BEHAVIOR OF MASONRY ASSEMBLIES WITH AND WITHOUT GFRP AND TRM STRENGTHENING UNDER STATIC INPLANE LOADING

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A Dissertation Submitted to
Indian Institute of Technology Hyderabad
In Partial Fulfilment of the Requirements for
The Degree of Master of Technology

भारतीय प्रौद्योगिकी संस्थान हैदराबाद
Indian Institute of Technology Hyderabad

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JULY, 2014

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Acknowledgements

I would like to express my highest appreciation to my supervisor, Dr.S.Suriya Prakash, who gave me the opportunity to work in this interesting area and for the patient guidance, encouragement and advice he has provided through my time as his student. His effort in supporting me throughout the work was invaluable. I have been lucky to have such a supervisor who cared so much about my work and who responded to my queries promptly. I also would like to thank Prof. K.V.L. Subramaniam for his precious guidance that represented a constant source of help and encouragement throughout the work. I really appreciate the discussions we have had.

ABSTRACT

The seismic events recently occurred all over the world and, in particular, in India have shown the high vulnerability of particular classes of buildings. The damage of structural masonry elements is one of the most widespread harming injuries and cause of loss of serviceability and seismic capacity for a building. The damage suffered by these masonry elements has laid emphasis to strengthen them with appropriate reinforcing systems in order to achieve an upgrading to the necessary seismic and energy dissipation capacity. Different Strengthening techniques have been proposed and studied during, with particular on to the type of materials, system configuration with respect to the element that is to be strengthened, difficulties in the process of application and effectiveness of the reinforcement. In the last years, though different studies have been carried out in this field, many issues regarding the methods to evaluate the actual behaviour of these techniques, and their effectiveness in the improvement of seismic behaviour of the elements to which they are applied, are still open.

In the present study the structural behaviour of unreinforced masonry assemblages without strengthening and with GFRP and TRM (Textile Reinforced Mortar) strengthening is studied. The assessment of the overall increase of capacity of the strengthened masonry assemblages is performed. first of all, the study is focused on the investigation of the mechanical characteristics of the strengthening system in itself. In fact, the structural behaviour of an externally applied strengthening system for masonry assemblages is examined. There are two reinforcing techniques considered in the present research, the first one is GFRP strengthening and the second one is TRM strengthening in which mortar layers incorporate a PP reinforcement in the form of grid. Both the GFRP and PP reinforcements are externally applied to the masonry assemblages. The mechanical behaviour of the parent materials such as brick, mortar is assessed and then the behaviour of assemblages under compression and shear loading is assessed through laboratory tests and constitutive laws can be proposed to characterize the reinforced mortar mechanical behaviour. The experimental characterization of the presented system is followed by and validated through numerical modelling and simulation of its mechanical behaviour.

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CHAPTER 1

INTRODUCTION

1.1 GENERAL

A large percentage of the building stock in India and around the world comprises of non-engineered unreinforced masonry (URM), unreinforced block or adobe masonry structures. The performance of these buildings in the past has shown that these masonry buildings are highly vulnerable to failure under seismic loads. In particular, URM exhibit brittle failure modes under seismic loading and are prone to complete collapse. Typical failure modes of the URM buildings under inplane and out-of plane modes are shown in Figure 1.1.

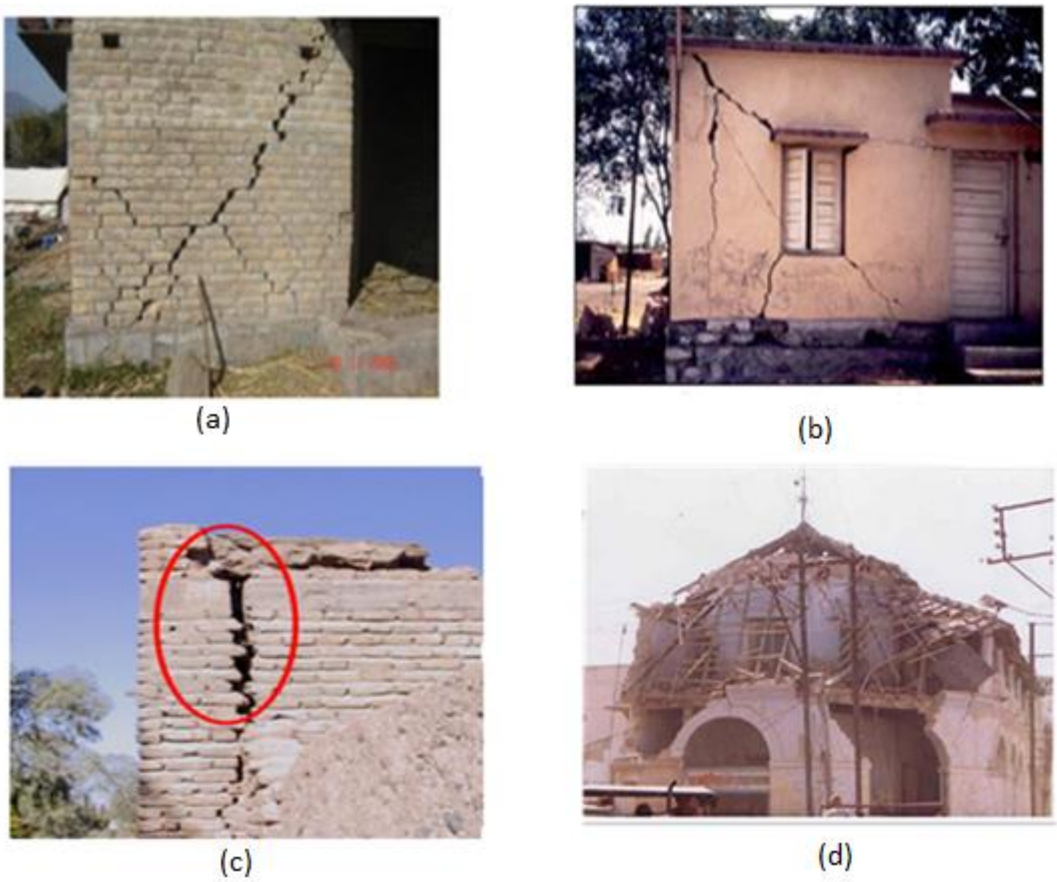


Figure 1.1 Failure modes of Unreinforced Masonry Systems (a) & (b) Diagonal cracking; (c) Vertical cracking; (d) Out of plane failure (Reference NICEE, 2014)

The most widespread collapsing mechanisms commonly encountered in URM buildings under seismic loading involve both the out-of-plane and in-plane failure modes. As the unreinforced masonry walls are the resistant system, or contribute to the lateral seismic resistance of the building, therefore the first possible failure mode is in-plane shear failure. The other type of failure is represented by the out-of-plane flexural failure due to the orthogonal inertial forces induced by the earthquake. A major reason for the reduction in the vertical load carrying capacity of URM walls is also due to excessive out-of-plane bending. Very few studies in the past has focused on behaviour of URM structures made of bricks with low strength and stiffness. Hence, it is essential to understand the behaviour of the URM structures made of bricks with low strength and stiffness under various loading conditions to improve their performance.

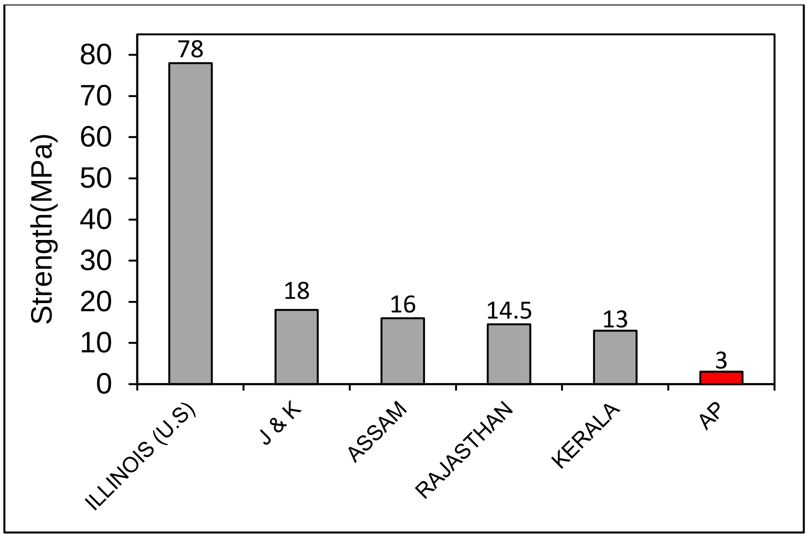


Figure 1.2 Variation in brick strength across different regions

(Reference: Various literatures Drysdale et al. 1994; Kaushik et al. 2005; etc)

Several studies have been carried out on behaviour of URM walls around the world [McNary and Abrams 1985; Drysdale et al. 1994; Triantafillou et al. 2000]. These studies had masonry made of bricks with high strength and stiffness or the strength and stiffness characteristics comparable to that of mortar. However, the strength of the bricks available in southern part of India particularly in Andhra Pradesh region is very low when compared to other regions [Figure 1.2]. Moreover, these bricks are very soft which causes different state of stresses to develop in masonry unlike in the masonry with stiffer and stronger bricks. If a masonry wall having stiff brick and soft mortar combination is subjected to compression, bricks will be in stress state of uniaxial compression and biaxial tension whereas the mortar will be under triaxial compression as shown in Figure 1.3(a). On the other hand, if the brick is softer than mortar, bricks will be in a stress state of triaixal compression and the mortar will be under uniaxial compression and biaxial tension as shown in Figure 1.3(b). Thus, changing the strength and stiffness characteristics of constituent materials of masonry could lead complete change in the failure modes.

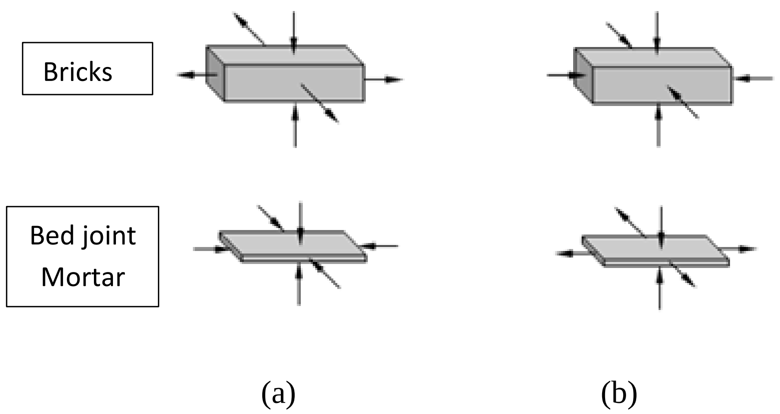


Figure 1.3 State of stress in Brick and Mortar joint for combination (a) Stiff brick- Soft mortar; (b) Soft brick-Stiff mortar

Understanding the performance of URM buildings made of softer bricks under both static and dynamic loadings requires a thorough consideration of change in failure modes due to different stress states because of change in constituent properties. The high vulnerability and the extensive damage suffered by URM buildings, in case of a seismic event, mining their safety and serviceability, have brought to light the necessity to strengthen them appropriately in order to achieve an upgrading to the required seismic capacity in terms of resistance and ductility. Among the available strengthening techniques, Fiber reinforced polymer (FRP) composites offer an attractive strengthening possibility for existing and historical unreinforced masonry structures. FRP composites have successfully been used in different construction applications such as strengthening of reinforced concrete, steel and timber structures in the past few decades. Lately, several studies have been conducted for evaluating the use of polymeric composites for repair and strengthening both unreinforced and reinforced masonry walls subjected to seismic, wind and lateral earth pressure loads. In most of the cases, both in-plane shear and out-of-plane flexural capacities are required to be upgraded in the seismic performance of old and historical unreinforced masonry structures.

1.2 MOTIVATION

The main motivation behind the study is to improve the understanding of brick masonry made of low strength and low stiffness bricks and assess the effectiveness of various strengthening schemes that includes FRP composites and Textile Reinforced Mortar (TRM) systems. This includes (i) experimentally characterising the mechanical properties such us stress strain curves for bricks, mortar and prisms cast with various mortar composition under pure compression and (ii) to experimentally assess the performance of masonry assemblies such as prisms and triplets with FRP and TRM strengthening. The percentage of building stock composing of unreinforced adobe, block masonry, and brick masonry (URM) construction in India obtained from Prompt Assessment of Global Earthquakes for Response (PAGER) survey is about 69 % [PAGER database 2007]. FEMA [1996] confirmed that building collapses remain the major cause of earthquake mortality, and that URM buildings are one of the most vulnerable building typologies in the world. There is increasing evidence that these non-engineered masonry buildings perform poorly even under moderate ground shaking. The large death toll in the 2001 Bhuj, India event [NICE Report 2003] is attributed to poor performance of masonry construction designed primarily for gravity loads. Hence, it is essential to understand the behaviour of these masonry systems to prevent the loss of life and property.

Masonry elements have been reinforced throughout the years by traditional methods involving, for example, filling of cracks or voids by grout injection, stitching of the large cracks or other weak areas with metallic elements or by concrete, application of the reinforced grouted perforations to improve the cohesion and tensile strength of masonry, single- or double-sided jacketing by steel mesh reinforced concrete, post-tensioning with steel ties. All the traditional techniques mentioned above have various disadvantages like difficult to implement, adds significant weight to the parent material and prone to corrosion. These disadvantages restricts the application of traditional strengthening techniques and prompted researchers to seek better solutions. The use of FRP composites is proposed to overcome the drawbacks commonly encountered with traditional techniques. This includes excellent mechanical properties of FRP composites such as high tensile strength, very high strength-to-weight ratio, and high resistance to corrosion in comparison to similar metallic strengthening systems, flexibility of application, protection of the geometrical and architectural detail of the walls. Alternative possibilities for strengthening URM walls other than FRP composites is also being continuously explored. One of such systems is represented by the use of textile-reinforced mortar (TRM) in substitution to the overlays of FRP. In the recent applications, the textile reinforcement is replaced by commercial FRP bi-directional grids, and the polymeric bonding resins substituted by cement- or lime-based mortars.

1.3 THESIS OUTLINE

The present thesis is organized in seven chapters. In *Chapter 1,* an overall outline of main issues associated with unreinforced masonry (URM) structures and motivation for the study are explained. In *Chapter 2,* review of the previous studies related to present work such as behaviour of URM structures, traditional and modern techniques available for retrofitting, numerical modelling are explained in detail. In *Chapter 3,* objectives and scope of the present study are illustrated. Chapter 4 describes in detail the experimental study carried out on characterization of mechanical behaviour of masonry constituents, compression tests on unretrofitted five brick stack bonded masonry prisms and shear tests on triplets. *Chapter* 5 deals with the experimental study carried out on masonry prisms and triplets retrofitted with GFRP composites and TRM strengthening systems. In *Chapter 6,* finite element modelling and validation of FE results with experimental data is presented. *Chapter 7* discusses the results and major conclusions of this study.

CHAPTER 2

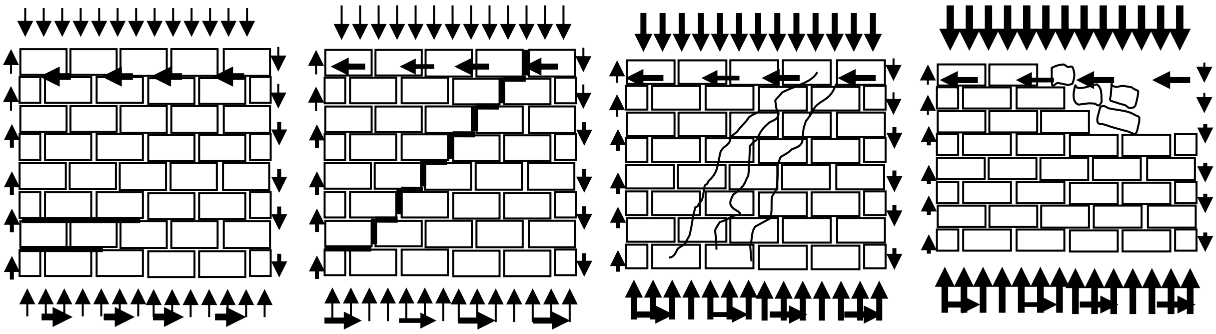
REVIEW OF LITERATURE

2.1 GENERAL

This chapter briefly reviews the existing studies on URM elements and discusses state of the art on various strengthening studies. The behaviour of unreinforced masonry load bearing walls (both experimental and analytical studies) carried out by various researchers on the behaviour of masonry constituents such as bricks and mortar, masonry assemblages is presented. Therafter, studies on URM assemblies with several conventional techniques to improve their seismic performance is briefly reviewed. Surface treatments (ferrocement, shotcrete), external reinforcement, grout injections and center core techniques are examples of such conventional techniques. Modern strengthening schemes include FRP and TRM that offer promising retrofitting possibilities for masonry buildings. Previous studies on using FRP and TRM techniques for masonry strengthening is briefly reviewed and finally the inferences from the literature review is presented.

2.2 BEHAVIOUR OF URM LOAD BEARING WALLS

The failure mode of a masonry load bearing wall depends on (i) the mechanical properties of constituent materials, (ii) geometry of wall and (iii) the combination of applied loads (Drysdale et al. 1994). The failure modes of load bearing walls can be classified into (i) sliding failure, (ii) diagonal tension failure and (iii) compression failure due to high axial load. Sliding or shear slip failure along a bed joint occurs when the lateral shearing forces exceed the adhesion and shear friction resistance between the mortar layers figure 2.1(a). This type of failure is likely to occur where the low axial loads are combined with high shear forces due to the reduced effect of friction because of low axial loads. The diagonal tension failure through mortar layers is due to the combination of high shear and axial loads figure 2.1(b). In this type of failure mode, the shear strength of masonry associated with diagonal cracking depends on tensile strength of brick units and mortar bond strength. Diagonal cracks can also propagate through the bricks, if the tensile strength of bricks is lesser compared to tensile strength of mortar figure 2.1(c). Predominance of the axial load leads to vertical cracking failure of masonry load bearing wall at the ultimate load and that is due to the incompatibility between the deformational characteristics of the materials such as brick, mortar and geometrical changes over the height of the wall. If the compressive stress due to axial load exceeds the material strength of masonry, it may lead to crushing failure figure 2.1(d). More localized compression failure can also occur at the toe of the wall with increased influence of overturning moment due to lateral load.



(a) (b) (c) (d)

Figure 2.1 Failure Modes of Load Bearing Walls (a) Sliding Failure (b) Diagonal Tension Failure through Mortar Joint (c) Diagonal Tension Failure through Brick Units and (d) Compression/Crushing Failure

2.3 STUDIES ON UNRETROFITTED URM

The compressive strength of masonry depends on characteristics of brick unit and mortar. During compression of masonry prisms with stiff bricks and soft mortar, the mortar bed joint will be in a state of triaxial compression whereas brick will have bilateral tension coupled with axial compression. This state of stress initiates vertical splitting cracks in bricks that lead to the failure of the prisms. [McNary and Abrams 1985; Atkinson and Noland 1983; Drysdale et al. 1994].

Monjur Hossain et al. (1997) carried out the experimental investigation of burnt clay brick masonry assemblages. The deformation characteristics of the bricks and mortar joints have been determined from 5 brick-high stack bonded prisms. The deformation characteristics of individual brick and mortar have also been determined and found to be different from their in-situ characteristics. This is due to composite action between brick and more softer mortar joint. The tensile strength of bond has been obtained from 3 brick-high prism and shear strength from brickwork triplets. Compression tests on stack bonded prisms and prisms with sloping bed joints gives in-situ properties of brick and mortar while splitting tests on stretcher bonded prisms are aimed at establishing the basic bond parameters between bricks and joints. It has been found that the strength and deformation characteristics of masonry constituents obtained from these tests are more representative of the actual composite behaviour of masonry. The properties of brick and mortar joint-determined from the tests are also found to be more appropriate for the study of non-linear behaviour of masonry structures. It is also observed that the tensile strength of brick was found to be 5% of the compressive strength determined by standard test while it was 8% of the compressive strength determined by the test when the load is parallel to bed joint orientation.

Kaushik et al. (2007) studied the uniaxial monotonic compressive stress-strain behaviour of unreinforced masonry and its constituent materials such as solid clay bricks and mortar had studied by several laboratory tests. On the basis of obtained results and observations of the comprehensive experimental study, nonlinear stress-strain curves were obtained for bricks, mortar, and masonry. Using linear regression analysis, a simple analytical model that can be used in the analysis and design procedures has been proposed for obtaining the stress-strain curves for masonry. The analytical model requires only the compressive strengths of bricks and mortar as input data that can be easily obtained experimentally and also are available in codes. For obtaining the modulus of elasticity of bricks, mortar, and masonry simple relationships have been identified from their corresponding compressive strengths. It was observed that for the stiff and strong bricks and mortar of lesser but comparable strength and stiffness, the stress-strain curves of masonry need not necessarily fall in between those of bricks and mortar

Dayaratnam (1987) and Sarangapani et al. (2002) reports that strength of bricks in India are comparatively lower than mortar and the stiffness of Masonry lie in between that of brick and mortar. Experimental study by Sarangapani et al. (2002) report that masonry prisms with soft bricks cause the development of triaxial compression in bricks and axial compression with lateral tension in mortar joints. Gumaste et al.(2007) observed from the experimental results that wire cut brick masonry specimens with 1:6 cement mortar failed due to loss of bond between brick and mortar whereas for specimens with 1:1.5:4 Cement-lime mortar failed due to diagonal shear. The failure mode observed for table molded brick masonry with 1:6 cement mortar was due to splitting of bricks whereas Bond failure was observed for specimen with 1:15:5 [Cement (C) :Soil (So) : Sand (Sa)]. The study implied that as mortar strength decrease comparative to brick strength, the Bond failure will be the dominant mode of failure and as mortar strength increase the masonry will fail by splitting of bricks.

McNary and Abrams (1985) have observed from stack bond prism test that as mortar strength decreased, prism strength also decreased but they observed that decrease was not linearly proportional to the mortar strength. Stress strain curve obtained from the experiment became increasingly nonlinear as mortar strength decreased. The prism strength is governed by splitting strength of brick and the deformational properties of mortar. Kaushik (2007) observed that stress-strain behavior of masonry made of bricks and mortar of relatively comparable strengths lie below the stress-strain behavior of both brick and mortar. Compressive behavior of masonry with lime mortar was observed to be much better than masonry made using mortar without lime. Based on these control points, an analytical model was developed by regression analysis of the experimental data to plot the masonry stress-strain curves, which follow a combination of parabolic and linear variation.

Freeda et al. (2013) studied the behaviour of masonry prisms. Clay bricks and fly ash bricks were used and as binding material fly ash cement mortar was used. The brick masonry is reinforced with woven wire mesh at the alternate bed joint and tested for its axial strength and elastic modulus of the prisms specimens. It is observed that The mortar with the ratio of 1:6 cement mortar with 20% replacement of fine aggregate with fly ash exhibited a higher compressive strength than the control mix after 28 days of curing and The compressive strength of unreinforced fly ash brick masonry was 34% more than the unreinforced clay brick masonry. The reinforced fly ash brick masonry was 20.7% more than the reinforced clay brick masonry. It is also concluded that the introduction of wire mesh in the clay brick masonry resulted in an increase of load carrying capacity by 25%, while the introduction of mesh in fly ash brick masonry resulted in an increase of load carrying capacity by 10% as the strength of the fly ash brick contributed more in the brick masonry strength.

2.4 TRADITIONAL STRENGTHENING TECHNIQUES

In many seismically active regions of the world there are large numbers of unreinforced masonry buildings, most of which have not been designed for seismic loads. The recent earthquakes have proved that many of such buildings are seismically vulnerable and should be considered for retrofitting. Various conventional retrofitting techniques are available to increase the strength and/or ductility of unreinforced masonry walls. In the subsequent sections a review on some seismic retrofitting techniques for masonry walls is presented.

2.4.1 Grout and epoxy injection

It is a very popular strengthening technique, as it does not affect the aesthetic and architectural features of the existing structures. The main purpose of injections is to maintain the original integrity of the retrofitted wall and to fill the voids and cracks, that are present in the masonry due to physical and chemical deterioration and/or mechanical actions. The success of a retrofit by injection depends on the injectability of the mix used, and on the injection technique adopted. The injectability of the mix is influenced by mix's mechanical properties and its physical chemical compatibility with the masonry to be retrofitted. This retrofitting technique improves the overall behaviour of the retrofitted URM and is effective at restoring the initial stiffness and strength of masonry.

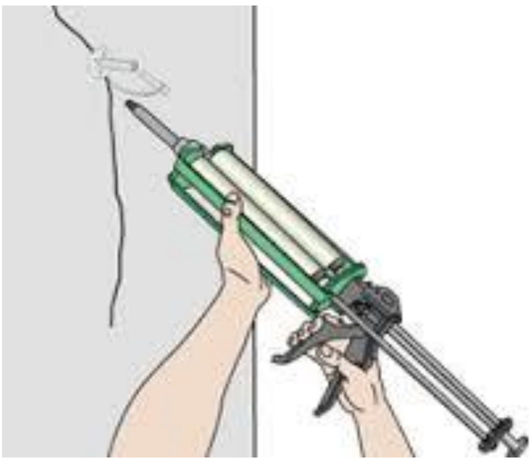


Figure 2.2 Grout injection Strengthening Technique (Angelno, 2001)

2.4.2 External reinforcement

Steel plates or tubes can be used as external reinforcement for existing URM structures. Steel system is attached directly on to the existing wall. The relative rigidities of the unretrofitted structure and the new steel bracing are an important factor that should be considered. In an earthquake event, cracking in the original masonry structure is expected and after sufficient cracking had occurred, the new steel system will have considerable stiffness and will be effective. The vertical and diagonal bracing improves the lateral in-plane resistance of the retrofitted wall. The increment in the lateral resistance is limited by crushing of the masonry at ends (toes) followed by vertical strips global buckling.

Figure 2.3 External reinforcement using vertical and diagonal bracing (Papanicolau, 2001)

2.4.3 Surface treatments

Surface treatment is a commonly adopted method that id largely developed through experience. Surface treatment incorporates different techniques such as ferrocement, shotcrete. By nature, this treatment covers the masonry exterior and affects the architectural or historical appearance of the structure.

Ferrocement consists of a thin cement mortar laid over a wire mesh, which acts as a reinforcement. It is relatively cheaper, durable, strong and the basic technique can be easily acquired. Although ferrocement is not strictly a 'sustainable' technology as it uses cement and steel, it employs them in a efficient and cost-effective manner. The mechanical properties of ferrocement mainly depend on mesh properties. This technique is ideal for low cost housing as it is cheap and can be done with unskilled workers. It enhances both in-plane and out-of-plane behaviour. The mesh helps to confine the masonry units after cracking and hense improves the in-plane deformation capacity. This retrofitting technique increases the lateral resistance in the in-plane direction and improves wall out-of-plane stability.

(a) (b)

Figure 2.4 Strengthening through Surface Treatment: (a) samples of reinforcement used in ferrocement (b) application of shotcrete (Gerofano,1991)

Shotcrete is an alternative strengthening technique. The overlays of shotcrete can be sprayed onto the surface of a masonry wall over a mesh of reinforcing bars. Shotcrete is more convenient and less costly than cast in-situ jackets. The thickness of the shotcrete can be maintained as per the seismic demand. Generally, the overlay thickness will be at least 60 mm. Shear dowels are fixed using epoxy or cement grout into holes drilled into the masonry wall to transfer the shear stress across shotcrete-masonry interface. The physical properties of a good shotcrete are comparable or superior to those of conventional concrete or mortar having the same composition. Improper application of shotcrete may create conditions much worse than that of untreated condition. Shotcrete is used instead of conventional concrete for reasons of cost or convenience. Shotcreting operations can often be completed in areas of limited access to make repairs to structures. The selection of shotcrete for a particular application should be based on experience, knowledge and a careful study of required material performance. Shotcrete retrofitting significantly increases the ultimate load carrying capacity of the walls. This retrofitting technique dissipates high-energy due to elongation and yield of reinforcement in tension.

2.4.4 Post-Tensioning

Post-tensioning involves a compressive force applied to masonry wall; this force counteracts the tensile stresses resulting from lateral loads. There has been little application of this technique; Post-tensioning is mainly used to retrofit structures characterized as monuments. Post-tensioning tendons are usually in the form of alloy steel thread bars, although mono-strand tendons are not uncommon. Bars typically show higher relaxation losses (2-3 times strand losses) and much lower strength/weight ratio; in addition, a major drawback for using of steel bars is corrosion. However, fibre reinforced plastic presents a promising solution for this problem. Tendons are placed inside steel tube (duct) either within holes drilled along the mid-plane of the wall or along groves symmetrically cut on both surfaces of the wall. Holes are cement grouted and external grooves are filled with shotcrete. In this case, the tendons are fully restrained (i.e. it is not free to move in the holes). This is true even if the tendon is unbonded, i.e. no grout is injected between the duct and the tendons. However, the holes can be left un-grouted (unguided unrestrained). This simplifies the strengthening procedure and allows future surveillance, re-tensioning, or even removal of the post-tensioning bars.

Figure 2.5 Post-tensioned URM wall (Reference: Peter ,1970)

2.4.5 Center core technique

The center core system consists of a reinforced, grouted core placed in the center of an existing URM wall. A continuous vertical hole is drilled from the top of the wall into its basement wall. The core achieved by this oil-well drilling technique may be 50-125 mm in diameter, depending on the thickness of the URM wall and the retrofitting required. After placing the reinforcement in the center of the hole, a filler material is pumped from the top of the wall to the bottom such that the core is filled from the bottom under pressure controlled by the height of the grout. This technique is successfully used to enhance the resistance of URM wall under cyclic actions, and lateral maximum lateral displacement, even if the energy dissipated is not so high. However, the system has several advantages: it will not alter the appearance of wall surface as well as the function of the building will not be impaired since the drilling and reinforcing operation can be done externally from the roof. The main disadvantage is this technique tends to create zones with widely varying stiffness and strength properties.

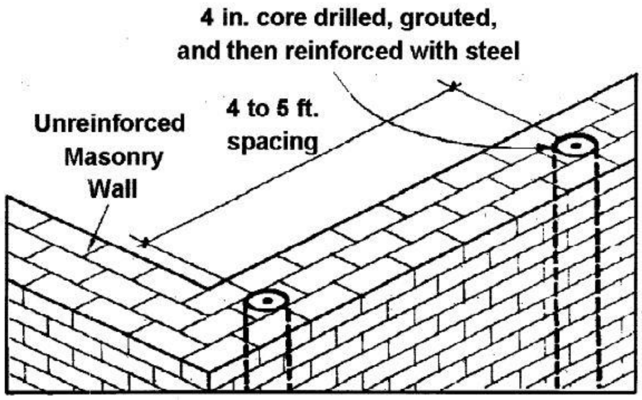


Figure 2.6 Center core technique (Reference: Peter ,1970)

2.5 MODERN TECHNIQUES FOR STRENGTHENING

During the years the researchers developed different strengthening techniques based on the use of Fibre Reinforced Polymers (FRP) externally bonded to the surfaces of the element to be reinforced. These techniques can be described in terms of the FRP typology, reinforcement arrangement, and connection system to the substrate. In general, the strengthening techniques can be devoted to the improvement of the out-of-plane flexural capacity, the in-plane shear resistance and the ductility of the system to which the reinforcement is applied. A number of researches have been performed in order to study the seismic strengthening of unreinforced masonry walls with FRP. Some results have shown that the reinforcement improves significantly the lateral stability of the walls, increases the shear strength.

It is further noted that this technique may lead to some problems that can limit more or less considerably its application for all cases, requiring additional studies. Since the reinforcement is made by continuous strips or sheets externally applied on the surface of masonry wall, this may create a water-proof barrier and produce difficulties for the natural transpiration of stone or ceramic material. In addition, some problems may arise regarding the fire resistance of the strengthening systems that, especially when used in combination with epoxy-based matrix or bonding material, can be particularly vulnerable.

An alternative strengthening method to previously described ones has been recently proposed by (Papanicolau et al., 2007, 2008, 2011) for strengthening of unreinforced masonry walls subjected to in-plane and out-of-plane cyclic loadings. As already described, numerous techniques have been developed in order to rehabilitate and strengthen URM structures; these may be roughly categorized as 'conventional' and as 'modern'. The former include surface treatments (such as shotcrete or ferrocement overlays), grout injections and internal or external prestressing with steel ties. The latter include the use of metallic or polymer-based grid-reinforced surface coatings, externally bonded fibre-reinforced polymers.

A technique that combines the benefits of both types of interventions (i.e. both 'conventional' and 'modern' ones) involves the use of textiles in the form of open fibre meshes (grids) externally bonded on the elements' surfaces by means of mortars; those materials are named as textile-reinforced mortars – TRM. The researchers introduced the TRM in the strengthening of unreinforced masonry walls in order to address the numerous drawbacks related to the use of FRP externally bonded to element surface and mainly associated to the employment of organic binders.

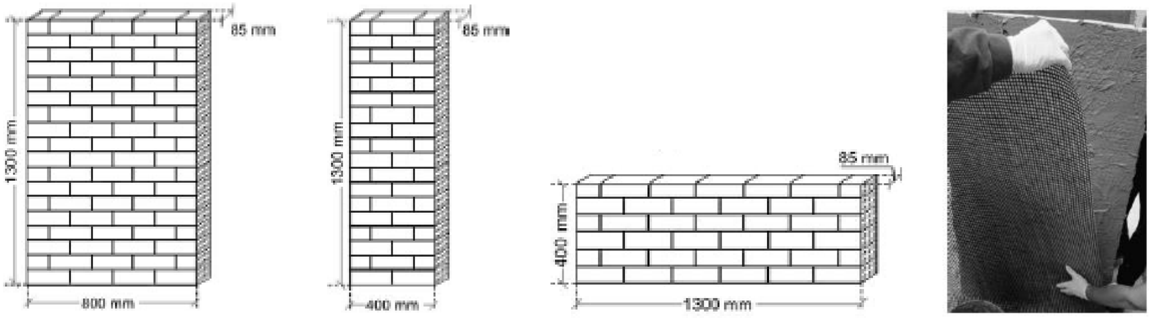
The drawbacks of FRP strengthening are attributed mainly to the use of organic binders (resins) and are summarized as follows

- Poor behaviour of resins at temperatures above the glass transition temperature;
- Relatively high cost of epoxies;
- Difficulty to apply FRPs on wet surfaces or at low temperatures;
- Incompatibility of epoxy resins and some substrate materials (e.g. clay);
- The manual worker will be subjected to potential hazards;
- Difficulty to assess the damage due to the earthquake on the masonry behind the FRP.

Hamid et al. (2005) studied the in-plane behaviour of unreinforced masonry (URM) wall assemblages retrofitted with fibre-reinforced polymer laminates. Tests were carried out on Forty-two unreinforced masonry assemblages under different stress conditions present in masonry shear and infill walls. Tests included prisms subjected to compression with different bed joint, specimens under diagonal tension and specimens subjected to loading under joint shear. The behaviour of each type of specimen was discussed with importance on failure modes, deformation characteristics and strength. Results showed that the FRP laminate strengthening on URM had a great influence on post peak behaviour, strength, as well as altering the modes of failure and maintaining the integrity of specimen. The retrofitted specimens reached compressive strength of 1.62–5.64 times that of their unretrofitted counterparts, depending on the bed joint orientation, and joint shear strength increased by eightfold. The masonry–FRP composite assemblages do not fail catastrophically as their URM counterparts. The FRP laminates resulted in a gradual prolonged failure under shear, and a stronger wall under compression with apparent post peak strength. This would also maintain the wall's structural integrity and would reduce the possibility of URM walls collapsing and spalling which, in itself, is a major source of hazard during earthquakes, even if the whole structure remained safe and functioning. The stiffening effect of the laminate on the moduli of elasticity of the on/off-axis compression assemblages was marginal; in average an 8.1% increase.

Thanasis et al. (2006) studied the application of textile reinforced mortar (TRM) as a means of increasing the shear resistance of reinforced concrete members. TRM jackets were provided in this study either by conventional wrapping of fabrics or by helically applied strips. Both systems resulted in excellent results in terms of increasing the shear resistance. However, compared with their resin impregnated counterparts, mortar-impregnated textiles may result in reduced effectiveness. On the basis of the test results it was conclude that closed-type textile-reinforced mortar jackets provide substantial gain in the shear capacity of reinforced concrete members. Two layers of mortar impregnated textile in the form of either conventional jackets or spirally applied strips were sufficient to increase the shear capacity of the beams, thus preventing sudden shear failures and allowing activation of flexural yielding. One layer of textile reinforcement proved less effective but still sufficient to provide a substantial shear resistance.

Catherine et al. (2006) experimentally investigated the application of textile-reinforced mortar (TRM), as a means of increasing the load carrying capacity and deformability of unreinforced masonry walls subjected to cyclic in-plane loading. The application of externally bonded TRM is considered as an alternative method to the application of fibre-reinforced polymers (FRP). Hence, the effectiveness of TRM overlays is evaluated in comparison to the one provided by FRPs. Medium scale tests were carried out on 22 masonry walls subjected to in-plane cyclic loading. Three types of specimens were used: (a) shear walls; (b) beam-columns; and (c) beams as shown in the figure 2.7. The parameters under investigation included the matrix material (mortar versus resin), the number of textile layers and the compressive stress level applied to shear walls and beam-columns.



(a) (b) (c) (d)

Figure 2.7 Experimental specimens (a) Shear wall specimen; (b) Beam-Column specimen; (c) Beam specimen; (d) Application of TRM (Triantafillau, 2008)

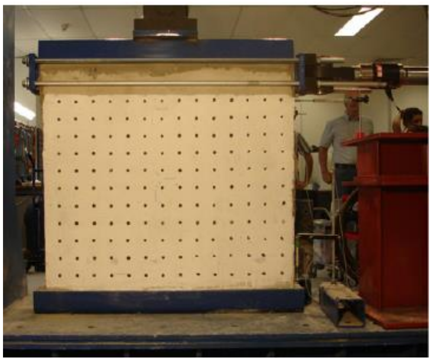


Figure 2.8 Experimental set up for in-plane loading (Triantafillau, 2008)

Based on the experimental results it was concluded that TRM overlays provide a substantial gain in strength and deformability. Compared with resin-based systems, TRMs result in reduced effectiveness for strength, the magnitude of which depends on the type of loading and on the number of textile layers used. It was also stated that, in terms of strength, TRM jackets are at least 65–70% as effective as FRP jackets with identical fibre configurations. In terms of deformability, which is of crucial importance in seismic retrofitting of unreinforced masonry walls, TRM jacketing was much more effective than FRP. The increased effectiveness is about 15–30% in shear walls, 135% in beam-column type walls and 350% in beam type walls, on the basis of tests conducted in this study. Moreover, regardless of the matrix material (mortar versus resin), the strength generally increases with the number of layers and the axial load, at the expense of deformability.

Catherine et al. (2008) experimentally investigated the application of textile-reinforced mortar (TRM), as a means of increasing the load carrying capacity and deformability of unreinforced masonry walls subjected to cyclic out-of-plane loading. The effectiveness of TRM overlays was evaluated in comparison to the one provided by fibre reinforced polymers (FRP) in the form of overlays or near-surface mounted (NSM) reinforcement. Medium- scale tests were carried out on 12 masonry walls subjected to out-of-plane bending as shown in figure 2.9. The parameters under investigation comprised mortar-based versus resin-based matrix materials, the number of layers, and the performance of TRM or FRP jackets in comparison to NSM strips.

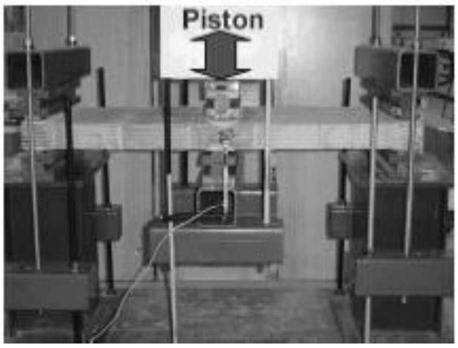


Figure 2.9 Experimental set up for out-of-plane loading (Papanicolaou, 2008)

From the experimental results of brick masonry wall specimens subjected to out-of-plane cyclic bending it was concluded that textile-reinforced mortar overlays provide a substantial gain in strength and deformability; this gain was higher as the number of layers increases. If failure was controlled by damage in the masonry, TRM overlays outperform their FRP counterparts on the basis of maximum load and displacement at failure, whereas if the failure mechanism involves tensile fracture of the textile reinforcement the effectiveness of TRM versus FRP was slightly reduced. NSM reinforcement was less effective in strength but more effective in deformability than both TRM and FRP overlays, due to controlled debonding of the FRP strips.

Aranha et al. (2013) studied the feasibility of the application of textile reinforced grids placed in sprayed mortar and to compare its effect on strengthening unreinforced masonry specimens with the technique of manual application of Textile Reinforced Mortar (TRM). The specimens consisted of masonry prisms stacked with nine bricks each; some were reinforced by textile reinforcement placed in sprayed mortar (TRSM) and a few were strengthened with TRM applied by hand as shown in figure 2.10. The specimens were subjected to three-point bending.

(a) (b) (c) (d) (e)

Figure 2.10 Application of TRM Strengthening (a) Fixing the grid; (b) Wetting the surface; (c) Spraying; (d) Hand application; (e) Strengthened specimen (Aranha et al, 2013)

On the basis of experimental results it was concluded that the application of textile reinforced sprayed mortar (TRSM) to unreinforced masonry structures is feasible and results in a huge savings in time. Regarding the load bearing capacity, the presented application technique of TRSM proved to be more effective than the manual application method only in the case of glass and carbon grids. The increase in strength was more than double in the case of specimens reinforced with glass grids and sprayed mortar compared to the one in which the glass grids were placed in mortar that was applied by hand. For the specimens reinforced with carbon grids, the gain in strength was not significant. The specimens reinforced with basalt fibres showed the most ductile failure and the specimens reinforced with steel grids displayed the highest gain in strength. With respect to the number of layers of reinforcement, the two specimens that had a double-layered reinforcement performed very well.

2.6 NUMERICAL MODELLING OF MASONRY

It is known that masonry is a material whose behaviour differs depending on the considered direction, due to the fact that the mortar joints surrounding masonry units, acting as planes of weakness, modify the mechanical properties and introduce a level of anisotropy. The characteristics of masonry should be reflected in the modelling technique adopted to study a particular mechanical aspect of such material, which also determines the level of accuracy of the model. This aspect clarifies that all modelling strategies are useful for understanding of masonry structures behaviour.

There are two different techniques for material description each of which has his own characteristics and field of application; in particular one can refer either to a micro-modelling or to a macro-modelling strategy. Micro-modelling are generally applied to small elements or portion of structures which require a more detailed representation, allowing the investigation of localized phenomena, while macro-modelling is employed for global modelling of entire structures in which the dimensions of the elements are large enough to neglect any unevenness in the stress distribution along the element. The characteristics of the macro-models and the small computational effort involved allow using them in cases that require fast analysis with a not very high level of detail.

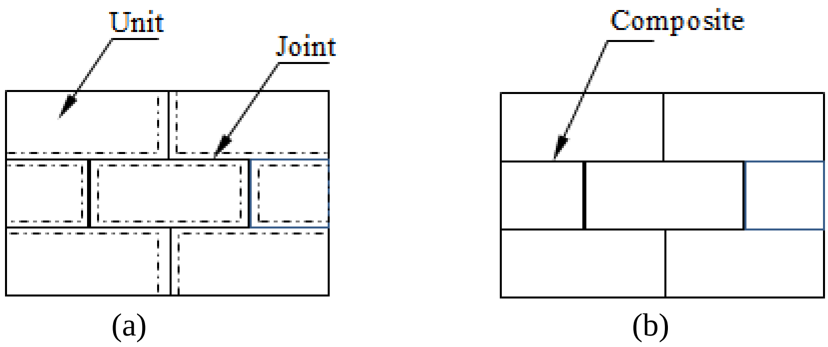


Figure 2.11 Modelling techniques for masonry (a) micro modelling; (b) macro modelling

Blackard et al.(2005) studied the failure processes in masonry prisms when composite clay bricks bonded by cement mortar subjected to axial compression. In this study the strength of the brick used was 33.34 MPa and that of the mortar was 5.04 MPa. It was observed that the thicker mortar joint would reduce the stiffness of the prism due to the development of high tensile stresses in brick. The applicability of 2D and 3D finite element models using damage-plasticity model in Abaqus was also verified and it was concluded that the 3D model furnishes a prism strength which agrees well with the experimental resut,it was 12% higher than the average of the experimental data with a COV of 9.8%. Due to the erronuous failure mode, the 2D plane stress model result yielded a prism srength which was 65% lower than test data. The results demonstrated that full 3D simulations are warranted when the proper failure mechanism is to be captured.The parametric studies indicated that the tensile strength of the brick had a significant effect on the prism strength which was far greater than the effect of the mortar properties. It was also concluded that the thickness of the mortar joint was much more significant than the compression strength of mortar.

Page (1978) developed a finite element program for the analysis of masonry considering brick and mortar separately. The developed finite element program was able to model the nonlinear joint properties and allowed the progressive joint failure. In-plane behaviour of masonry was modeled using a continuum of plane stress elements for bricks with superimposed linkage elements simulating mortar joints. The authors concluded that the developed model was simple but it could not predict the ultimate load since the failure criterion for brick was not included.

2.7 INFERENCES FROM LITERATURE REVIEW

Few important inferences have been drawn from the literature review and they are illustrated as follows:

- Previous studies in the literature on URM with and without strengthening indicated that masonry had a stiffer and stronger brick than mortar. Results from these studies may not be directly applicable to masonry made of low strength and stiffness compared to mortar. In southern states of India, particularly in Andhrapradesh, the clay bricks have very low compressive strength (<10 MPa) stiffness (<500 MPa) compared to that of mortar with significantly higher strength and stiffness. Hence, more research should focus on understanding the behaviour of masonry with softer bricks.
- In an unreinforced masonry made of stiff brick-soft mortar combination subjected to compression, brick will be in uniaxial compression and bi-axial tension and mortar will be in tri-axial compression but in the case of soft brick-stiff mortar combination subjected to compression, brick will be in tri-axial compression and mortar will be in uniaxial compression and bi-axial tension.
- No design guidelines are available for assessing the performance of masonry made of low strength and stiffness bricks. Simplified equations have to be developed for obtaining constitutive properties of the masonry. More research should focus on development of strengthening solutions of masonry walls including FRP and TRM composites.
- Review of literature indicates that very few investigations have investigated the flexure performance of these URM structures made of low strength and stiffness bricks. The understanding on behavior of FRP and TRM composite retrofitted masonry walls subjected to Out-of-plane loading also needs to be studied in detail.

CHAPTER 3

OBJECTIVES AND SCOPE

3.1 OBJECTIVES

The main objectives of the present study is to (i) Characterize the mechanical properties of masonry assemblies made of bricks with low strength and stiffness and (ii) Understand the effectives of FRP and TRM strengthening in improving their performance under static inplane loading.

3.2 SCOPE OF THE STUDY

The main issues investigated in the present study are related to the characterization of mechanical behaviour of brick, mortar and masonry assemblies such as triplets and prisms with and without strengthening by means of GFRP composites and TRM systems.

- Characterization of the mechanical behaviour of the brick and mortar under compression;
- Characterization of the mechanical behaviour of the masonry assemblages with and without GFRP,TRM strengthening systems by means of compression and shear tests;
- Studying the influence of mortars with different strength on the performance of masonry prims and triplets with and without strengthening;
- Investigation of the effectiveness of the connection between the external reinforcing system and the masonry substrate;
- Numerical modelling of the system in order to validation of numerical results with the experimental evidences.

3.3 METHODOLOGY

The strengthening technique taken into account in the study is represented by externally applied unidirectional glass fibre fabric and bidirectional polypropylene grid embedded in epoxy resin and mortar respectively. The mortar encloses the reinforcement passing through the grid’s openings allowing an effective mechanical interlocking that assure a composite behaviour of the system. The described system will be applied on the surfaces of the unreinforced masonry prisms, triplets. The effectiveness of the reinforcing system will be explored in case of in-plane static loading conditions.

The study will be focus first on the characterization of the mechanical behaviour of the bricks, mortar and masonry assemblies such as prisms and triplets with and without the considered strengthening system. For this purpose, the influence of different types of mortar with different strength for the reinforcing system will be investigated. Simultaneously the FEM modelling of the system will be carried out and FE resutlst will be validated the experimental evidences. Figure 3.1 shows the flow chart of present study

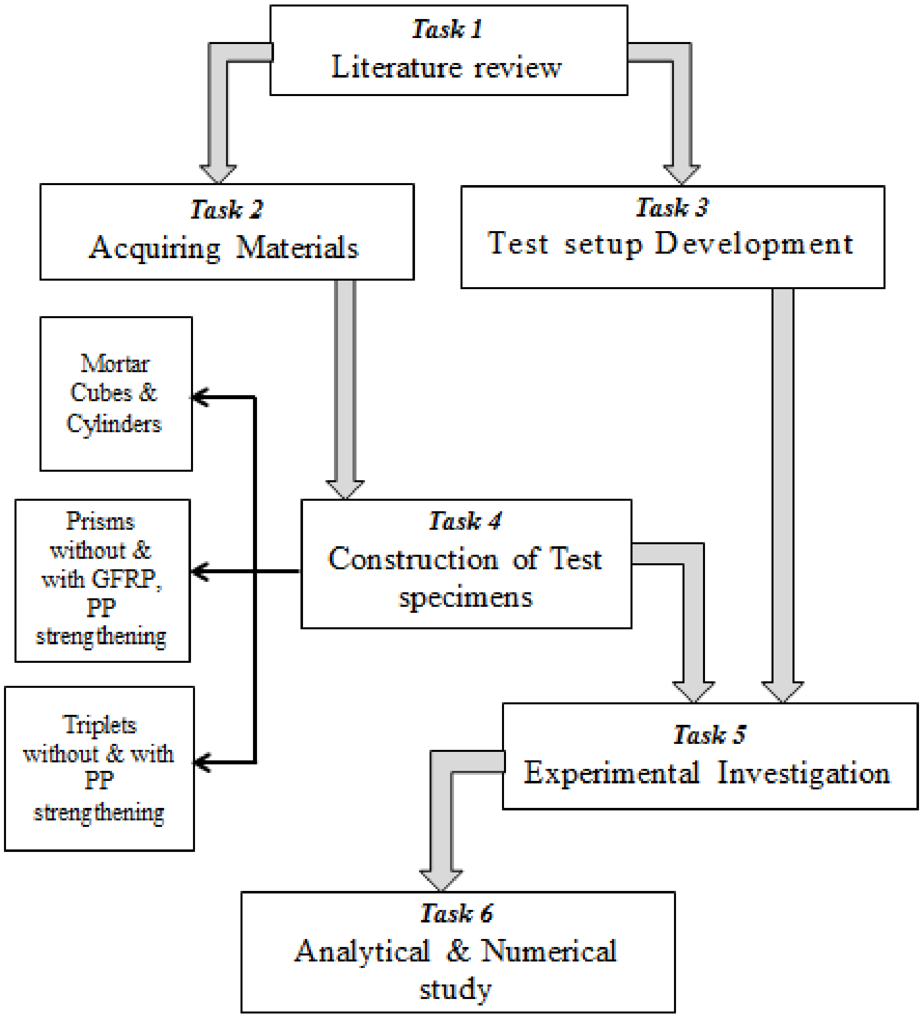


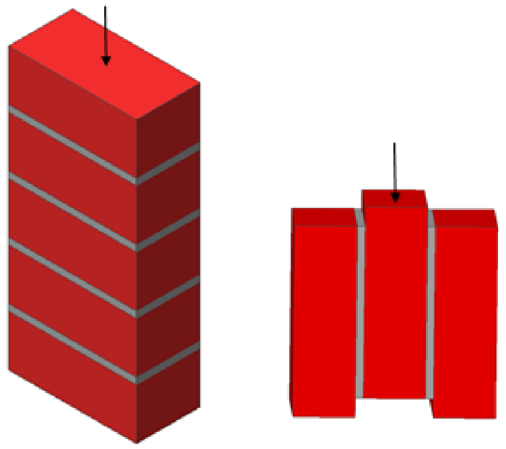
Figure 3.1 The scope of work

CHAPTER 4

EXPERIMENTAL STUDY ON UNRETROFITTED ASSEMBLIES

4.1 INTRODUCTION

The experimental study on unreinforced masonry constituents such as brick, mortar and masonry assemblies such as prism and triplet is explained in this chapter. Prism is a masonry assemblage having five bricks arranged in stack bonded pattern with mortar being in the joints as shown in Figure 4.1(a) and triplet is a three brick assemblage as shown in Figure 4.1(b). The tests on prisms gives the compressive strength of URM and triplets give the shear strength of brick-mortar joint.



(a) (b)

Figure 4.1 Masonry assemblages (a) Prism and (b) Triplet

4.2 COMPRESSION TESTS ON BRICKS

Locally available table molded bricks of dimensions 220x100x75mm were used in this study. The bricks were tested under compression as per IS 3495 (Part-1)-1992. To ensure application of uninform compression, brick surfaces were made even with application of Plaster of Paris (POP). A 2mm LVDT is fixed on each specimen on front and back side to measure the deformation. The test setup and failed specimen are shown in figure 4.2.

(a) (b) (c) (d)

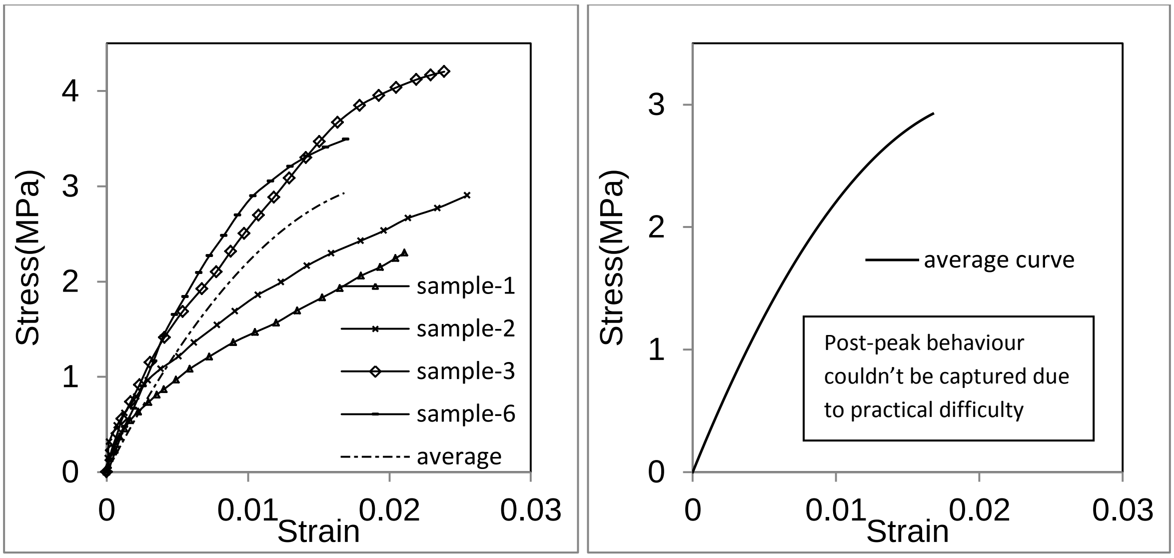
Figure 4.2 Brick testing under compression (a) Brick with LVDTs; (b) Test setup; (c) Detachment of LVDT from the brick; (d) failed specimen

Table 1. Summary of brick Strength under Compression

Sample no.	1	2	3	4	5	6	7	8	9	10	11	12	Average strength (MPa)
Compressive strength (MPa)	3.2	4.3	3.7	2.3	5.4	3.5	3.6	2.0	5.9	3.8	4.5	6.3	4.0(0.33)*

* Value in parenthesis indicates coefficient of variation (COV)

Table 1. Shows the average strength of brick as 4MPa with a COV value of 0.33 which indicates the large variability in brick strength. The stress-strain curves for different samples of brick and the average stress-strain curve are shown in figure 4.3(a),(b) respectively. The post-peak portion of stress-strain curve couldn’t be captured due to the spalling of material from the sides of specimen which led to the detachment of LVDT as shown in figure 4.2(c). There is no standard method available for determining the modulus of elasticity of brick. Typically, a secant modulus of elasticity described by the slope of the line from zero stress to 33% of the brick strength is taken as the modulus of elasticity (Eb). In the present study E_b is found to be 260MPa (COV=0.31) which is approximately equal to 65 times the average brick strength.



(a) (b)

Figure 4.3 Behaviour of Bricks under Compression (a) Stress-strain curves for different samples; (b) Average stress-strain curve

4.3 COMPRESSION TESTS ON MORTAR SPECIMENS

Three different grades of mortar (cement: sand by volume) have been used in the present study, viz., 1:3, 1:4.5 and 1:6 with water-cement ratio 0.75. The density of sand used is 1610kg/m^3 and the grade of cement used is 53. The gradation curve of the sand used in the present study is shown in figure 4.4. Mortar cubes of 70mm size were casted, kept under water for a curing period of 28 days and tested as per IS 2250 (1995) to obtain the compressive behaviour.

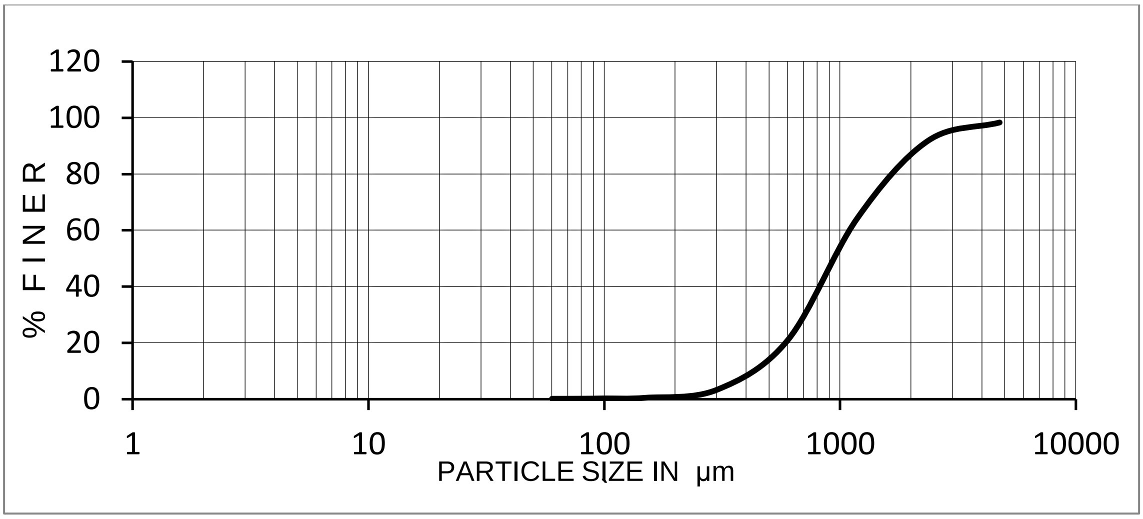


Figure 4.4 Gradation curve for sand

Testing of mortar cubes under compression is carried out in a servo hydraulic controlled compression testing machine of capacity 5000kN. Two numbers of 2mm LVDTs of HBM make were fixed to the cube specimens for capturing the true deformation of mortar cubes under compression. HBM DAQ system is used to collect the experimental data. The test setup and failure modes of tested cubes are shown in figure 4.5.

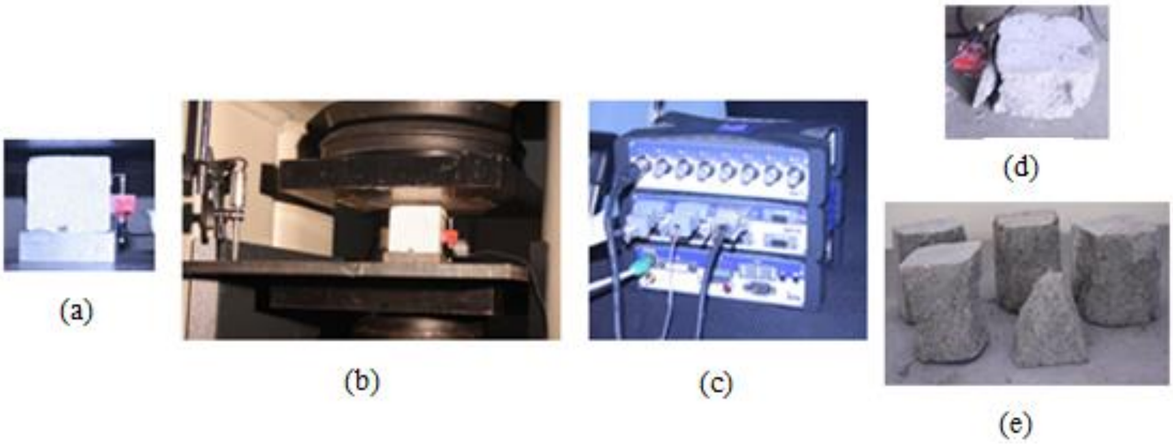


Figure 4.5 Mortar Cubes under compression (a) Cube with LVDT;
(b)Test setup; (c) HBM DAQ (d) failed specimen (e) Pyramidal failure.

During testing, when the load reached to maximum value, the cube specimen failed due to spalling of mortar from sides and it led to the detachment of LVDT from surface as shown in Figure 4.5(d) due to which the post-peak behaviour of stress-strain curve became difficult to capture. In order to overcome this practical difficulty cylinders of dimensions 200mm length and 100mm diameter were casted with above mentioned mortar proportions and were tested under uni-axial compression after 28 days of curing. The deformation of specimens is measured over a length of middle 40 mm with the help of 5mm LVDTs Which were held in position by acrylic rings attached to the specimen and Teflon sheets were kept were used to remove the end friction due to platen effect. Test setup and failed specimen are shown in figure 4.6.

(a) (b) (c) (d)

Figure 4.6 Mortar Cylinders under Compression (a) Cylinder specimen; (b) Test setup (c) & (d) Failure Modes

4.4 STRESS-STRAIN CHARACTERISTICS OF MORTAR

Stress-strain curves for the mortar of three different grades are compared in Figure 4.8. It is observed that mortar with more cement content, i.e, 1:3 mortar has more compressive strength 24 MPa with a coefficient of variation (COV) 0.008 and mortar with low cement content, i.e., 1:6 mortar has the least compressive strength 8MPa with a COV of 0.15 whereas the mortar of grade 1:4.5 has the compressive strength 15MPa with a COV of 0.18. Mortar strength (f_j'), corresponding strain (ε'_j) and modulus of elasticity (E_j) of the tested specimen is summarized in Table 2.

Table 2. Test results of mortar specimens under Compression

S.No	Mortar Proportion	W/C	No of specimens	f_j' (MPa)	ε'_j	E_j(MPa)
1	1 : 3	0.75	10	24 (0.08)*	0.0046(0.26)	17432
2	1 : 4.5	0.75	10	15 (0.18)	0.0022(0.06)	10840
3	1 : 6	0.75	10	8 (0.15)	0.0020(0.14)	5987

*Values in parenthesis indicates coefficient of variation (COV)

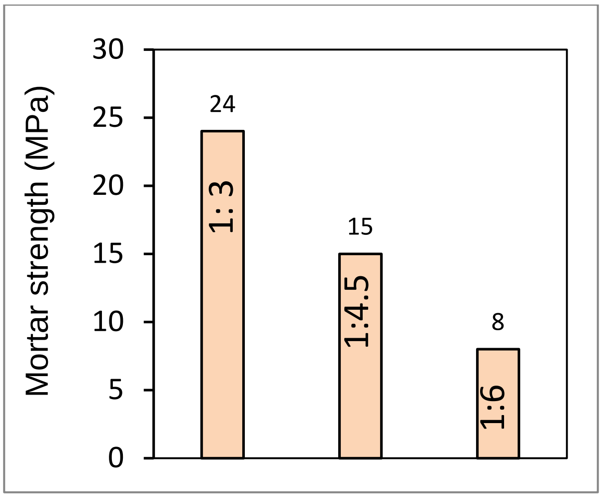


Figure 4.7 Comparison of mortar strength for different grades

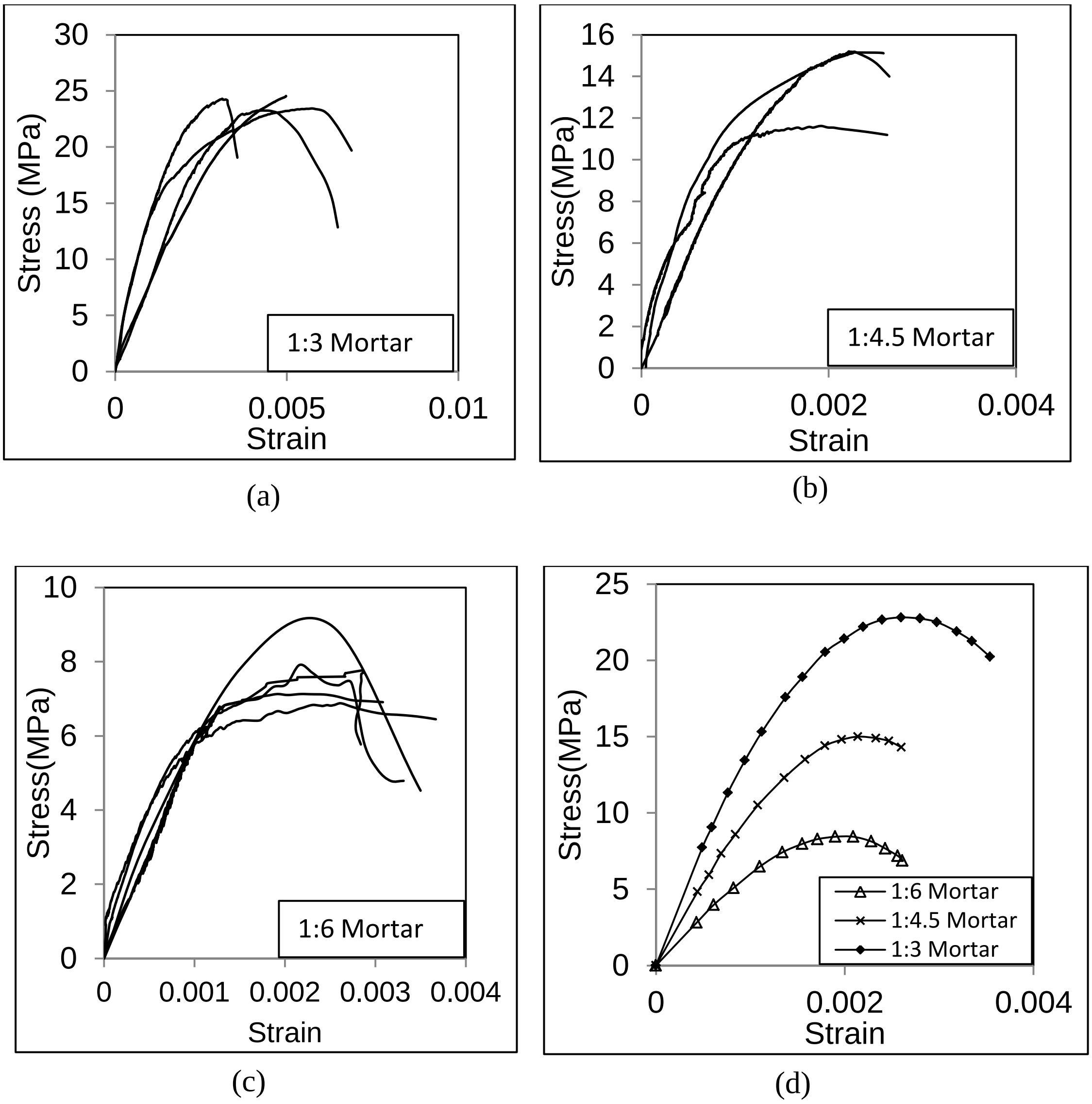


Figure 4.8 Stress-Strain curves for different samples of (a) 1:3 mortar (b) 1:4.5 mortar and (c) 1:6 mortar specimens (d) Comparison of stress-strain curves

The slope of the chord joining origin to 30% of the peak stress ($f_j^{'}$) is taken as modulus of elasticity (E_j) of the mortar. This modulus of elasticity is 741.5,726.5 and 692 times the strengths($f_j^{'}$) of 1:3,1:4.5 and 1:6 mortar respectively. An average value of modulus of elasticity is equal to 720 times the mortar strength. Figure 4.8(d) shows the comparison of stress strain behaviour for specimens with different grades of mortar.

4.5 COMPRESSION TESTS ON MASONRY PRISMS

In the present study stack bonded masonry prisms of five bricks were constructed using three different grades of mortar and one brick type combination. Thickness of mortar joint 10mm maintained strictly with the help of wooden frames. After 28 days of curing, the specimens were tested under compression as per IS 1905-1987 to obtain the stress-strain behaviour. 5mm LVDTs are fixed to second and fourth bricks to measure the deformation of specimen. Most of the prism specimens failed due to vertical cracking. The test setup and failed and failed specimen are shown in figure 4.9. Table 3 shows the strength of the different prism specimens (f'_m), corresponding strains (ε'_m) and modulus of elasticity (E_m). The slope of chord drawn from 5% of prism strength to 30% of prism strength is taken as the modulus of elasticity (E_m). Figure 4.10 shows the stress-strain curves for the three different prism specimens and their comparison.

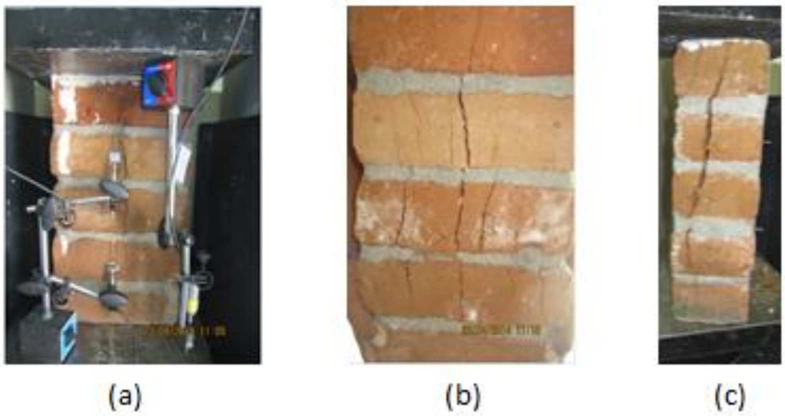
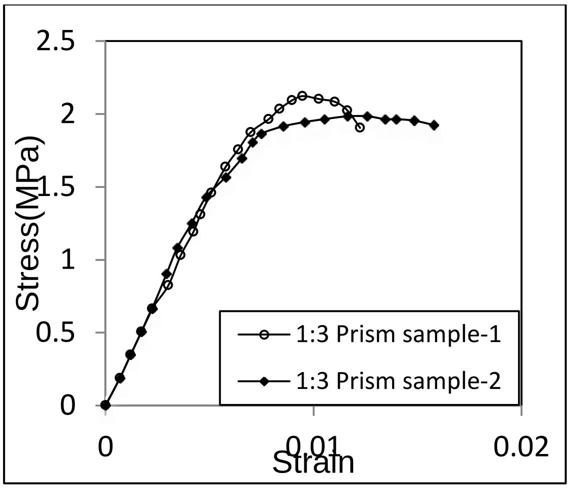


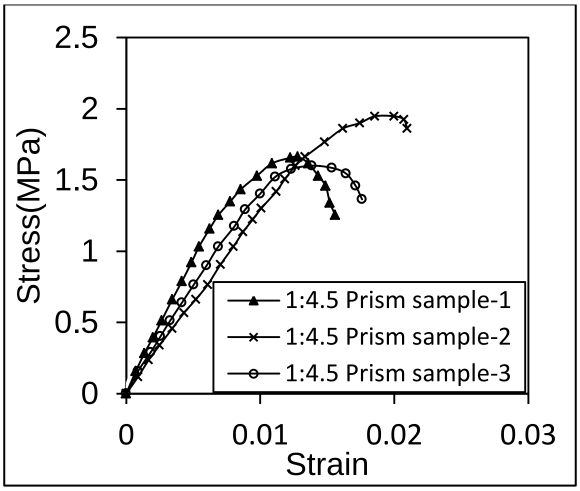
Figure 4.9 Masonry Prisms under Compression (a) Test setup; (b) & (c) Failure Modes

Table 3. Summary of test results of masonry prisms

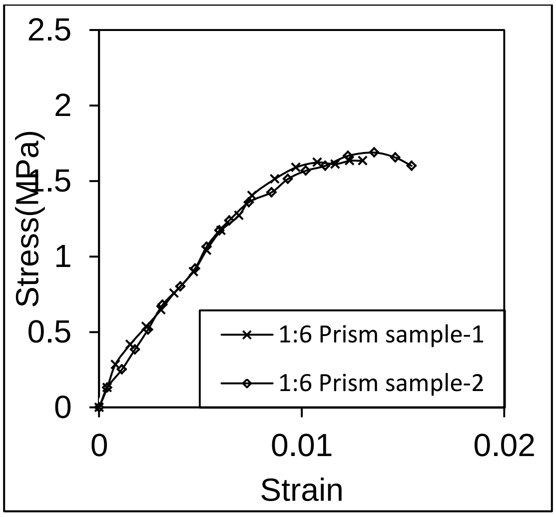
S.No	Mortar Proportion	No.of specimens	f'_m (MPa)	ε'_m	E_m(MPa)
1	1 : 3	5	2.06(0.13)	0.0130(0.20)	273.3
2	1 : 4.5	5	1.78(0.08)	0.0140(0.29)	229.0
3	1 : 6	5	1.45(0.19)	0.0145(0.17)	219.0



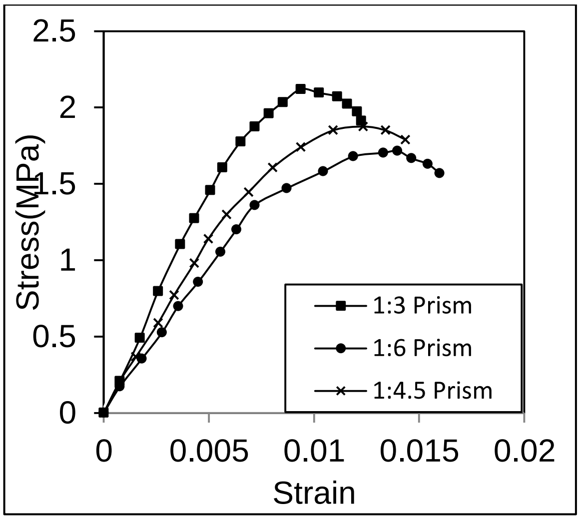
(a)



(b)



(c)



(d)

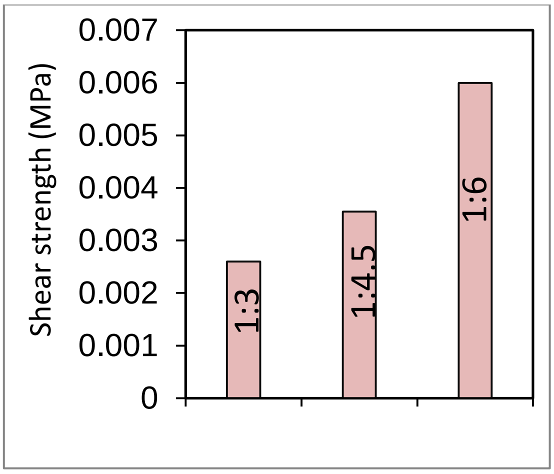
Figure 4.10 Stress-strain curves for Masonry Prisms under Compression (a) 1:3 Mortar, (b) 1:4.5 Mortar and (c) 1:6 and (d) Comparison of different grades

4.5 SHEAR TESTS ON MASONRY TRIPLETS

To characterize the shear strength of brick-mortar joint in the present study, triplet tests were performed. Seven specimens of aforementioned each grade of mortar and brick combination were tested after 28 days of curing. LVDTs were fixed to the specimens to capture the deformation but as these specimens failed at very load only, the deformations could not be captured. Figure 4.11 shows the test setup, failed specimen and Table 4 shows the summary of test results.

(a) (b)

Figure 4.11 Shear Triplets (a) Test setup (b) Failure Mode



(c)

Figure 4.12 Comparison of shear strength

Table 4. Summary of shear testing results

S.No	Proportion	No.of specimen	Shear strength (MPa)	Standard Deviation
1	1:3	3	0.0026	0.004
2	1:4.5	3	0.0035	0.003
3	1:6	3	0.0060	0.002

All the specimens have very low shear strength and on relative comparison it can be observed that the mortar joint with low cement content (1:6 mortar) has more shear strength. It can be noticed in Figure 4.11(b) that the specimens in triplet test were failed due to the sliding of mortar joints.

CHAPTER 5

EXPERIMENTAL STUDY ON RETROFITTED ASSEMBLIES

5.1 GFRP RETROFITTING

Behaviour of GFRP retrofitted stack bonded prisms is studied under compression to understand the effectives of GFRP retrofitting. Nine prims were cast with three different grades of mortar. Prims with different grades of mortars with cement: sand (1:3, 1:4.5 and 1:6) were cast and wrapped with unidirectional woven glass fibre fabric (Sikawrap-100G) in hoop direction using Sikadur-330 as an epoxy resin. The properties of fibre, epoxy and laminate are mentioned below

5.1. 1 Fibre properties:

- Fibre type: Glass fibres.
- Fabric construction:
  - Fibre orientation : 0^0 (unidirectional)
  - Warp direction : White glass fibres (98% of total weight)
  - Weft direction : White thermoplastic fibres (2% of total weight)
- Technical data :
  - Tensile strength : 2300MPa
  - Tensile E-modulus : 76000MPa
  - Elongation at break : 2.8%
  - Fibre density : 2.56 g/cm^3
  - Fibre thickness : 0.34mm

5.1.2 Epoxy resin properties:

- Sikadur-330 (two part epoxy resin).
- Part A: Resin; Part B: Hardener.
- Technical data :
  - Compressive strength: >75MPa (7 days at 30^{0}C).
  - Tensile strength: 30MPa (7 days at 30^{0}C).
  - Elongation at break: 2.0% (7 days at 30^{0}C).
  - Density: 1.32kg/lt.
  - Thermal resistance : Continuous exposure to +45^{0}C

5.1.3 Laminate properties:

- Laminate thickness 1.3mm per layer.
- Design cross section per 1000mm width is equal to 1300mm^2.
- Technical data :
  - Tensile strength : 525MPa
  - Tensile E-modulus: 18kN/mm^2.

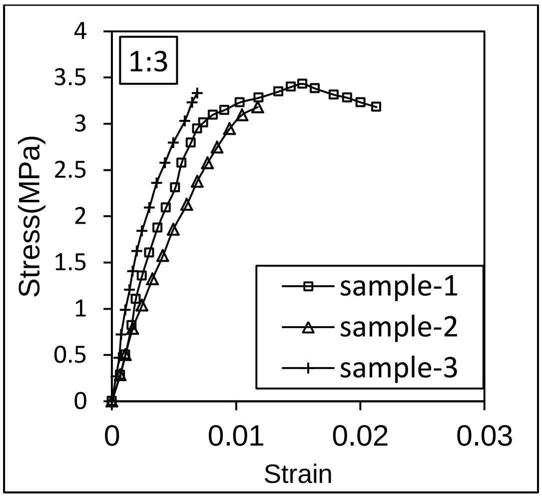
The application procedure of GFRP composite on the surface of the masonry prism specimen is shown in figure 5.1. The surface of the masonry prism is cleaned to remove all the dust, loose and friable material. Thereafter, the unevenness on the surface is filled with mortar to obtain a uniform surface. The GFRP fabric is cut to the required size and the resin and hardener parts were mixed in 4:1 proportion as prescribed by the supplier. After thorough mixing, epoxy is applied onto the prism surface and a layer of fabric is wrapped on the specimen. An overlap length of 150 mm is provided and a gentle press is applied with an impregnation roller to remove the entrapped air between the fabric and specimen surface. These strengthened specimens were tested under compression as shown in figure 5.2 in order to obtain their strength and stress-strain behaviour. Figure 5.3 shows the stress-strain behaviour for the different specimens.

(a) (b) (c) (d) (e)

Figure 5.1 Application of GFRP Wrapping (a) Fibre fabric and mixing of Epoxy resin and hardener; (b) Preparation of surface; (c) Application of epoxy; (d) Application of fabric; (e) Rolling with impregnation roller

(a) (b) (c) (d) (f)

Figure 5.2 GFRP Retrofitted Specimens under compression: (a), (b) Test setup; (c)&(d) Failure Modes of specimen; (e) Buckling of fibres at the centre; (f) Dislocation of LVDT due to bulging.



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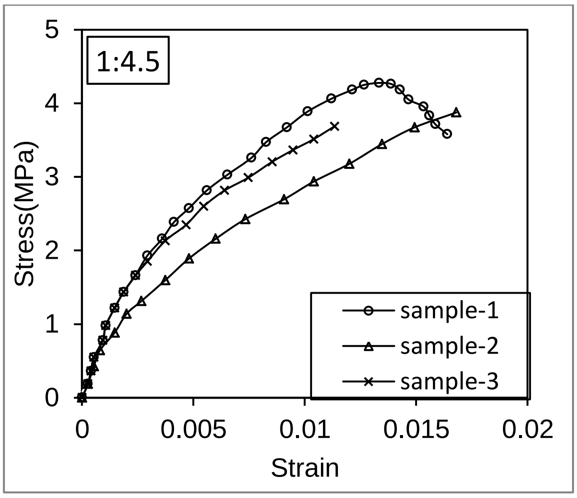

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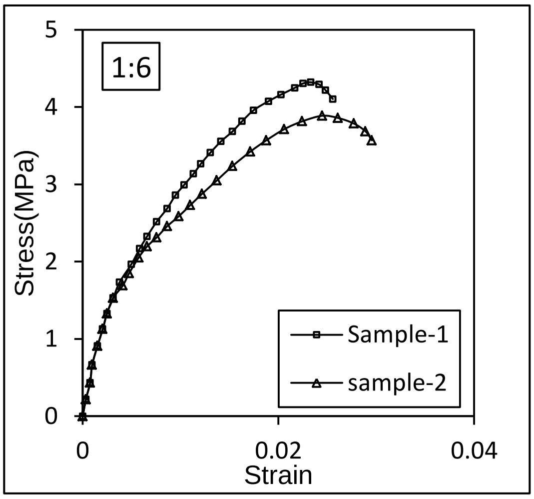


(c)

Figure 5.3 Stress-strain curves for GFRP wrapped Prisms with (a) 1:3 Mortar; (b)1:4.5Mortar (c) 1:6 Mortar

5.2 TRM RETROFITTING

To assess the effectiveness of textile reinforced mortar (TRM) as a strengthening technique for improving the behaviour under compression and shear, five brick stack bonded prisms and triplets with different combinations of mortar grades in the joints are strengthened with a bidirectional polypropylene (PP) grid. The properties of PP grid are given below. Mortar of 1:3 (Cement: Sand) proportion is used for binding the grid onto the surface of specimens. The triplet and prism specimens were wetted with water prior to the application of TRM to avoid any suction of water present in mortar by bricks during the application. Firstly, a layer of mortar is applied by hand onto the specimen's surface. Thereafter, polypropylene (PP) grid cut to the suitable size is placed over it. Finally, one more layer of mortar is applied over the grid to achieve better bonding. Initially, the unretrofitted specimens were kept for 28 days of curing. The process of application of TRM is shown in figure 5.4. After curing, the prism specimens were tested under compression and triplets were tested under shear as that of their unstrengthened and GFRP strengthened counterparts. Due to the presence of TRM layer, it is difficult to measure the deformation of the specimens on the stretcher face of bricks. Hence, the deformation of the prism specimens is measured on the header face of second and fourth brick by means of LVDTs. The test setup is shown in figure 5.5 and failure mode of the specimens is shown in figure 5.6. The summary of shear testing of triplets is illustrated in Table 5. The obtained stress-strain curves are shown in figure 5.7.

5.2.1 Polypropylene (PP) Grid Properties

Structure: Welded straps.

- Aperture size: 32mm.
- Ultimate tensile strength: 40kN/m in both machine direction (md) and cross machine direction.
- Tensile Modulus: 800kN/m at 1% elongation and 600kN/m at 2% elongation.
- Junction strength: 11kN/m in both md and cmd.

(a) (b) (c)

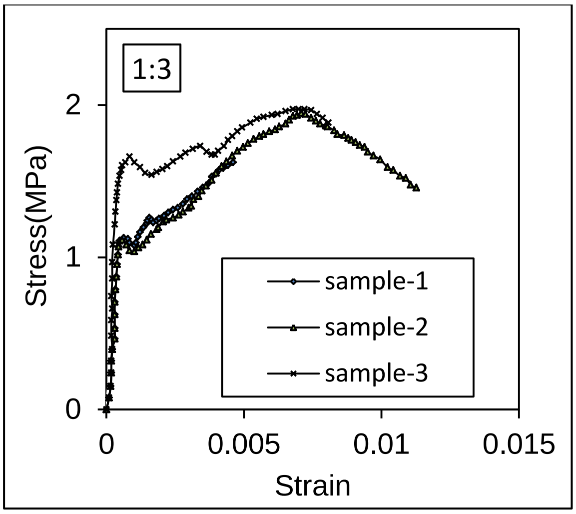
Figure 5.4 Application of TRM (a) Fixing PP grid over a layer of mortar; (b) Application of second layer of mortar over PP grid (c) TRM Strengthened specimens

(a) (b)

Figure 5.5 Testing of TRM strengthened specimens (a) Prism under compression; (b) Triplet under shear

(a) (b) (c)

Figure 5.6 Failure Mode of TRM strengthened specimens (a) and (b) Prisms; (c) Triplet.



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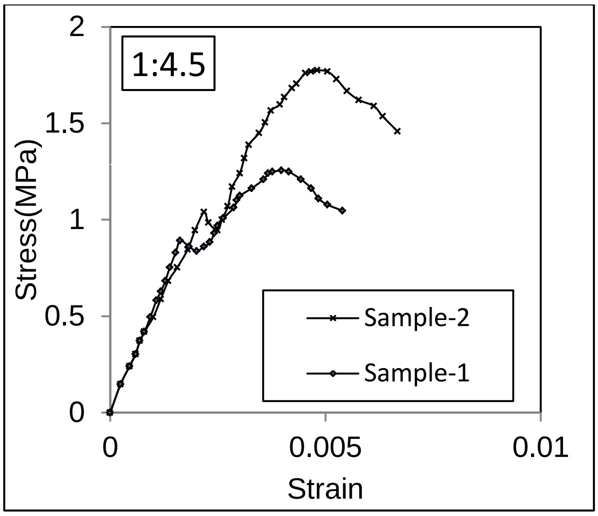

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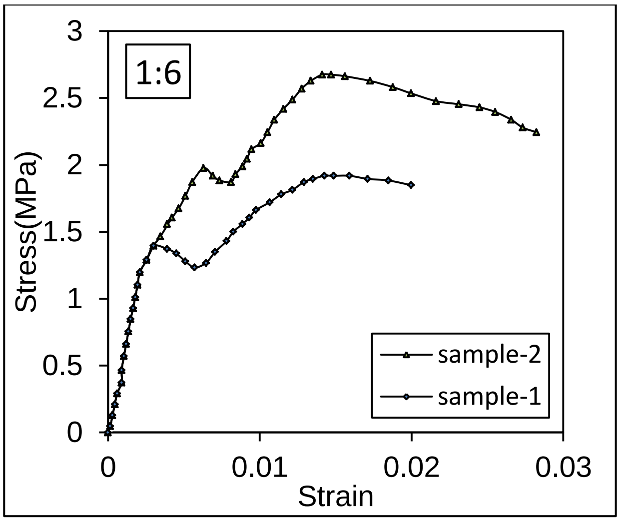


(c)

Figure 5.7 Stress-strain curves for TRM strengthened Prims with (a) 1:3 Mortar; (b) 1:4.5 Mortar and (c) 1:6 Mortar

Table 5. Results of TRM strengthened Triplets

S.No	Proportion	No.of specimens	Shear strength(MPa)	COV
1	1 : 3	3	0.654	0.052
2	1 : 4.5	3	0.660	0.121
3	1 : 6	3	0.56	0.180

CHAPTER 6

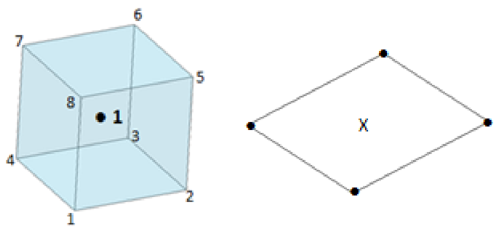
FINITE ELEMENT AND ANALYTICAL STUDIES

6.1 INTRODUCTION

In this chapter, numerical modelling (Finite Element –FE) of masonry prism is presented. FE results of control and retrofitted prims are validated with experimental data and the results are discussed. Finite element software tool ABAQUS is used for the analysis. The constitutive model considered for modelling of brick and mortar joints is 'Damage plasticity model' as it addresses both the irreversible (plastic) deformations and micro-cracking contributing to the nonlinear response of unreinforced masonry. Analytical equations derived based on the experimental data to predict the masonry strength and its stress-strain behaviour are also presented in this chapter.

6.2 NUMERICAL STUDY

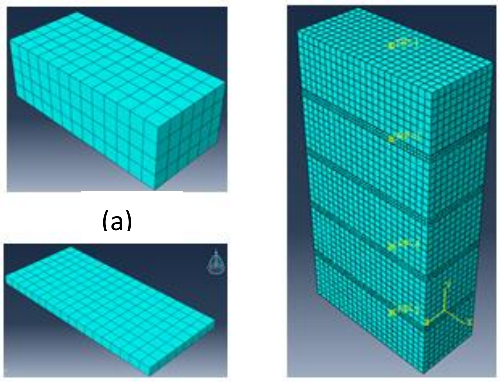
Three-dimensional models of the unretrofitted and GFRP retrofitted prism specimens subjected to compression are built using solid brick element C3D8R for both the brick and mortar. The element C3D8R is a linear brick element with reduced integration (one integration point) as shown in Figure 6.1(a). For modelling of the GFRP laminate of retrofitted prism specimens, a 4-noded reduced integration shell element S4R is used which is shown in figure 6.1(b).



(a) (b)

Figure 6.1 Finite elements used (a) C3D8R element; (b) S4R element

The model has the same dimensions as that of the tested specimens. As the analysis carried out is a non-linear analysis, the load is applied in terms of control of displacement. A displacement of 15mm is applied on the top most face of the specimen in 20 steps. Adopted mesh size for brick, mortar and GFRP laminate is 17mm, 12mm and 10mm respectively. The GFRP laminate thickness is given as 1.3mm. The results obtained from experimental investigation are given as material properties and few material properties that are necessary for numerical modelling have been taken from existing literature. Tensile strength of brick and mortar is taken as 10% of the respective compressive strength. Table 6 shows the material properties used in numerical study. Figure 6.2 shows the meshed brick, mortar joint and prism. The stress-strain behaviour of unretrofitted and GFRP retrofitted specimens obtained through numerical study is shown in figure 6.3 and figure 6.4. The experimental and numerical results for unretrofitted and GFRP retrofitted specimens are compared in figure 6.5 and figure 6.6 respectively. It is observed that the predicted stiffness through numerical study closely matches with that of experimental study, whereas the strength predicted is much higher in when compared to experimental counterpart.

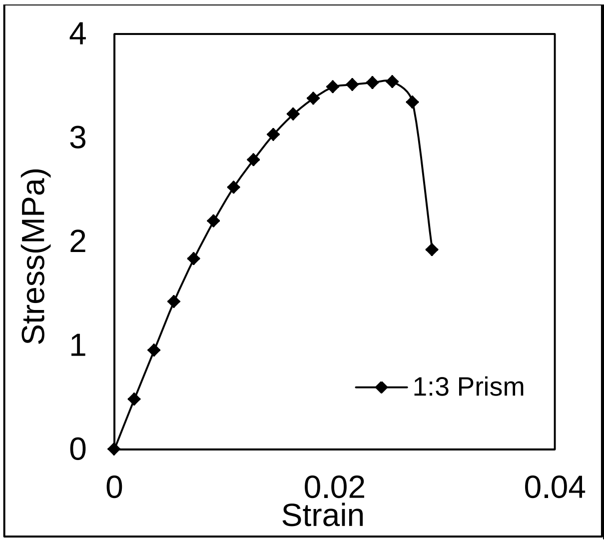


(b) (c)

Figure 6.2 Finite element mesh (a) Brick; (b) Mortar joint; (c) Prism

Table 6. Material Properties for Damage Plasticity Model

Material Property	Brick	Mortar
Modulus of Elasticity(MPa)	260	720($f_j^{'}$)
Uniaxial Compressive strength(MPa)	4	$f_j^{'}$
Uniaxial Tensile strength(MPa)	0.4	10% of $f_j^{'}$
Tensile Fracture Energy(N/mm)	0.08	0.34
Dilatancy Angle	20^0	20^0
Friction Angle	19^0	19^0
Deviatoric Out-of-Roundness(K)	0.7	0.7
Biaxial Strength ratio	1.15	1.15
Vertex Rounding	0.1	0.1
Poisson ratio	0.22	0.2



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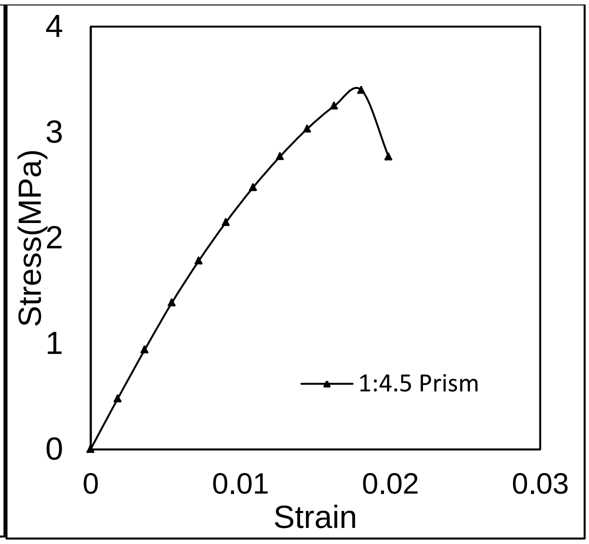

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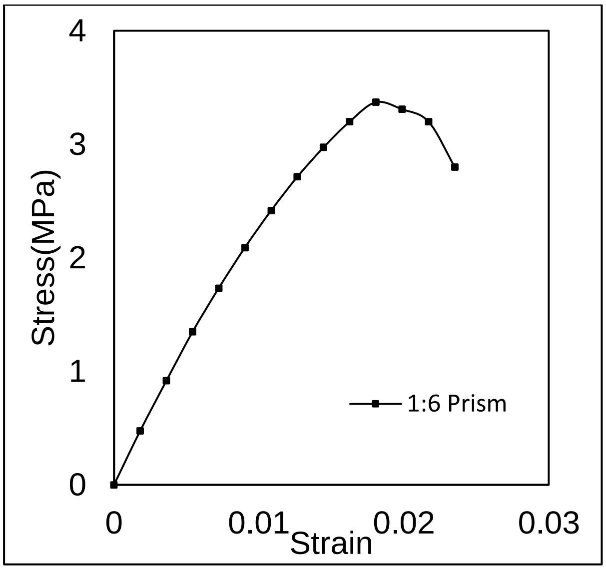

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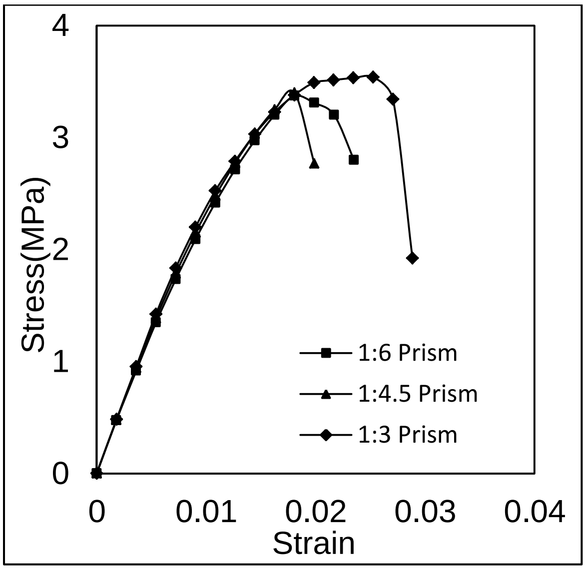


(d)

Figure 6.3 Stress-strain curves for Unretrofitted Prisms with (a) 1:3 Mortar; (b) 1:4.5 Mortar; (c) 1:6 Mortar and (d) comparison for different grades of mortar

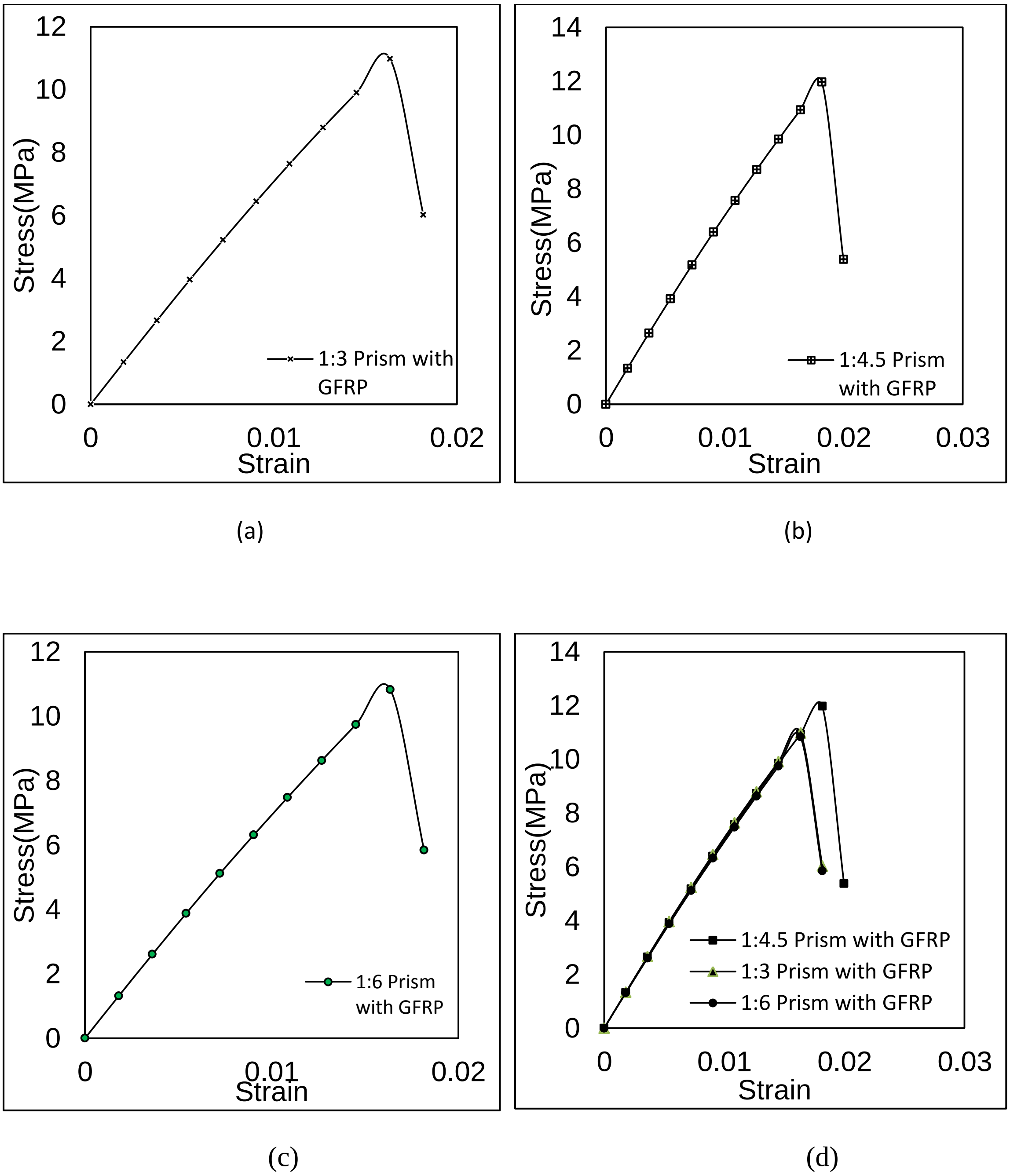
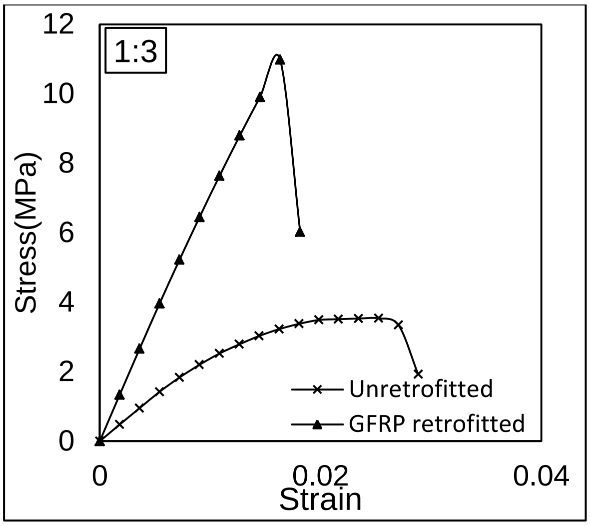
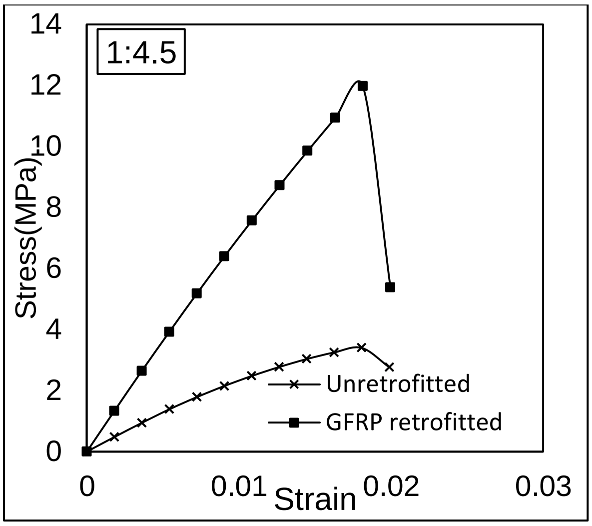


Figure 6.4 Stress-strain curves for GFRP retrofitted Prims with (a) 1:3 Mortar; (b) 1:4.5 Mortar; (c) 1:6 Mortar and (d) comparison for Different Grades of Mortar



(a)



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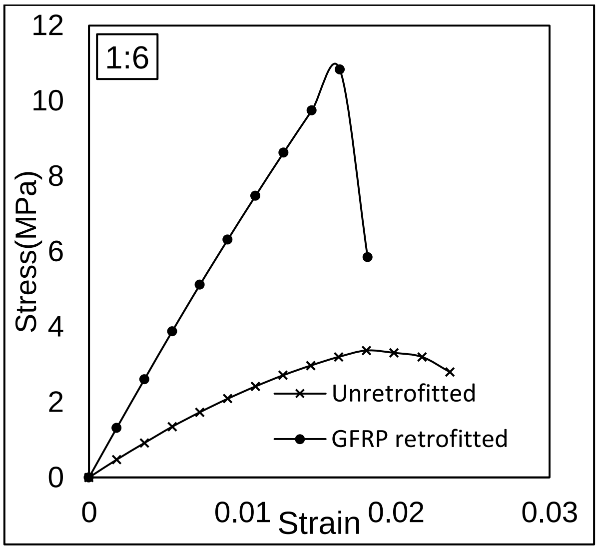
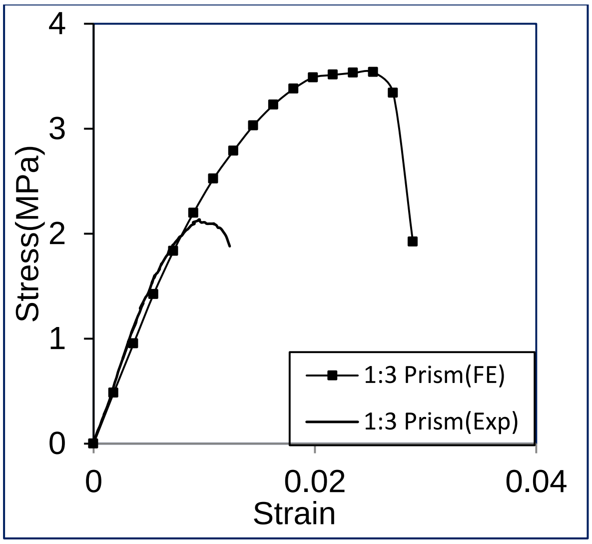


(c)

Figure 6.5 Comparison of FE results of unretrofitted and GFRP retrofitted Prism Specimens with (a) 1:3 Mortar; (b) 1:4.5 Mortar; (c) 1:6 Mortar



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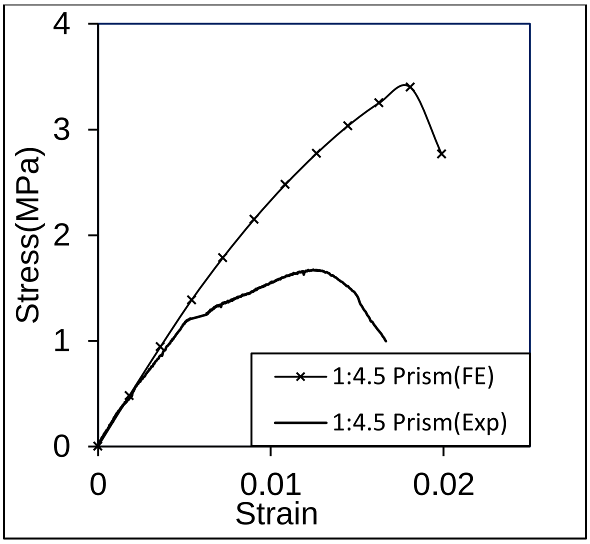

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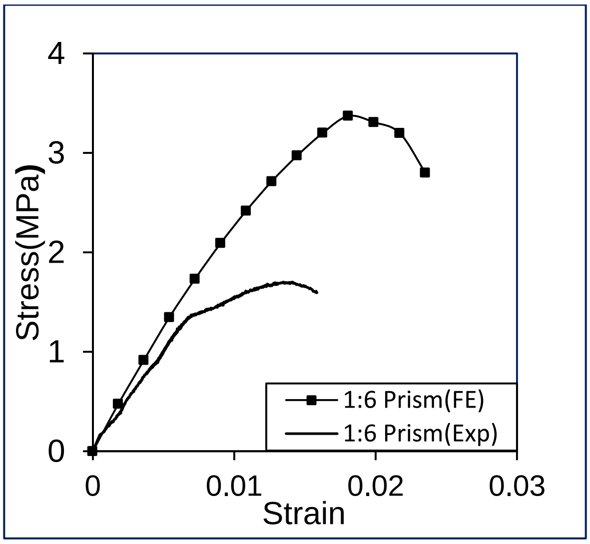
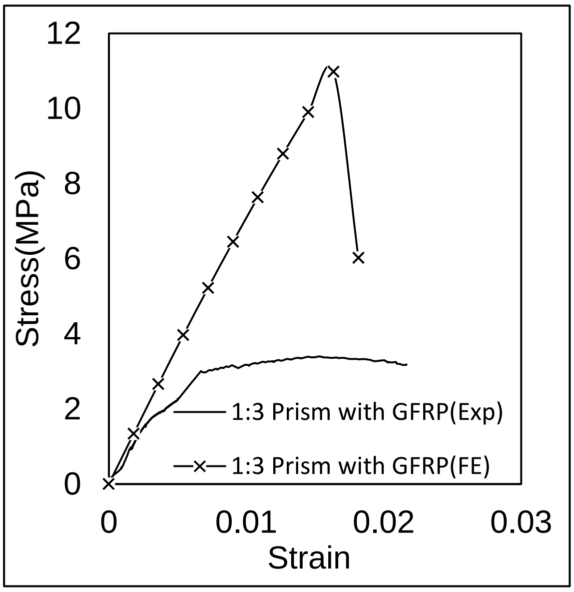
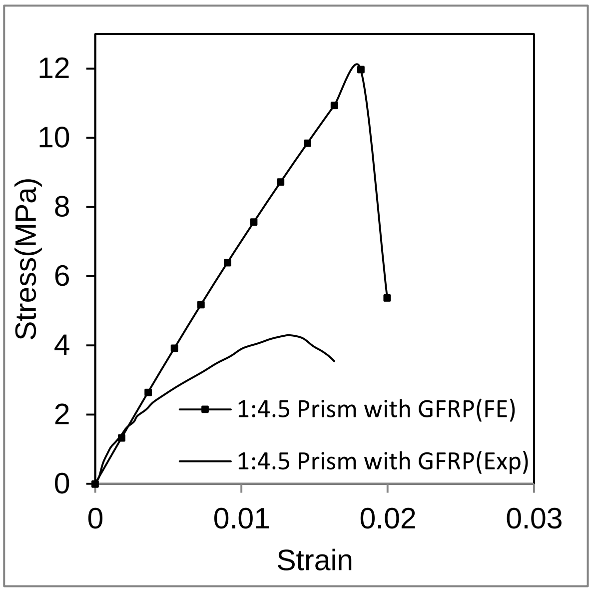


(c)

Figure 6.6 Comparison of Experimental and FE results of unretrofitted Prism Specimens with (a) 1:3 Mortar; (b) 1:4.5 Mortar; (c) 1:6 Mortar



(a)



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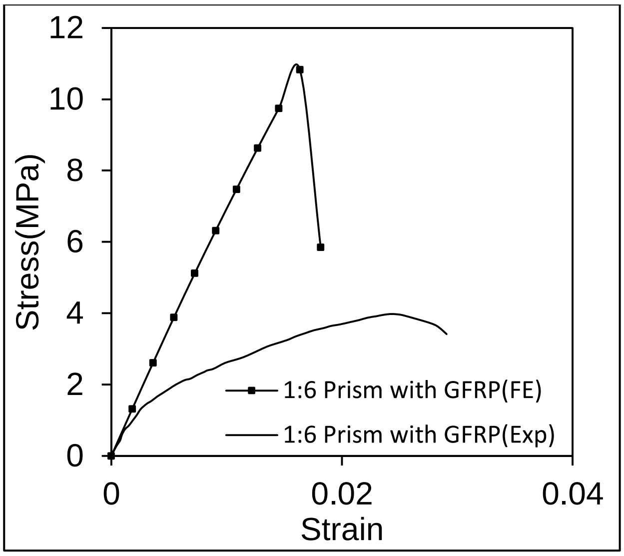


(c)

Figure 6.7 Comparison of experimental and FE results of GFRP retrofitted Prisms with (a) 1:3 Mortar; (b) 1:4.5 Mortar; (c) 1:6 Mortar

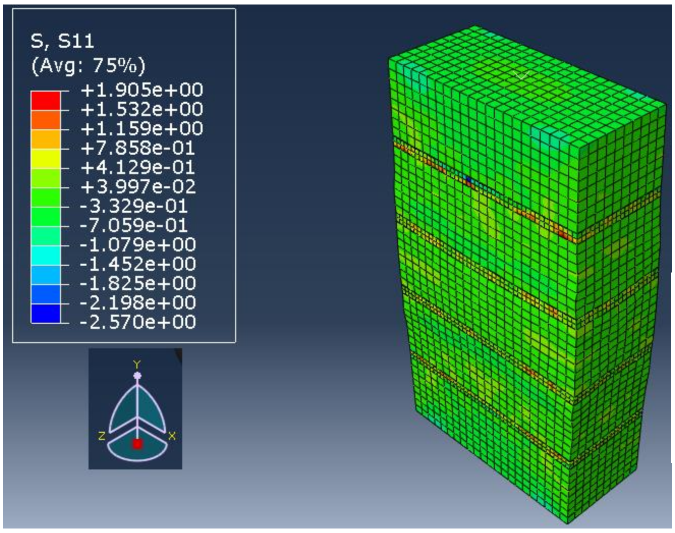


Figure 6.8 Stress contours of stress in the stretcher direction in unretrofitted 1:3 prism specimen

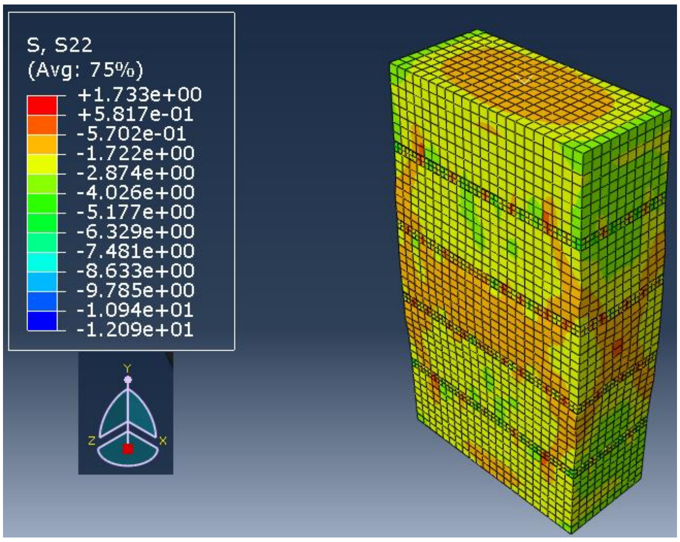


Figure 6.9 Stress contours of vertical compressive stress in unretrofitted 1:3 prism specimen

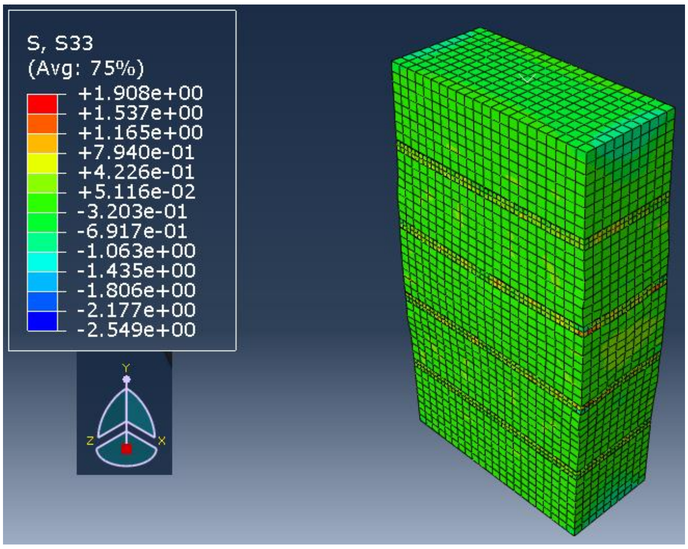


Figure 6.10 Stress contours of stress in the header direction in unretrofitted 1:3 prism

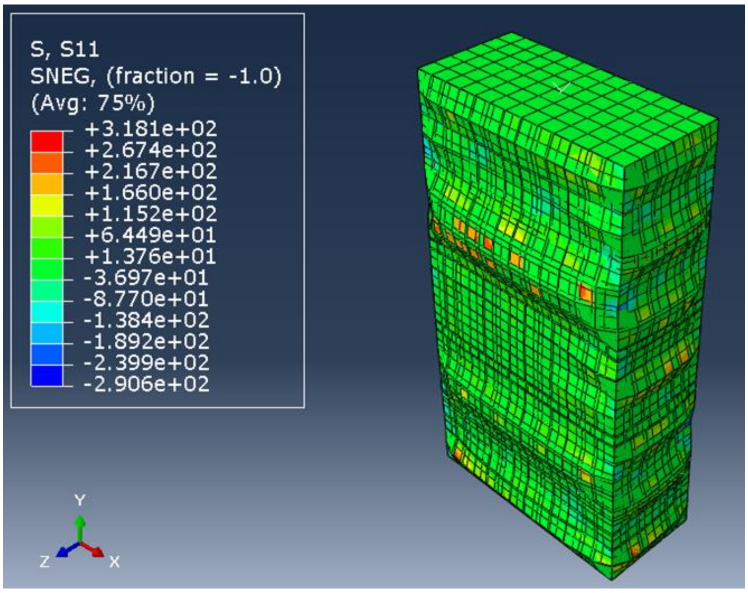


Figure 6.11 Stress contours of stress in the stretcher direction in GFRP retrofitted 1:3 prism specimen

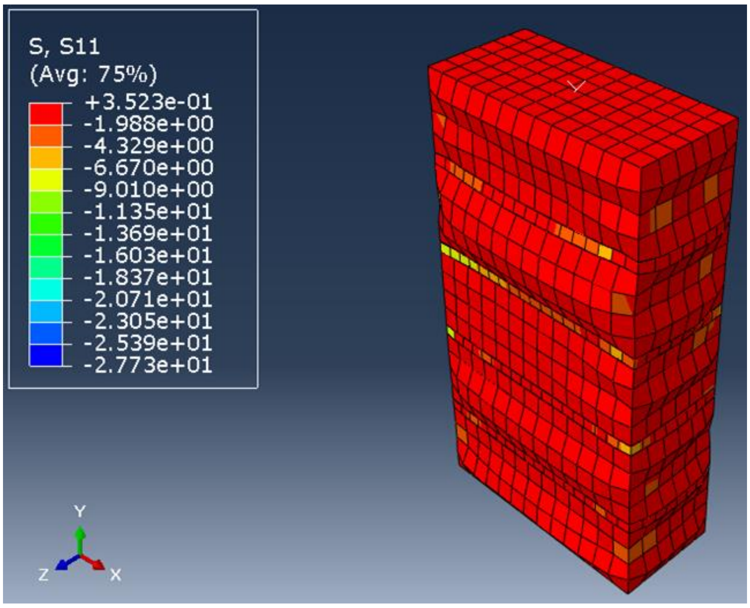


Figure 6.12 Stress contours of stress in the stretcher direction in GFRP retrofitted 1:3 prism specimen (removing wrap)

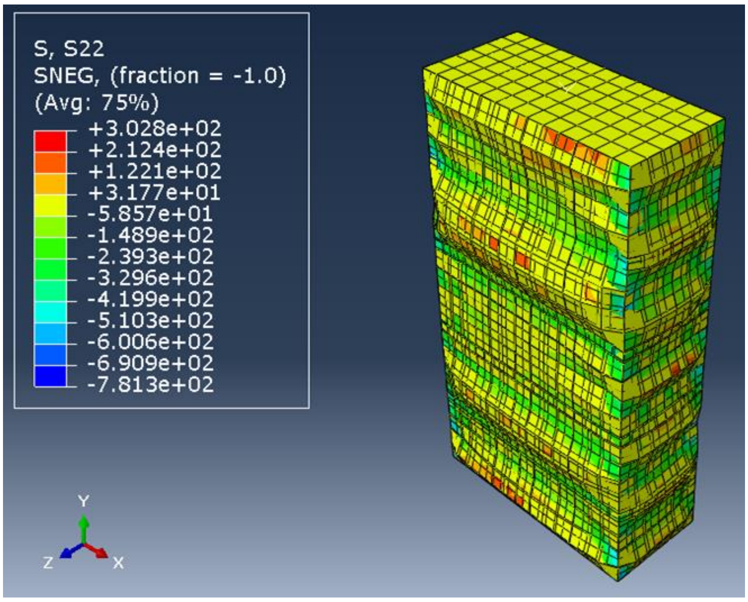


Figure 6.13 Stress contours of vertical compressive stress in GFRP retrofitted 1:3 prism specimen

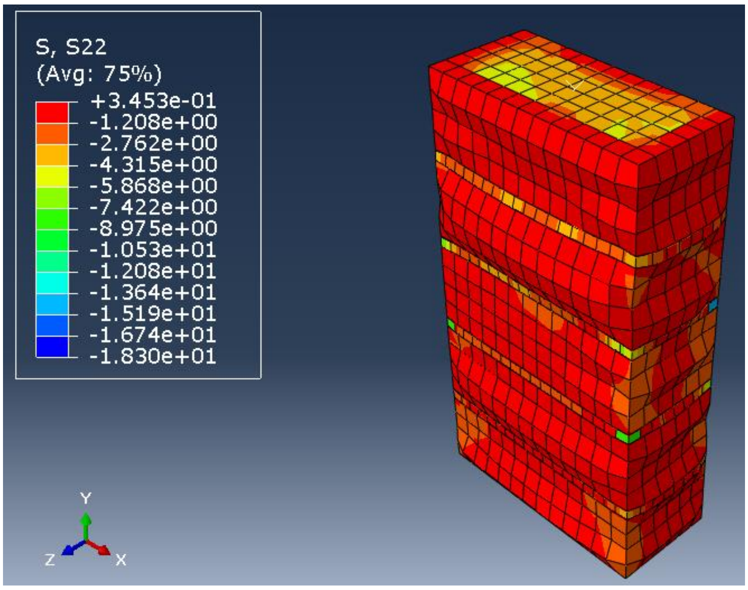


Figure 6.14 Stress contours of vertical compressive stress in GFRP retrofitted 1:3 prism specimen (removing wrap)

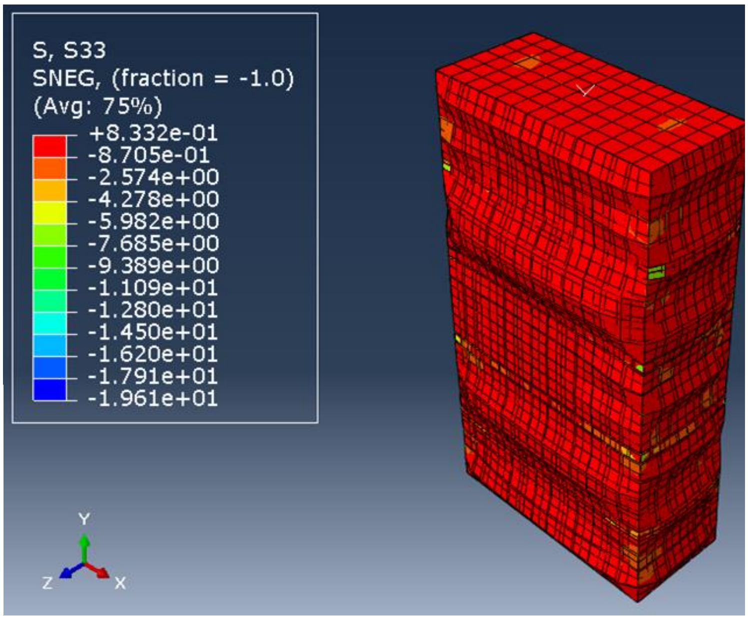


Figure 6.15 Stress contours of stress in the header direction in GFRP retrofitted 1:3 prism specimen

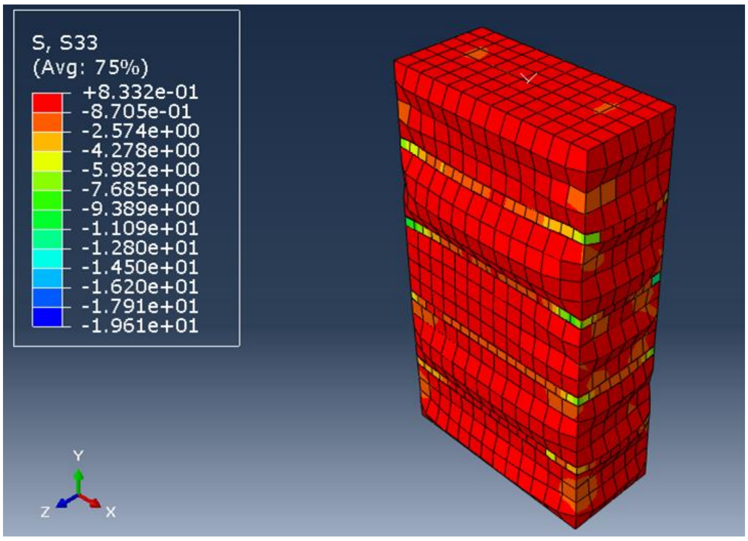


Figure 6.16 Stress contours of stress in the header direction in GFRP retrofitted 1:3 prism specimen (removing wrap)

6.3 ANALYTICAL STUDY

Semi-empirical equations are developed using the test data on bricks, mortar and prisms. The main objective of proposing simple relations using the compressive strengths of brick and mortar is to (i) estimate the strength of unretrofitted masonry prisms and (ii) estimate strain corresponding to peak stress. These values can be easily used for design calculations. The suitability of available parabolic model is verified to predict the stress-strain behaviour of unretrofitted masonry. Simple relations have been proposed to estimate the modulus of elasticity of brick, mortar and unretrofitted masonry. Table 7 presents the relationships for obtaining the moduli of elasticity of brick, mortar and unretrofitted masonry prisms using their respective compressive strengths.

Table 7. Relationship between moduli of elasticity and compressive strength

S.No	Component	Compressive strength (A)	Modulus of elasticity (B)	Ratio (B)/(A)	COV
1	Brick	f_b	E_b	65.0	0.02
2	Mortar	f'_j	E_j	730	0.31
3	Unretrofitted masonry	f'_m	E_m	135	0.085

The analytical equations proposed to estimate the compressive strength of masonry (f'_j) and the corresponding strain (ε'_m) are expressed below

$$f'_m = 0.395(f_b)^{0.49} x (f'_j)^{0.3}$$

$$\varepsilon'_m = \frac{0.42(f'_m)}{(f'_j)^{0.25} x (E_m)^{0.6}}$$

To predict the stress-strain behaviour of unretrofitted prism specimens, available parabolic model given below is compared with the experimental results and it is observed that the model fits well to the experimentally obtained stress-strain curves. The comparison of stress-strain curves obtained in experimental investigation and analytical study using parabolic model are shown in figure 6.17

Parabolic model $$\frac{f_m}{f'_m} = 2\frac{\varepsilon_m}{\varepsilon'_m} - \left(\frac{\varepsilon_m}{\varepsilon'_m}\right)^2$$

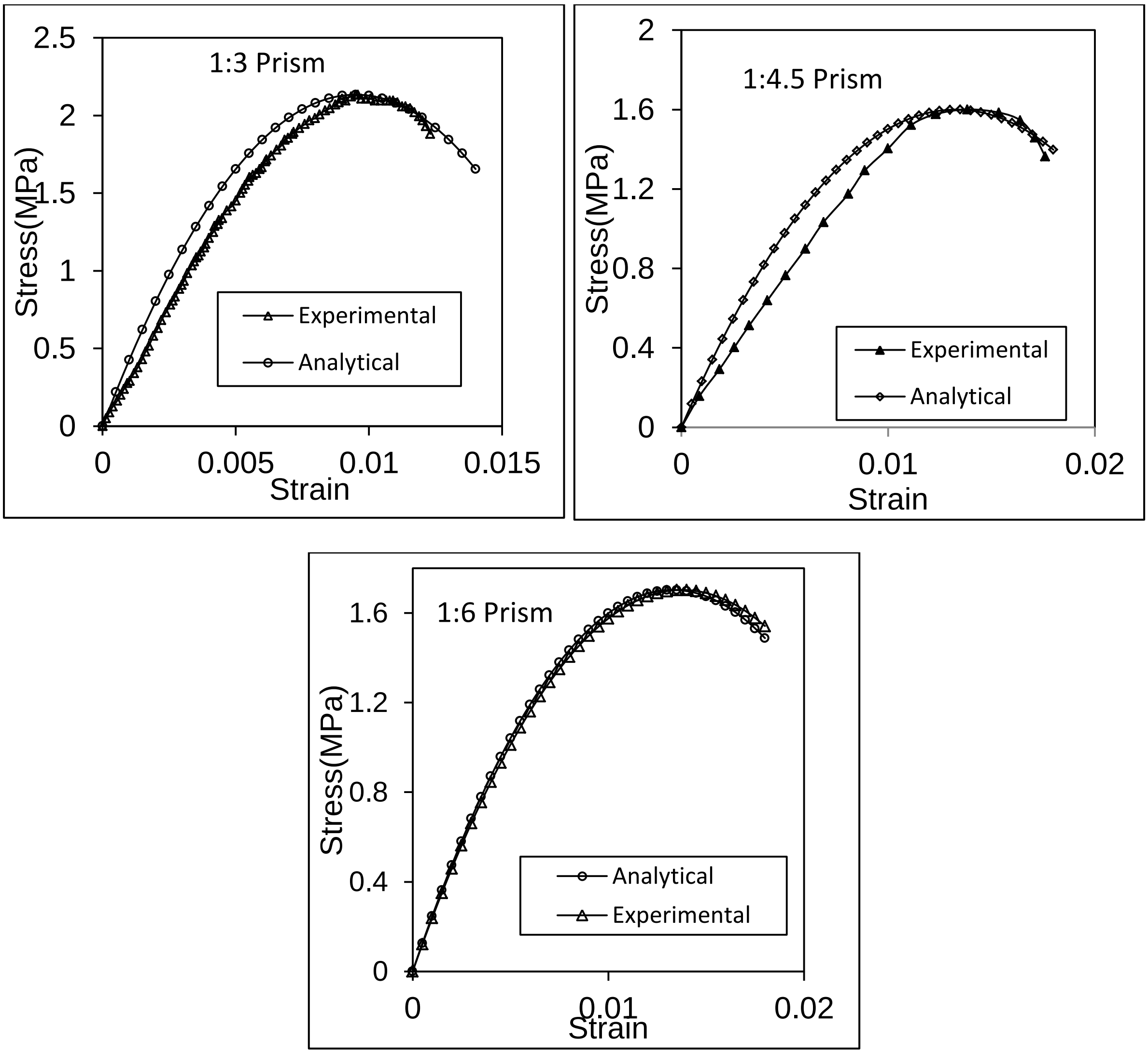


Figure 6.17 Comparison of experimental and analytical results for unretrofitted prisms

CHAPTER 7

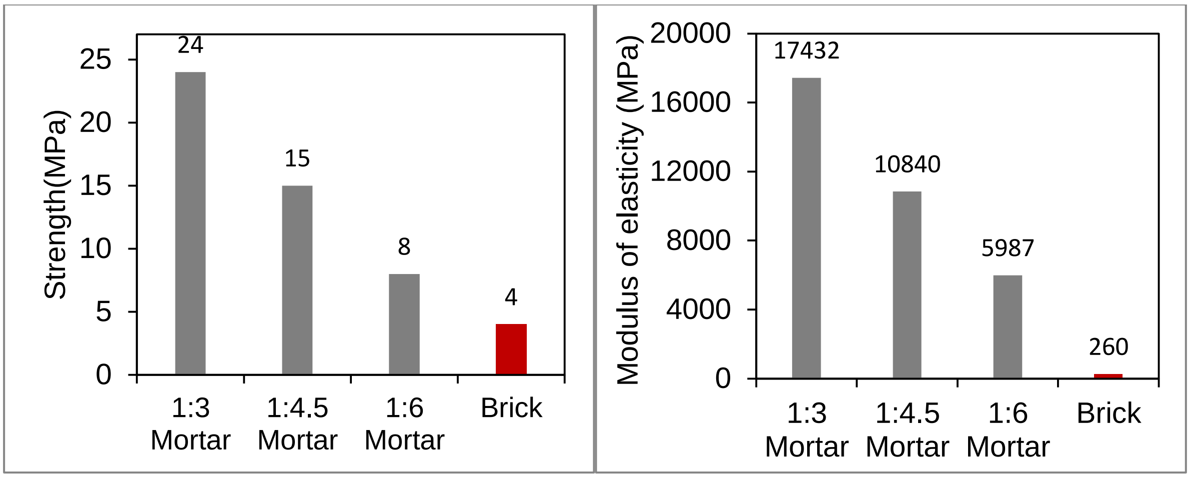
RESULTS AND DISCUSSION

7.1 OVERVIEW

Tests were carried out under compression on bricks and mortar to understand their strength and stiffness characteristics. The complete stress strain characteristics of brick and mortar under compression was studied. Thereafter, control masonry prism and triplet cast with different grades of mortar was investigated experimentally under compression and shear. Control prims and triplets were retrofitted with GFRP and TRM to understand their effectives in strengthening them. Retrofitted prisms and triplets of different mortar grade were tested under compression and shear respectively. The observations from the experimental and numerical study are enlisted below.

7.2 TEST RESULTS OF BRICKS AND MORTAR

Compression testing of bricks and different grades of mortar revealed that brick had low compressive strength and bricks were much softer than all the three mortar grades considered in this study. Figure 7.1 shows the comparison of strength and stiffness of the brick and different grades of mortar. Among the three different grades of mortar considered, as expected 1:3 mortar has more strength, stiffness and it failed at a higher strain. The stiffness of brick is only 260 MPa compared to mortar stiffnesses of 5900 MPa, 10,800 MPa and 17,400 MPa for grades 1:3, 1:4.5 and 1:3 respectively. This clearly shows the failure modes will differ significantly compared to the conventional masonry made of bricks with high strength and stiffness available in the literature.



(a) (b)

Figure 7.1 Comparison of strength and stiffness of brick and different grades of mortar

7.3 TEST RESULTS OF UNRETROFITTED MASONRY ASSEMBLIES

It has been observed from the compression tests on prisms and shear tests on triplets that 1:3 prism has more compressive strength 2.06MPa whereas 1:6 prism is being the lowest one 1.45MPa as shown in figure 7.2. All the triplets have failed due to sliding at the brick-mortar joint and have shown very poor behaviour in shear. It is observed that all the three different prisms considered in the present study have low compressive strength than brick and respective mortar grade.

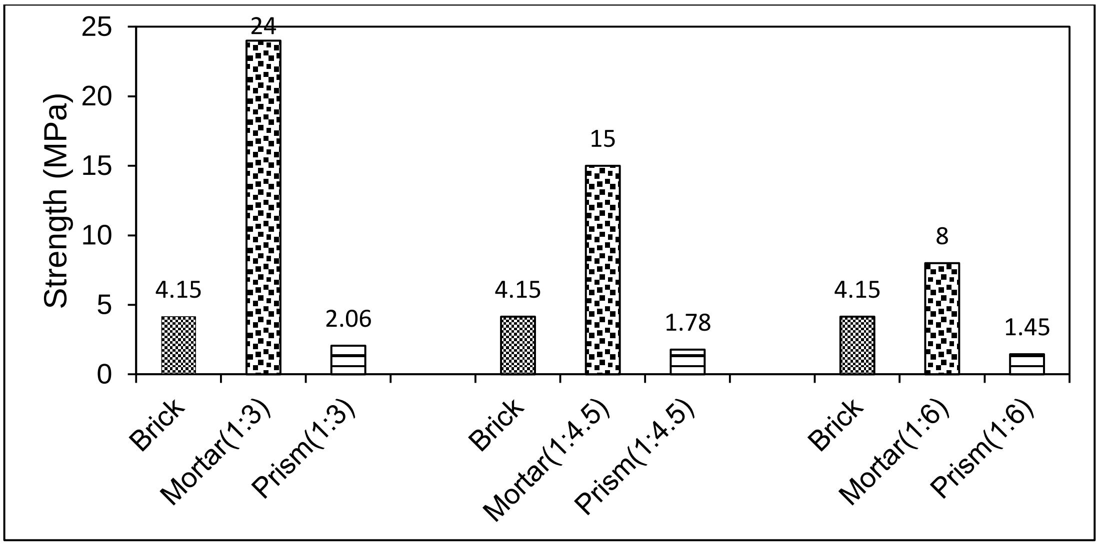


Figure 7.2 Comparison of brick, mortar and prism strengths

It is observed from the comparison of brick, mortar and prism strengths shown figure 7.2 that the prism strength is much lower than its constituent materials, this is due to the tensile failure of stiff mortar in lateral directions at very low loads. Figure 7.3 shows the comparison of strains corresponding to peak strengths in brick, mortar and prism specimens. The strain in prism is much higher than its respective mortar.

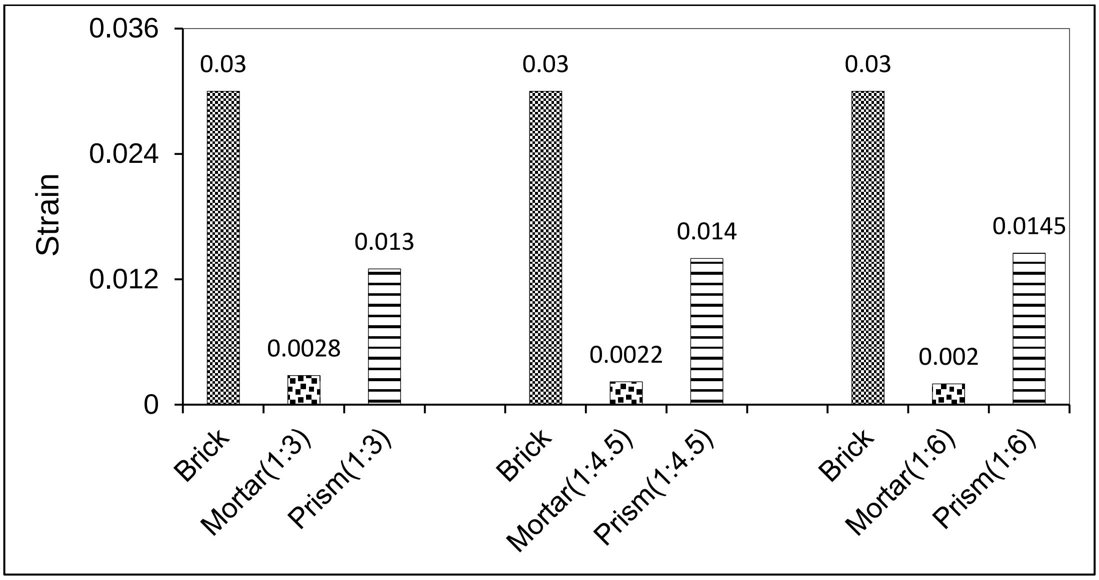
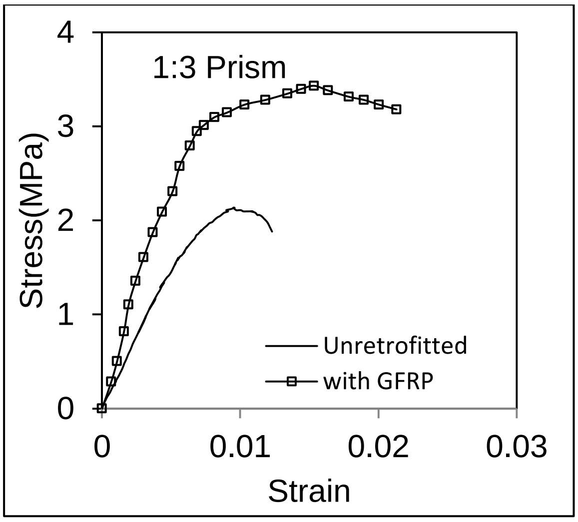


Figure 7.3 Comparison of strains corresponding to peak strength in brick, mortar and prism

7.4 TEST RESULTS OF RETROFITTED MASONRY ASSEMBLIES

It the present study experimental investigation is carried out on GFRP and TRM retrofitted masonry assemblies to assess their effectiveness for soft brick-stiff mortar combination. It is observed that GFRP strengthened prism specimens have more strength, stiffness and ductility when compared to their unretrofitted counterparts. It can observed from figure 7.4 that the GFRP retrofitted specimens can more energy than that of their unretrofitted counterparts, this is due to the confinement offerd by GFRP wrap. On the other hand, TRM retrofitted prism specimens showed very low strength but higher stiffness as compared to unretrofitted specimen. The reason can be attributed to the incompatibility between the softer brick and stiffer mortar layer that is used for binding the polypropylene grid onto the surface. The mortar layer is getting separated along with the brick material which can also be a for the reduction in strength of TRM retrofitted specimens. The shear testing of TRM strengthened triplets revealed the significant improvement in shear capacity due to TRM retrofitting. Figure 7.5 shows the comparison of stress-strain behaviour of 1:3 prism specimen with and without TRM retrofitting and further study is required in the case of TRM retrofitted 1:4.5 and 1:6 prism specimens to acquire consistent data.



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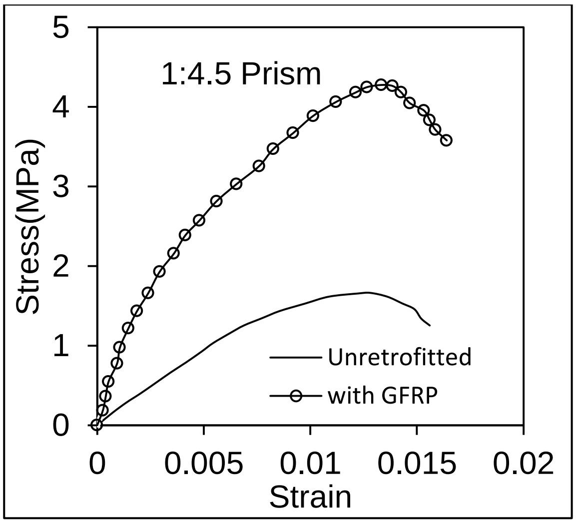

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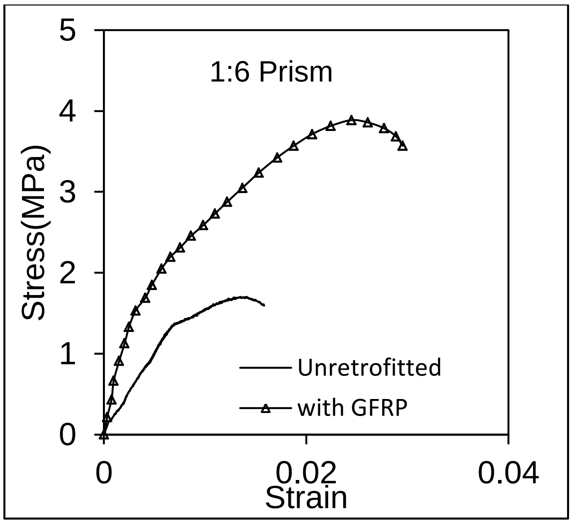

(c)

Figure 7.4 Comparison of stress-strain curves of unretrofitted and GFRP retrofitted
(a) 1:3 Prism; (b) 1:4.5 Prism; (c) 1:6 Prism

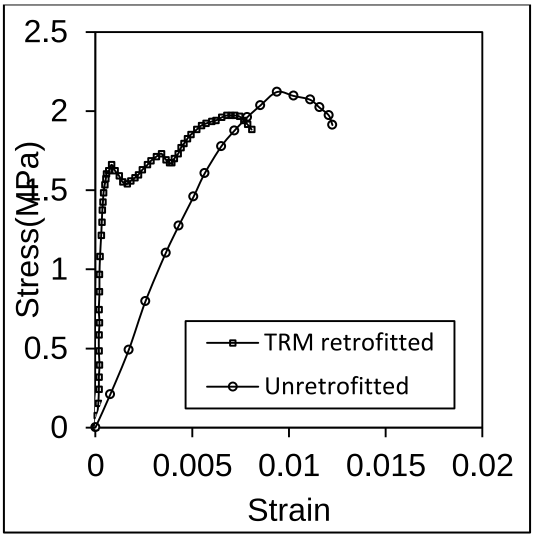

Figure 7.5 Comparison of stress-strain curves of unretrofitted and TRM retrofitted 1:3 Prism

7.5 FINITE ELMENT AND ANALYTICAL STUDIES

In the present study, two analytical equations are proposed to estimate the strength and corresponding strain of unretrofitted URM from the properties of its constituents. The suitability of parabolic model was verified. The predictions of the model showed good comparison with the experimental results. FE results obtained from three dimensional modelling of unretrofitted and GFRP retrofitted prisms have shown more strength and ductility than that of their experimental counterparts, this can be attributed to the material properties taken from literature due to lack of data and high variation in the brick strength(COV=0.33) which is difficult to consider in the numerical study. Through FE study it is predicted that brick is under triaxial compression and mortar is under uniaxial compression-biaxial tension which true for soft brick-stiff mortar combination considered in the present study. The FE results predicted the stiffness closely. However, there was significant difference in the ultimate strength. This could be due to assumed tension behaviour for bricks and mortar. Future work should clarify the discrepancies of the FE results by incorporating correct material behaviour for bricks and mortar under tension.

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