrapping’ 36, 37, 38, 40, 41, 43, 44 and 46. Very little work has been carried out by using ‘Discontinuous Wrapping’ technique 39 and 46. In case of brick masonry, continuous wrapping will change nature of basic material. Even it has been mentioned in CNR-DT200 42 that FRP reinforcement that completely encases the strengthened member may prevent migration of moisture, such FRP systems shall not be applied continuously to ensure the migration of moisture. As it has been proved by researchers experimentally, that the ‘Continuous Wrapping’ technique enhances the performance of masonry columns, it is essential to evaluate efficiency of ‘Discontinuous Wrapping’ technique experimentally and propose some alternative composite wrap systems.

The experimental program for the present study has been planned after critical review of available literature. The detailed experimental program is presented in Chapter 4.

2.2.2 Analytical Research Work

Among the research work on masonry columns, very less work has been done on analytical studies as compared to experimental studies. However, for development of analytical models for masonry columns confined with FRP; the basic concepts are adopted from the confinement of RC columns by steel reinforcement or by FRP. The calculation of the effect of confinement on strength of FRP reinforced compressed members is done as sum of the strength of unconfined element and an additional strength due to confinement and that depends on the confinement capability of wrap. In this section, the analytical models developed or modified by various researchers have been discussed in detail.

2.2.2.1 Analytical Model by Krevaikas and Triantafillou 38

Krevaikas and Triantafillou 38 in 2005 developed analytical model for strength and ultimate strain of FRP confined masonry. This model is discussed here in detail.

- **Stress Model**

The basis of this model is the concept and expressions for confined concrete.
\[ f_{MC} = f_{MO} \left( \alpha + k_1 \left( \frac{\sigma_{lu}}{f_{MO}} \right) \right) \leq f_{MO} \]  

where,

\( f_{MC} \) = Compressive Strength of Confined Masonry,
\( f_{MO} \) = Compressive Strength of Unconfined Masonry,
\( \alpha \) and \( k_1 \) = Empirical Constants and
\( \sigma_{lu} \) = Confining Stress at Failure.

The plot of \((f_{MC} / f_{MO}) \) Vs \((\sigma_{lu} / f_{MO})\) is provided and values of \( k_1 \) and \( \alpha \) are found out as 1.65 and 0.6 respectively. Substituting these values in above equation and taking \((f_{MC} / f_{MO}) = 1\), gives value of \((\sigma_{lu} / f_{MO})\) as 0.24. Hence, the model for strength has been finalized as follows:

\[ f_{MC} = f_{MO} \quad \text{if} \quad (\sigma_{lu} / f_{MO}) \leq 0.24 \]
\[ f_{MC} = f_{MO} \left( 0.6 + 1.65 \left( \frac{\sigma_{lu}}{f_{MO}} \right) \right) \quad \text{if} \quad (\sigma_{lu} / f_{MO}) > 0.24 \]

\section{Strain Model:}

For strain prediction also the basic equation is used which has been developed for concrete by other researchers.

\[ \varepsilon_{Muc} = \varepsilon_{Muo} + k_2 \left( \frac{\sigma_{lu}}{f_{MO}} \right) \]  

\( \varepsilon_{Muc} \) = Ultimate Strain of confined masonry,
\( \varepsilon_{Muo} \) = Ultimate Strain of unconfined masonry,
\( k_2 \) = Empirical constant and
\( \sigma_{lu} \) = Confining stress at failure.

From the experimental results, value of ‘\( k_2 \)’ has been obtained as ‘0.034’ and hence the analytical model developed for the ultimate strain of confined masonry is as follows:

\[ \varepsilon_{Muc} = \varepsilon_{Muo} + 0.034 \left( \frac{\sigma_{lu}}{f_{MO}} \right) \]  

It has been suggested by the authors that further experimental verification to account for types of masonry materials other than those used in their experiments should be carried out.
2.2.2.2 Analytical Model by Aiello et al. \(^{41}\) for Limestone Masonry

The calibration of the analytical model proposed by Krevaikas and Triantafillou \(^{38}\) has been done by Aiello et al.\(^ {41}\) for Limestone masonry. The analytical model for limestone masonry is as follows

\[
f_{MC} = f_{MO} \left( 1 + \frac{\alpha u}{f_{MO}} \right) \tag{2.5}
\]

Hence \(\alpha\) and \(k_1\) are found out as 1 for limestone masonry and above model has been obtained by substituting values of \(\alpha\) and \(k_1\) in Krevaikas and Triantafillou Analytical Model (Equation No. 2.1).

It has been mentioned by the authors that this equation is able to represent the tested conditions even if different strengthening schemes and corner radius were experienced.

2.2.2.3 Calibration of Basic Model of ‘Confinement of FRP strengthened Concrete and Reinforced Concrete Members’ for Confinement of Masonry members

The expression to predict the peak stress of a concrete element confined with a steel spiral is still in use and it was originally proposed in 1929 by Richart et al.\(^ {49}\).

\[
f_{cc} = f_{co} + k'f \tag{2.6}
\]

Where,

- \(f_{cc}\) = Compressive Strength of Confined Specimen,
- \(f_{co}\) = Compressive Strength of Unconfined Specimen
- \(k'\) = Confinement Coefficient and
- \(f\) = Lateral Uniform Confining Pressure.

Richart et al.\(^ {49}\) considered value of Confinement coefficient (\(k'\)) as 4.1 for confinement by steel spiral. Further, some researchers calibrated the Equation 2.6, by proposing different values of \(k'\) for FRP confinement of concrete members.

Toutanji and Deng\(^ {50}\) obtained value of \(k'\) as function of effective confining stress \(f'\) and unconfined concrete compressive strength \(f_{co}\), as follows.

\[
k' = 3.5 \left( \frac{f'}{f_{co}} \right)^{-0.15} \tag{2.7}
\]
The effective confining pressure \((f')\) is calculated from the lateral pressure \((f)\) as under

\[ f' = ke f \]

Where, \(k_e\) is effectiveness coefficient and it depends on the shape of cross section and transverse and longitudinal distribution of reinforcement.

Many researchers have modified Equation 2.7 by replacing 3.5 and -0.15 by other values for concrete members.

The above explained model of the year 1929, 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.

Borri and Grazini \(^{51}\) in 2004 and Corradi et al. \(^{52}\) in 2007 have calibrated Equation 2.6 as follows.

\[ k' = 2.4 \left( \frac{f'}{f_{cc}} \right)^{-0.17} \] \hfill (2.8)

In 2009, Alecci et al. \(^{43}\) carried out experimental investigations on scaled cylindrical masonry columns (discussed in section 2.2.1 of this chapter) and proposed the analytical model for confined masonry columns; which is also based of Equation 2.6 proposed in 1929.

\[ f_{cc} = f_{co} + 3.68f \] \hfill (2.9)

It shows, Alecci et al. \(^{43}\) have suggested value of \(k'\) as 3.68.

**2.2.2.4 Analytical Model by Ludovico et al.\(^{44}\)**

Experimental investigations on clay brick masonry columns and tuff masonry columns confined with FRP have been carried out by Ludovico et al. \(^{44}\) in 2010. The researchers have also studied the analytical models proposed by other researchers \(^{38, 42\text{ and } 52}\) and have suggested refined equations for prediction of strength gains of confined masonry columns.

**Tuff Masonry:**

\[ f_{MC} = f_{MO} (1 + k'(f_{1\text{eff}} / f_{MO})) \] where \(k' = 1.09 (f_{1\text{eff}} / f_{MO})^{-0.24} \) \hfill (2.10)

**Clay Brick Masonry:**

\[ f_{MC} = f_{MO} (1 + k'(f_{1\text{eff}} / f_{MO})) \] where \(k' = 1.53 (f_{1\text{eff}} / f_{MO})^{-0.10} \) \hfill (2.11)
It can be seen that, analytical models suggested for Tuff masonry and Clay brick masonry are modification of Krevaikas and Triantafillou \(^{38}\) model. The analytical models developed for confinement of masonry columns with FRP are based on the concept of calculation of strength of confinement of concrete columns. All the models developed are on the basis of experimentation conducted by researchers on masonry columns wrapped by FRP. Experimental and analytical research is being carried out on use of FRP as strengthening alternative for masonry structures since last two decades. Hence, more and more research work is required in this context to establish this innovative technique for strengthening the large number of masonry structures.

2.3 Retrofitting of Masonry Walls with FRP

Walls are the main structural members in masonry structures. In most of the existing structures these are designed to carry gravity loads. The masonry being strong in resisting compression, walls can take these loads safely. However, as masonry is weak in resisting tension, the walls are most vulnerable to seismic loads. The design of strengthening or seismic retrofitting technique requires understanding of failure pattern of the member. In this chapter, the failure patterns of masonry walls are discussed under lateral loading and the research work carried out on retrofitting of masonry walls using FRP is presented. Retrofitting for In-Plane failure of masonry walls using FRP has been discussed in detail.

2.3.1 Failure Pattern of Masonry Wall subjected to Various Types of Loads

Load bearing masonry walls are subjected to gravity loads due to dead load and live load. Lateral load is generated due to wind or earthquake. Various types of stresses are induced in wall due to different types of loads, which leads to failure if wall is not capable of resisting the stresses. Hence, it is essential to study and understand failure patterns in order to avoid failure by retrofitting the walls.

2.3.1.1 Vertical Compression Load

In a load bearing masonry structure, walls are mainly subjected to vertical compression, which causes compressive stresses in wall. The design codes gives guidelines to calculate the allowable compressive strength of the masonry wall considering the dimensions of the member, end conditions, slenderness ratio and any other significant parameter. Hence, the
axial vertical load causes compressive stresses in wall and depending upon the dimensions, basic material properties, compressive strength of the wall can be calculated and checked whether, the compressive stress due to loads is within the compressive capacity of the wall. Most of the time the wall takes these superimposed vertical loads safely as masonry is strong in resisting compression and they are designed for it. The failure may take place in compression mode due to additional loads on members because of modifications done in building, change in use of structure or deterioration of material on ageing.

### 2.3.1.2 Out-of-Plane Bending

If the vertical compression is not purely axial and there exists some eccentricity, then along with compressive stresses some flexural stresses are also developed. These flexural stresses are Out-of-plane in nature. Hence, the combined axial and bending load causes compressive as well as tensile stresses in wall. Here, the eccentricity of the load plays an important role and the codes provide guidelines for calculation of eccentricity. The IS 1905:1987 states that the eccentricity of loading depends on the extent of bearing, magnitude of loads, relative stiffness of slab or beam and wall, degree of fixity at the support and with these all requires judgement. The masonry wall for this case is either checked for no tension condition or checked whether the tensile stresses due to out-of-plane bending are within limits of permissible tensile stresses. Hence, if axial compression is with eccentricity, it will cause out-of-plane bending of the walls and wall can fail due to flexure.

Out-of-Plane bending is also caused by transverse loads due to wind or earthquake. Masonry walls subjected to out-of-plane loading resist the load by flexural action. The load capacity of unreinforced masonry wall panels depends upon the dimensions and support conditions, the level of compressive stress in the wall and the tensile strength of the masonry. Masonry walls behave differently under simple bending in one direction (for example between top and bottom supports) and bending in two directions (such as when the wall has support on at least two adjacent edges).

### 2.3.1.3 In-Plane Bending

The predominant horizontal earthquake forces are transferred to walls in proportion to their stiffness from the floor, which acts as horizontal diaphragm. This horizontal force causes In-Plane bending of wall. The walls resisting these lateral forces of earthquake or wind are also termed as masonry shear walls. The walls are subjected to vertical compression as well as lateral in plane loads. The masonry shear wall typically fails in the following three modes.
- Sliding Shear Failure: The failure occurs by sliding along the bed joint. The bed joint sliding tends to occur only in very squat members\(^5\). Also in a wall with poor mortar strength or low pre-compression, sliding shear failure takes place\(^5\).

- Diagonal Cracking: The failure is attained by formation of diagonal crack. The diagonal crack usually develops at the centre and may propagate through brick units or through mortar joints in stepped pattern. In walls, with low to moderate aspect ratios (height/length) and high axial loads, this type of failure occurs\(^5\) and\(^5\).

- Rocking: If the applied vertical load is low with respect to compressive strength, the horizontal load produces tensile flexural cracking at corners and uplift of the heel.

### 2.3.2 Experimental Research on Retrofitting of Walls with FRP

As mentioned earlier, Schwegler and Saadatmanesh were the first researchers to analyse the use of FRP for strengthening of masonry structures\(^3\). Ehsani and Saadatmanesh have done a lot of research work on FRP application for masonry structures. In 1996, Ehsani and Saadatmanesh\(^5\) conducted flexural tests on brick masonry beams and shear tests on brick masonry specimens, retrofitted with FRP. In both the test they found significant increase in load carrying capacities of specimens due to FRP. Further in 1997 Ehsani et al\(^5\) studied the shear behaviour of URM retrofitted with FRP overlays. In 1999, same group of researchers along with Velazques-Dimas\(^5\) tested three wall specimens strengthened with GFRP strips subjected to out-of-plane cyclic loading. The compressive strength of bricks used was 45 MPa. (Bricks available in India are of range 3-10 MPa\(^4\)). The tested specimens were capable of supporting lateral load up to 32 times the weight of wall. Regarding failure pattern, the researchers observed that, URM walls and composite strips behave in brittle manner; the combination resulted in a system capable of dissipating some energy. This experimental work was extended further and four wall specimens were tested for out-of-plane loading in the year 2000\(^5\). J. I. Velazques-Dimas and M. R. Ehsani\(^5\) in 2000, conducted experimental investigations again on out-of-plane behaviour of masonry walls strengthened with GFRP. Seven half-scaled brick masonry walls were tested. Parameters studied in this experimental work were amount of composites, height to thickness ratio of wall specimens, tensile strain in composites and mode of failure. Based on the experimental work, it was concluded that, the behaviour of the walls is best predicted with a linear elastic approach.
Triantafillou\textsuperscript{60} in 1998, tested wall specimens of dimensions 120 x 400 mm in cross section and 900 mm length (dimensions, almost like beam specimens). Six specimens were tested for out-of-plane and six were tested for in-plane static loading. In each test, two specimens were un-retrofitted and served as control specimens and rest four were retrofitted with unidirection CFRP laminates. Out-of-plane bending specimens failed by crushing of masonry in compression zone, indicating flexural failure, whereas, in-plane specimens failed by peeling off of the CFRP laminates. In both the tests, the difference between load carried by control specimens and retrofitted specimen was significant. Also, it can be seen by comparison of results that, specimens of same dimension, retrofitted with same amount of CFRP laminates, took almost double load when subjected to in-plane load, that of subjected to out-of-plane load.

In last decade, experimental research work to study structural behaviour of masonry walls, retrofitted with composite materials to resist out-of-plane loading has been carried out by various researchers\textsuperscript{61, 62, 63, 64, 65, 66, 67, 68, 69}. The experimental research done on walls subjected to in-plane lateral load is discussed in next section (2.3.2.1).

\textbf{2.3.2.1 Retrofitting of Walls with FRP, subjected to In-Plane Lateral load}

Masonry walls are subjected to lateral in-plane loads due to seismic forces. In most of the earthquakes, in-plane failure of masonry walls has been observed. The 1985, earthquake in Chile produced extensive damage in reinforced masonry buildings with more than 3 stories due to in-plane shear actions\textsuperscript{70}. The overall seismic performance of URM building depends on the capacity of in-plane walls to transfer lateral forces to the foundation and hence intact in-plane walls provide post-earthquake stability necessary to avoid collapse of the entire structure\textsuperscript{71}. The researchers have reported that very little work on in-plane behaviour of FRP strengthened masonry walls has been done\textsuperscript{72, 73}.

The literature available on the FRP retrofitted masonry walls subjected to in-plane lateral load, reveals two methods of testing. In one type of testing, the in-plane lateral load is applied horizontally at top of the wall (Figure 2.1A) whereas in another type, the load is applied along the diagonal of the wall (Figure 2.1B). The later test is termed as diagonal compression test, which have been standardized\textsuperscript{74} for URM walls measuring 1200 mm × 1200 mm, although a number of variations have been reported in the literature\textsuperscript{71}. Diagonal compression test has been performed by most of the researchers by keeping the wall specimens such that one diagonal will be horizontal and other will be vertical and the compressive load has been applied on the specimen along the vertical diagonal. Whereas, Hamid Mahmood & Jason
Ingham \textsuperscript{71} tested the walls without changing the orientation of walls and applying the compressive force along one of the diagonal.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2_1}
\caption{Test arrangements for Wall Specimens subjected to In-Plane Lateral Load}
\end{figure}

The experimental work carried out by researchers in this context has been discussed in this section considering the test procedure for in-plane walls.

- **Diagonal Compression Test**

A. Prota et al. \textsuperscript{75} studied experimental in-plane behaviour of tuff masonry strengthened with cementitious matrix-grid (CMG) composites. The basic material characterization has been carried out for tuff masonry units, mortar and masonry. The tests included compression test on tuff and mortar samples, flexural test on mortar, bond shear tests between tuff and mortar. Set up and instruments used for diagonal compression test have been explained in detail. Compression test on one wall panel was conducted and diagonal compression test on twelve panels was conducted; out of which four were control specimens and eight were strengthened with composites. All panels were of dimensions 1030 x 1030 x 250 mm. The panels were strengthened on both sides but some with one ply of CMG and some with two plies. The experimental results showed that the shear capacity of the strengthened walls was substantially increased by the CMG reinforcement with an increase of about 170 and 220 \%. When double CMG layers were applied at both sides a more uniform cracking was attained, leading to better shear performance.

In 2009, non-linear analysis of Tuff masonry walls strengthened with cementitious matrix grid (CMG) composites was carried out by Gian Piero Lingnola et al. \textsuperscript{76} considering the experimental work carried out in 2006 \textsuperscript{77}. The detailed discussion on behaviour of
strengthened specimens has been presented in this research paper along with finite element analysis for the same. The finite element analysis will be discussed in next section (‘Analytical Research Work’) in the same chapter.

Along with detailed discussion on crack patterns, result comparisons one more important issue has been discussed in this study. The authors reported that, almost identical tested masonry panels could provide scattered results. This is mainly due to variability of basic material properties and potential workmanship defects. Whereas, the strengthened panels were less sensitive to workmanship defects and the strengthening performances were superior if applied to deficient panels.

Petersen et al. 78, investigated in-plane behaviour of FRP strengthened masonry panels experimentally. The FRP strengthening was done by using Near Surface Mounted (NSM) strips of carbon fibers. Four un-reinforced masonry walls and seven FRP strengthened walls were tested in diagonal load test. All the specimens were of size 1200 X 1200 mm and 110mm in thickness. The CFRP strips of 15mm width and 2.8 mm thickness were used for strengthening in different patterns. One specimen was strengthened with two vertical NSM CFRP strips on one side. Two specimens were strengthened with total four strips, two on each side. Further, two specimens were retrofitted with four horizontal strips, two on each face of the wall. Rest two were strengthened with combination of vertical and horizontal strips. Thus effect of vertical, horizontal, FRP on one face, FRP on both faces, and combination of vertical and horizontal was investigated in this experimental work. The increase in load carrying capacity was obtained in the range of 1% to 46 %. Form the experimental results, researchers concluded that, NSMFRP strips are an effective shear strengthening technique. Vertical strips bonded into the brick units are effective at restraining both the opening of diagonal cracks and sliding along mortar joint cracks, resulting in increases in strength and ductility. Horizontal strips bonded into the brick units are only effective at restraining the opening of diagonal cracks. Horizontal reinforcement is most effective when combined with vertical reinforcement that is designed to restrain mortar bed joint sliding.

Diagonal compression tests were performed on 17 FRP-retrofitted solid clay brick masonry wallets by Hamid Mahmood and Jason M. Ingham 71 in 2011. Walls were of dimensions 1170 x 1170 and 1170 x 1070 mm with thickness 225 mm. Clay bricks of compressive strength 11.2 to 21.2 MPa and weak mortar (1 cement :2 lime :9 sand) of compressive strength 1.4 to 3.2 MPa were used as basic materials. GFRP and CFRP were used for retrofitting the walls. The wallets were retrofitted with FRP materials, including uniaxial
and biaxial GFRP fabrics and pultruded CFRP plates and NSM rectangular bars. Out of 17 walls, only two walls were retrofitted by applying FRP on both faces whereas, for rest 15 walls FRP were applied only on one face. Total eight walls were retrofitted with GFRP with each wall in different configuration. The configuration included, full surface with uniaxial, biaxial GFRP, horizontal strips, vertical strips, diagonal strips and grid of horizontal and vertical strips. Five walls were retrofitted with CFRP plates, whereas, four walls were retrofitted with CFRP NSM bars. Plates were applied in similar patterns that of GFRP (except full surface). In case of NSM bars, two walls were strengthened on one face whereas two walls were strengthened on both faces. The bars were fixed in two patterns, one as vertical and second horizontal. For each configuration only one specimen was tested. The diagonal compression test was conducted for each specimen; however the testing arrangement was different as compared with previous research works. Instead of rotating wall specimens, hydraulic jack was inclined such that load will be transferred diagonally to walls. The Fig No. 2.2 shows testing arrangement used by Hamid Mahmood and Jason M. Ingham \(^{71}\) in experiments carried out for diagonal compression or shear test.

![Testing arrangement: Hamid Mahmood and Jason M. Ingham \(^{71}\) in 2011](image)

**Figure 2.2:** Testing arrangement: Hamid Mahmood and Jason M. Ingham \(^{71}\) in 2011

The maximum increase in shear strength (0.54 MPa) was achieved with full surface biaxial GFRP fabrics. Application of strips cut from the fabrics was less successful in increasing shear strength, except for the diagonal and grid configurations. Use of the NSM CFRP rectangular bars on both faces resulted in the highest strength increase (0.46 MPa) of all CFRP-retrofitted wallets, with single-faced NSM CFRP being comparatively ineffective, thus, indicating better performance when the NSM application was installed on both faces of
the wallettes that failed by diagonal shear cracking. Significant shear strength increase was also obtained with the diagonal configuration of CFRP plates. A significant increase in shear strength was also obtained for walls with only vertical FRP elements. Overall, an increase in shear strength of 31–325% (0.11–0.54 MPa) of the unretrofitted wall strength was achieved with the application of the various retrofit interventions.

The experimental program consisted of large number of configurations, however, GFRP and CFRP results could not be compared directly as both these materials were used in different form and configurations.

- **Horizontal Lateral Load Test**

The horizontal lateral in-plane force is applied on wall specimens in this type of test. In addition, vertical compressive load can be applied on the specimen, which is more close to situation in walls of existing structures, as walls are subjected to slab and walls load from upper story.

The experimental research carried out in this context, is discussed in this section.

Chuang et al. 79 conducted experimental investigations on seismic retrofitting of URM walls by FRP Strips. Three full-scale clay brick masonry walls retrofitted with FRP have been tested under combined compression and racking cyclic loads. Wall with aspect ratios of less than 1.0 have flexural strength higher than their shear strength. These walls should fail in shear in a non-ductile manner. The wall dimensions were 940 x 940 x 110 mm. vertical and lateral load was applied by using hydraulic jacks. Axial load of 0.2 MPa was applied to the wall to simulate an applied roof and second story onto the wall. Identical axial loads were applied to all specimens to make it convenient to compare the results between specimens. One wall was tested as control specimen and remaining two walls were retrofitted with two different configurations of CFRP strips. First configuration was two diagonal strips and the other was with two diagonal and two vertical strips (total four strips.)

The un-retrofitted wall behaved in a combination of rocking and sliding. The reason cracking occurred above the third course of masonry rather than the first is due to the metal bracket to prevent the wall from moving.

The improvement of the ultimate lateral load resistance of the retrofitted walls with two FRP strips and four FRP strips strengthening was respectively 3 times and 4 times the capacity of unreinforced wall. Experiments conducted in this study show that FRP strips retrofitted to low-rise masonry walls are effective in significantly increasing their in-plane strength, ductility, and energy dissipation capacity.
In 2004, Stratford et al. 80 carried out the research work in which, clay and concrete block masonry specimens, strengthened with GFRP were tested for lateral in-plane load along with vertical compression. Single sided strengthening was done, as it is often not practicable to apply reinforcement on both sides of walls. Three clay brick wall specimens of dimensions 1.2 m x 1.2 m were tested, out of which one specimen was unstrengthened which served as control specimen. Rest two specimens were strengthened by applying biaxial GFRP sheets on one entire side of the wall. Compressive strength of bricks was 62 MPa and that of mortar was around 11 MPa.

Vertical compression load was applied through two hydraulic jacks and lateral load was applied by one horizontally fixed hydraulic jack. Horizontal deflection was measured using lvdt and strain in FRP was measured using strain gauges. Small regions of local debonding initially formed and the debonded region spread suddenly, roughly along the compressive diagonal. Debonding of the GFRP from the masonry occurred in the same manner as in the small-scale pull off specimens. In the clay walls, failure was either at the epoxy–brick interface (possibly due to imperfect cleaning), between the adhesive and filler layers, or beneath the surface of the brick. In the concrete walls, the failure was between the cement render and the bricks.

Strengthening the clay walls with GFRP increased the load–capacity from approximately 115 to 190 kN (an increase of 65%). The stiffness and deformation-capacity of the specimens was not changed by the GFRP.

ElGawady et al. 81 studied in-plane seismic response of URM walls upgraded with FRP. The experimental tests included two phases: the first phase consists of testing five reference URM specimens until a predefined degree of damage occurred; the second phase consists of upgrading these reference specimens, using one layer of FRP on one face, then retesting them.

Half-scale single wythe walls were constructed using half-scale hollow clay masonry units. Two mortar types were used: Type 1 was a strong mortar (M9) and Type 2 was a weak mortar (M2.5). The average compressive strengths were 7.2 and 5.7 MPa for masonry assemblages built using mortar Types 1 and 2, respectively. One of the walls was upgraded with two composite materials; the wall was first strengthened with CFRP plates and tested. Then the CFRP plates were removed and GFRP was applied on full surface and tested again. This type of work is not reported in literature. The specimens were tested on the uniaxial earthquake simulator. Form the total six tests, conclusions were drawn. The FRP upgrading is promising; it improved the wall lateral resistance by a factor of 1.3–2.9. Expectedly, the
increased ratio is higher for lower normal force. It has been reported by the researchers, that within the test conditions, one sided upgrading was successful. No out-of-plane or uneven response of the walls was observed. The X shape-upgrading configuration had the maximum drift of all the specimens. In some cases there was debonding of the fiber. Along with these conclusions, two interesting observations have been mentioned in this work. The fabric prevented falling of debris from the wall after failure, thus preventing possible injuries to occupants in the vicinity of the wall in the event of a real earthquake. This aspect adds to the advantages of using FRP for retrofitting of masonry structures. And the second observation was, mortar compressive resistance had little influence on the URM-FRP lateral resistance.

Another experimental research was conducted in 2006 by Santa Maria et al. ⁸², on FRP retrofitted masonry walls subjected to in-plane loading. Two URM walls and four URM walls with externally bonded CFRP were subjected to in-plane cyclic loading. Two external reinforcement configurations were used: diagonal and horizontal. The objective of these tests was to quantify the improvement in shear resistance and to study the effect of the orientation of the reinforcement in the behaviour of the walls.

The masonry walls were of nominal dimensions 1975 x 2000 x 140 mm. The hollow clay bricks of 11 MPa compressive strength and premixed mortar of 25 MPa compressive strength was used for walls. Two walls were not reinforced. Two horizontally reinforced walls (HRM) had three horizontal strips of carbon fabric bonded on each side and two diagonally reinforced walls (DRM) had one strip bonded to each diagonal, on each side of the walls. The walls were subjected to displacement controlled in-plane cyclic shear load and a simultaneous constant vertical load, by means of hydraulic rams attached to the reaction frame. The nominal vertical load of 98 kN was applied on walls.

In the reinforced walls the first major crack occurred at approximately 3 mm of lateral displacement, compared to only 1.2 mm average for the URM walls. Also, the load at which the major crack was observed increased from 120 kN in the URM walls to between 160 to 190 kN in the reinforced walls. The DRM walls had an increase in strength of 63% and 84%, while de HRM walls had 57% and 61% increase of strength.

In 2008, this experimental program was extended and sixteen wall specimens were tested by horizontal load test ⁸². Sixteen hollow clay brick masonry walls with dimensions 1975 x 2400 x 140 mm were subjected to cyclic shear loads. Twelve walls were without shear reinforcement and four walls were with shear reinforcement. CFRP strips were bonded on both faces of masonry walls in different patterns. Hollow clay bricks of average
compressive strength 11.3 MPa were used for construction of walls. The nominal vertical load of 98 kN was applied on walls, corresponding to load on a ground floor wall in a three story building. The cracking pattern changed from large diagonal cracks to a network of several diagonal cracks of smaller width, in case of non shear reinforcement walls. Whereas, the cracking pattern of FRP retrofitted shear reinforced walls was same as control wall, as shear steel reinforcement controlled the cracks.

The CFRP strengthening was more effective in non shear reinforcement walls, increasing the maximum load between 49 to 84 % whereas in case of walls with shear reinforcement, the increase varied from 13 to 34 %. The strength increased with increase in amount of CFRP material. One more interesting conclusion has been drawn from this experimentation is, the retrofitted walls with only one horizontal or diagonal CFRP strip had a brittle failure with sudden loss of strength, whereas the CFRP reinforcement distributed as three strips showed less brittle failure, with residual strength and larger post-peak-load deformation capacity.

The testing of infill walls was also carried out to assess effectiveness of FRP retrofitting for in-plane masonry walls. In 2007, Tarek H. Almusallam and Yousef A. Al-Salloum \(^{83}\) studied the infill walls behaviour. The researchers mention here that little work has been reported on in-plane behavior of FRP strengthened masonry walls as compared to out-of-plane. In this experimental program, behaviour of infill masonry walls strengthened with GFRP, subjected to in-plane cyclic loading has been studied. Three different tests were conducted on two infill masonry wall specimens, cast in concrete frame. First specimen was tested without any GFRP application and hence served as control specimen. This control specimen was tested till diagonal cracking, on application of cyclic loading. In the second test, this specimen was repaired using GFRP sheets and retested under in-plane lateral cyclic loading up to failure. The third test was conducted on undamaged specimen by strengthening with FRP sheets, subjected to in-plane lateral cyclic loading till failure.

The infill wall specimens were of dimension, 2100 mm x 1550 mm x 100 mm and were made up of concrete block masonry. The compressive strength of concrete blocks was 7.1 MPa. Three horizontal strips of GFRP were applied on both sides of walls. The control wall failed in shear by showing diagonal cracking on both sides and breaking of bonds between walls and columns were also observed. In case of GFRP applied specimens, at the failure stage, it was observed that there was an almost horizontal long crack at the interface of the longitudinal edge of the FRP sheets and the wall surface. Also some longitudinal fiber failure and debonding of FRP sheets were observed. The results showed that the gain in the load
carrying capacity of the repaired specimen was 6% over the control specimen. However, the load carrying capacity of the strengthened specimen decreased by 11%, while the deformation increased twice that of control specimen.

The literature review on retrofitting of masonry walls with FRP shows that more research work on walls subjected to in-plane lateral load is required to be carried out. The efficiency of ‘Discontinuous wrapping’ technique needs to be evaluated for masonry walls in Indian scenario.

### 2.4 Masonry Codes

Until 1950’s there were no engineering methods of designing masonry for buildings and thickness of walls was based on *Rule-of-Thumb* tables given in Building codes and Regulations. Thereafter the intensive research on masonry was conducted in advanced countries and the codes on masonry were established. In this section, the review of masonry codes from number of countries has been presented to understand the global scenario of masonry codes. The codes are discussed here in three sub sections as, 1) the codes available for design of Masonry Structures, 2) codes for Repair / Strengthening / Retrofitting of Masonry Structures and 3) codes for Strengthening / Retrofitting of Masonry Structures using FRP.

#### 2.4.1 Codes for Design of Masonry Structures

- **Eurocode 6 (BS EN 1996)**

  This code was published by the European Committee for Standardization (CEN) and is to be used with the National Application Document (NAD) of member countries. It consists of four documents. Part 1-1 is for General rules for reinforced and unreinforced masonry structures, Part 1-2 is for structural fire design, Part 2 discuss about Design considerations, selection of materials and execution of masonry and Part 3 gives simplified calculation methods for unreinforced masonry structures. Seismic design aspects are not covered in Eurocode 6, however Eurocode 8 is for design of structures in seismic regions and 86.

- **Building Code Requirements For Masonry Structures**

  *(ACI 530-02/ASCE 5-02/TMS 402-02)*

  This code provides minimum requirements for the structural design and construction of masonry elements consisting of masonry units bedded in mortar. The code discuss in detail,
‘Allowable Stress Design’ and ‘Strength Design’ for Unreinforced and Reinforced Masonry. This code has been adopted as standard of the American Concrete Institute (ACI) in 2002, the Structural Engineering Institute of American Society of Civil Engineers in 2001 and The Masonry Society in 2002.

- **International Building Code 2000**
  International Building Code 2000 has been developed by International Code Council, designed to meet need for a modern, up-to-date building code addressing the design and installation of building systems through requirements emphasizing performance. A separate chapter (Chapter 21) has been provided for Masonry. This chapter covers the materials, design, construction and quality of masonry. Masonry design by ‘Working Stress Method’, ‘Strength Design’ and ‘Empirical Design’ has been discussed in this code. Seismic design requirements for masonry are also provided in this code.

- **Canadian Standards Association (CSA) Standards, Design of masonry structures (S304.1-04)**
  This is a limit states design standard. This Standard provides requirements for the structural design of unreinforced, reinforced and prefabricated masonry structures and components in accordance with the limit states design method of the *National Building Code of Canada*. This Standard also provides requirements for the structural design of prestressed masonry beams, walls and columns. In addition, this Standard provides requirements for the empirical design of unreinforced masonry.

  This code has been established by ‘Standards Council’ superseding NZS 4230:Parts 1 and 2:1990 ‘Practice for the Design of Concrete Masonry Structures’. This latest document recognizes the predominant use of reinforced concrete masonry for structural applications in New Zealand and incorporates research findings specifically pertaining to the performance of reinforced and prestressed concrete masonry.

- **IS 1905:1987 Code of Practice for Structural Use of Unreinforced Masonry**
  IS 1905:1987 is Indian Standard code for structural use of Unreinforced Masonry. This code gives recommendations for structural design aspect of unreinforced load bearing and non-
load bearing walls, constructed with solid or perforated burnt clay bricks, sand-lime bricks, stones, concrete blocks, lime based blocks or burnt clay hollow blocks in regard to the materials to be used, maximum permissible stresses and the methods of design.

2.4.2 Codes for Repair / Strengthening / Retrofitting of Masonry Structures
There are few codes or guidelines available for repair/ strengthening / retrofitting of Masonry Structures.

- FEMA 547: 2006: Techniques for the Seismic Rehabilitation of Existing Building 19
This document describes the common seismic rehabilitation techniques used for existing buildings. FEMA 547 19 supersedes FEMA 172 18: NEHRP Handbook for Seismic Rehabilitation of Existing Building; which was published in 1992. In FEMA 546, various techniques for seismic retrofitting of existing Unreinforced and Reinforced Masonry buildings have been discussed in detail. The techniques covered in this document are ‘Concrete Overlay to Masonry Walls’, ‘Addition of Concrete or Masonry Shear Wall’, ‘Addition of Steel Moment Frame’, ‘Addition or enhancement of crosswalls’ and ‘Addition of Veneer Ties in URM Wall’. FEMA 547 has also suggested ‘Fiber Reinforced Polymers Overlay to Masonry Wall’ as one of the strengthening technique. It has been mentioned that improving inadequate in-plane wall strength is the primary purpose of a new fiber-reinforced polymer (FRP) overlay, but the overlay can also improve out-of-plane bending capacity. It has been also mentioned that there are no code guidelines or FEMA 356 92 provisions explicitly addressing FRP overlays on unreinforced masonry.

- Indian Standard Codes
IS 13828:1993 93 (Reaffirmed 2008) ‘Improving Earthquake Resistance of Low Strength Masonry Buildings – Guidelines’, this code discuss the technique of providing lintel band and roof band to masonry buildings. IS 13935:2009 94 ‘Seismic Evaluation, Repair and Strengthening of Masonry Buildings- Guidelines’. The 1976 version of IS 4326 95, contained some recommendations for low strength brick masonry and stone buildings, which have been covered in greater detail in IS 13935:2009. This code discusses the selection of material and technique for strengthening. Techniques such as Grouting, Shotcrete, Strengthening with wire mesh, seismic belts around door and window openings, Prestressing, Providing seismic belts
are discussed in this code. The code mentions that Fibre-reinforced polymers/plastics are a recently developed material for strengthening of reinforced concrete and masonry structure.

2.5.3 Codes for Strengthening / Retrofitting of Masonry Structures with FRP

Separate codes for Strengthening / Retrofitting of Masonry Structures using FRP are not available, however AC125, 2003 and CNR DT 200 (2004, R1/2013) discuss about the masonry structures or elements retrofitted with FRP.

- AC125, 2003: Interim Criteria For Concrete and Reinforced and Unreinforced Masonry Strengthening Using Fiber-Reinforced Polymer (FRP) Composite Systems
  
  This criterion establishes minimum requirements on fiber-reinforced polymer (FRP) composite systems used to strengthen concrete and masonry structural elements. In this code, qualification tests for various elements of structures have been discussed, for masonry walls Out-of-plane and In-plane load tests are discussed. Minimum acceptance design criteria for flexural strength enhancement, axial load capacity enhancement and shear strength enhancement using FRP has been discussed.

  
  This document is developed by National Research Council, Advisory Committee on Technical Recommendations for Construction, Italy. This document contains sections on Materials, Basic concepts on FRP strengthening, Strengthening of reinforced and prestressed concrete structures, Strengthening of masonry structures. Design guidelines for use of FRP as strengthening material for masonry columns and walls are provided in detail in this code.

No Indian Standard is available till date for Masonry Structures retrofitted with FRP.

2.5 Concluding Remarks

From the available literature, it is observed that experimental work has been carried out by several researchers but the results and analytical models based on these experimental works cannot be applied directly in Indian scenario as the properties of basic materials that constitute masonry vary drastically.
FRP has been applied as ‘Continuous Wrapping’ in majority of experimental studies, whereas, experimentation on application of FRP as ‘Discontinuous Wrapping’ is limited. It is essential to evaluate efficiency ‘Discontinuous Wrapping’ technique experimentally and propose some effective wrapping technique for masonry members.

Literature review reveals that very limited information is available on Strengthening / Retrofitting of masonry structures as far as Indian codes are concerned and further no IS code is available for Strengthening / Retrofitting of masonry structures using FRP. Reliable experimental data base is required to be created for developing such guidelines in Indian scenario also, in the regions where masonry material properties are similar.

Hence, it is essential to study the behaviour of FRP strengthened / retrofitted masonry columns and walls experimentally and to develop the analytical model /analysis for further applications in the field, considering the Indian conditions.