Strengthening of Masonry Structures: A Review

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Abstract -*Masonry can be said as one of the oldest construction systems. Therefore, strengthening of these structures are of greater concern. Different techniques that are used to strengthen masonry structures are discussed in this paper. Fibre Reinforced Polymer (FRP), Engineered Cementitious Composite (ECC) and Geotextile were used to strengthen masonry walls in a less invasive manner. The application of different types of FRPs like carbon, glass and basalt fibre reinforced polymers were discussed and their contribution to the enhancement of the strength of the masonry structures were also dealt with. Geotextiles were used in the in-plane and out-of-plane strengthening of masonry walls. The above techniques were successful in enhancing the structural strength of the masonry structures. Thus, the use of such techniques was useful in the conservation of historic masonry structures.*

Key Words: Fibre Reinforced Polymer (FRP), Engineered Cementitious Composite (ECC), Geotextile, in-plane, out-of-plane strength.

1. INTRODUCTION

Various studies have been done over a number of years to develop strengthening techniques which will improve the performance of masonry. Many unreinforced masonry structures are seismically deficient and several research studies have been conducted to improve the seismic performance of these structures. Strengthening methods such as the addition of new structural elements, steel plate bonding, external post tensioning, steel bracing, Fibre Reinforced Polymer (FRP) and many more have been applied with some degree of success. However, an innovative retrofitting technique using Geotextile has gained recognition and acceptance. Fibre-reinforced polymer is a composite material. It is made of a polymer matrix reinforced with fibres. Glass, carbon, or aramid are the fibres commonly used. Sometimes fibres such as paper, wood or asbestos are also used. The major advantages of FRP composites include lightweight, non-corrosive and they also exhibit high specific strength and stiffness. Thus, it can be used to satisfy performance requirements. FRP composites are thus used for new construction and rehabilitation of structures.

Babatunde [15] stated that improving the ability of the structure to absorb inelastic deformation is the objective of a strengthening technique. The strengthening techniques can be of different types like concentrated at joints by near surface mounted (NSM) or repointing techniques or may be applied on the entire masonry wall. The load carrying capacity of the structure and integrity can be improved by the use of fibre reinforced polymer (FRP). FRP include high resistance fibre impregnated with polymeric resin which has got high tensile strength and corrosion resistance. The main load carrying component in FRP is the fibres and the resin transfers shear. FRP are light weight. High cost, low impact resistance and high electrical conductivity are some of the disadvantages. Glass, Aramid and Carbon are the three basic types of FRPs used. Commercially it is available in the form of laminates, meshes, tendons and rods. Researchers concluded that FRP helped in improving the strength and ductility of the masonry walls. Post tensioning with CFRP tendons helped in reducing the size of cracks in damaged structures. It also helped in improving serviceability and increase cracking moment of resistance in masonry structures. Near Surface Mounted (NSM) FRP system follows the method of cutting grooves having a diameter of one and a half times the bar diameter in the bed joint and then cleaning and filling with cement-based mortar or epoxy. Then the FRP bars are inserted into the groove. FRP reinforcement is placed symmetrically on both faces of the walls to avoid the tilting or twisting of the strengthened wall. NSM FRP system is said to be three times more efficient than externally bonded FRP system. Increasing the thickness of the epoxy cover and using adhesives of high tensile strength can reduce the tensile stresses. Thus, the masonry walls strengthened with NSM FRP bars showed an increase in the shear capacity. In this paper we will be dealing with the strengthening techniques that were adopted during the past few years.

2 MATERIALS AND METHODS

2.1Fibre Reinforced Polymer (FRP)

Albert [4]et. al conducted an experimental program at the University of Alberta and observed that the fibre reinforced polymer (FRPs) applied externally on unreinforced masonry walls subjected to out-of-plane flexural loads were effective in increasing the load-carrying capacity. The experimental parameters investigated were the following:(1) type of fibre reinforcement; (2) amount of fibre reinforcement; (3) layout of fibre reinforcement; (4) effects of moderate compressive axial load; and (5) cyclic behaviour. It was observed that the fibre reinforcement was easy to handle and apply. Also, the results concluded that strengthening with FRP increased the strength and ductility of the specimens.

2.1.1 Carbon Fibre Reinforced Polymer (CFRP)

Triantafillou [1] et.al summarizes the properties of fibre-reinforced polymer materials, the prestressing systems and reversible consolidation and strengthening of historic masonry structures. Here the masonry monuments were strengthened with the application of unidirectional fibre-reinforced polymer tendons. In order to provide horizontal confinement, the tendons were anchored to the masonry only at the ends and were also applied circumferentially on the external face of the structure and post tensioned. It was concluded that the strengthening using carbon fibre reinforced polymer (CFRP) provided a simple and effective method for the structural preservation of historical structures.Kolsch [2] introduced a method to strengthen the existing buildings and infill masonry walls subjected to the bending loads due to earthquake. Here additional overlays were applied as external reinforcement to the surfaces of the structural members. Textiles of carbon fabrics embedded in a cement-based matrix were used to strengthen the masonry wall. The masonry walls strengthened using the CFCM system were exposed to bending loads and it was concluded that the system prevented partial or complete collapse of masonry walls when subjected to out of plane bending.

Hamoush [3] et.al investigated the effectiveness of strengthening masonry wall using fibre- reinforced composite overlays to resist out-of-plane static loads. The unreinforced masonry walls strengthened using externally bonded composite overlays showed an increase in flexural strength. The masonry walls retrofitted by a continuous web overlay on the entire wall area showed slightly a higher strength than the ones retrofitted using unidirectional strips applied in two directions.Tan and Patoary [5] strengthened thirty masonry walls using three different Fibre-reinforced polymer (FRP) systems with three anchorage methods. Systems consisting of high-performance fibres externally bonded to masonry walls provided an increase in out-of-plane capacity. Premature failure due to FRP debonding can be prevented with appropriate surface preparation and anchorage. The increase in the thickness of the FRP laminates increased the load carrying capacity in all cases. From the tests carried out it was concluded that the combination of surface grinding and fibre bolt anchorage system resulted in the increase in wall strength. It was also observed that if an appropriate adhesive is used then the Bidirectional fibre glass woven fabrics could provide higher strength enhancement than carbon or glass fibre sheets.

Mahmood and Ingham [10] undertook a research program to investigate the effectiveness of fibre- reinforced polymer systems as a seismic retrofit intervention. In-plane loaded URM walls that were prone to fail in a shear mode during earthquakes were considered. Externally bonded (EB) glass FRP fabrics, EB pultruded carbon FRP (CFRP) plates, or near-surface mounted pultruded CFRP rectangular bars were used to retrofit the URM wallettes. A diagonal compressive force was applied to the wallettes and data for applied force and corresponding wall drift were recorded. Then the results were compared with the wallettes that were not retrofitted. From the results they determined that the FRP systems increased the shear strength, pseudo-ductility and the toughness of the wallettes.

2.1.2 Glass Fibre Reinforced Polymer (GFRP)

Al-Salloum and Almusallam [6] stated that FRP in the form of laminates and rods are available for strengthening masonry walls. Carbon, glass and aramid are the three types of fibres that are commonly used. It is bonded to the exterior surface of the walls using epoxy thus making the block elements act as an integrated system. It was concluded that the flexural capacity and ductility of the masonry walls subjected to out of plane loading can be greatly enhanced by bonding of GFRP sheets to the tension side of walls. Lateral and vertical in-plane stresses can be resisted if the walls are strengthened using GFRP sheets. Sivaraja [13] et al stated that Glass fibre-reinforced polymer (GFRP) composites offers higher strength and Young modulus than traditional steel devices. Therefore, it is widely used for reinforcing and strengthening applications in building trade. Here they evaluated the effectiveness of increasing the shear strength of brick masonry strengthened with Glass Fibre-Reinforced Polymer (GFRP). The out of plane behaviour of burned clay brick masonry wall and strengthened with Glass Fibre-Reinforced Polymer (GFRP)was studied.

Borri [14] et al carried-out shear tests on wall panels reinforced with Glass Fibre Reinforced Polymers (GFRP) jacketing and a reinforced repointing of mortar joints using high strength stainless steel cords. The technique involving GFRP was applied by the means of jacketing with GFRP mesh inserted inside an inorganic matrix. The diagonal compression test was done. They were able to conclude that the in-plane shear strength of the masonry wall increased compared to the unreinforced masonry walls.

Nanda [18] et al here Glass Fibre Reinforced Polymer (GFRP) was used to strengthen masonry walls subjected to out of plane bending. The masonry panels subjected to three-point loading test was considered for the study. Different geometric patterns were considered and was applied on one side and also on both sides of the wall panels. Flexural strength and failure load was observed to be increased in the case of retrofitted specimens. Also, cross retrofitting showed more efficiency in flexural strength, bending moment, stiffness and deformation capacity compared to the other patterns. Giaretton [20] et al aimed at improving the in-plane shear strength and displacement capacity of clay-brick and hollow clay block masonry walls using a composite material composed of multiaxial hybrid glass-fibres and polypropylene fabric coated in a hydraulic lime-based mortar. It is also referred to as textile-reinforced mortar. It was found that the strengthened wall maintained their load carrying capacity. Proença [19] et al considered a wall with opening and the aim was to strengthen the opening such that the wall would behave like the one with no opening. A structural steel window frame composed of a profile forming a closed ring inside the opening was installed and properly tied to the surrounding masonry wall. The results helped to conclude that there was a significant increase in strength, in-plane deformation capacity and cumulative dissipated energy at collapse for the ones strengthened.

2.1.3 Basalt Fibre Reinforced Polymer (BFRP)

Padalu [23] conducted an experimental study on unreinforced masonry wallettes strengthened using basalt fibre reinforced polymer (BFRP) composite wrap. The un-strengthened and strengthened wallettes were tested in two orthogonal directions. The flexural strength, deformability and energy dissipation capacity were enhanced up to 6.4 times, 30 times and 214 times respectively for the strengthened wallettes.

2.2 Engineered Cementitious Composite (ECC)

Maalej [8] et al tested masonry walls to assess the extent to which a cementitious-based material known as Engineered Cementitious Composite (ECC) can enhance the out-of-plane resistance of unreinforced masonry (URM) walls. It was tested under both quasi-static and dynamic loadings. The masonry wall panels retrofitted with an ultra-ductile hybrid-fibre ECC strengthening system was subjected to the following types of load patterns that is patch load, uniformly-distributed load and low-velocity projectile impact. The results obtained lead to the conclusion that the ECC strengthening systems helped in improving their ductility, enhancing their resistance against multiple low-velocity impacts and increasing the ultimate load-carrying capacity of URM walls. Also helped in preventing sudden and catastrophic failure. It was also found effective in contributing to damage mitigation in the event of blast or explosion.Hamed and Rabinovitch [9] Here the masonry walls were laterally strengthened with externally bonded composite materials. Their structural behaviour to resist out-of-plane loads was studied theoretically and experimentally. In this study, hollow concrete block and solid autoclaved aerated concrete AAC block were selected for examination. Both experimental and analytical results demonstrated the potential of lateral fibre-reinforced polymer strengthening of AAC masonry walls. The study revealed the improved strength, deformability and integrity at failure characteristics of the laterally strengthened AAC masonry walls.

2.3 Textile Reinforced Mortars (TRM)

Yardim and Lalaj [16] made a comparison of different strengthening techniques for unreinforced masonry walls. Textile reinforced mortars (TRM) plastering, applied on one and both faces of the wall, polypropylene fibre reinforced mortar (PP-FRM) and ferrocement reinforced mortar plastering were the three materials considered. Diagonal compression test was carried out to test the shear performance of the strengthened walls. Significant improvement in the shear strength capacity was exhibited by the walls reinforced with ferrocement and polypropylene mortar plaster.

Wang [21] et al used Textile Reinforced Mortars (TRMs) to strengthen historical masonry buildings. Steel, carbon and basalt textiles embedded in cement mortar matrices were used as shear reinforcement of masonry panels. Cement-based or lime-based mortar matrices were used. Experimental investigations carried out helped to conclude that steel-TRM showed higher strength before tensile failure and better bonding between the textile and matrix.

Ambra [24] et al dealt with the analysis of unreinforced and FRCM reinforced masonry walls subjected to out-of-plane loading. The out of plane behaviour is important in both flat walls and curved structures. Both strengthened and un-strengthened walls were constrained on two consecutive side. It was loaded by a pointwise force orthogonal to the wall mid plane. It was applied at the top free corner which induced a biaxial behaviour. The application of FRCM was found to be effective in improving their structural strength.

2.4 Geotextile

Rawal [7] et. al stated that Geotextile is any permeable textile material used for purposes like filtration, drainage, separation, reinforcement and stabilisation. This serves as an integral part of civil engineering structures of earth or construction materials. In other words, it is a permeable textile used in manmade projects to provide a conjunction with soils or rocks. Both natural and synthetic fibres are used to make geotextile. High strength, high modulus, low elasticity and low breaking extension is offered by natural fibres. For reinforcement applications, the tensile strength of the geotextile becomes an important property which is to be considered. Jute, sisal, Flax, hemp, abaca, ramie and coir are some of the plant fibres used in the manufacturing of geotextile. Natural fibre-based geotextiles are specifically used for temporary functions since they are biodegradable. Low cost, robustness, strength, availability, good drapeability and biodegradability are the major advantages of using natural fibres. Synthetic fibres are also widely used in the manufacture of geotextiles. Polypropylene, polyester, polyamide and polyethylene are the four predominant polymer families used as raw materials for geosynthetics. Polypropylene, due to its low cost, acceptable tensile properties and chemical inertness is most widely used polymer for the production of geotextile. Sensitivity to ultraviolet (UV) radiation, high temperature, poor creep and mineral oil resistance are the disadvantages of Polypropylene. Therefore, the environmental conditions must be investigated before the installation of polypropylene-based geotextiles. Polyester that is polyethylene terephthalate (PET) is another important synthetic polymer used in the manufacture of geotextiles. This is used where the geotextile is subjected to high stresses and elevated temperatures since they exhibit superior creep resistance and tenacity values.

Correia [11] et al stated that deformation is the key issue which is to be addressed when the development of the soil-reinforcement is dealt with and thus it is vital for design too. The brick-faced retaining walls reinforced with geotextile has reinforcing elements that are very extensible compared with other materials. Therefore, it is important to introduce the concept of serviceability. They were able to present a simple method to predict the face deformations of brick reinforced walls reinforced with geotextiles. The investigations showed no rupture of reinforcing elements and internal sliding of reinforcement was stated as the reason for excessive deformation which led to the failure of walls.

Nanda [12] et al stated that geosynthetics can be used for seismic stability of earth slopes, retaining walls, embankments and landfills. Thus, expanding the civil engineering applications. The seismic energy can be absorbed by the geosynthetics placed under the foundation. Here, a sliding interface was provided between the soil and the foundation base in order to permit relative motion between the super structure and substructure. This helped in the study of geosynthetic as a seismic protection system.

Behera [25] studied the use of two varieties of geosynthetics for strengthening the brick masonry panels against in-plane shear and its performance was evaluated. Geotextile surface wrapping using epoxy resins and geogrid reinforcement at the bed joints embedded in brick mortar were used to strengthen the walls. Diagonal compression test was carried out to find out the in-plane shear strength. Here the geotextile surface wrapping using epoxy resins was done in a parallel pattern whereas geogrid reinforcement was provided as shown in Fig (1).

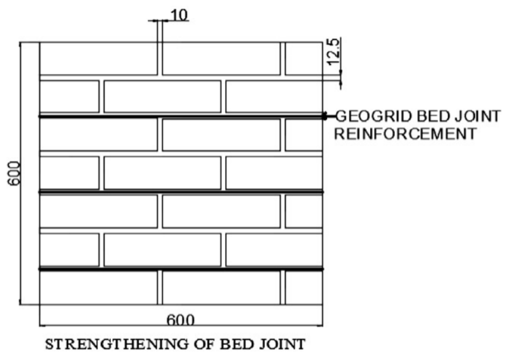

Fig -1: Geogrid strengthened wall

For both surface wrapping and bed joint reinforcement shear strength under diagonal loading and in-plane strength increased. Geogrid reinforcement (43%) showed more increase in in-plane shear strength than the surface reinforcement (29%) when it is compared with the un-strengthened walls. The above techniques can be considered as a low-cost technique for strength enhancement in earthquake prone areas.

2.4.1 In-plane strength strengthened using geotextile

Khan [17] et al strengthened the in-plane strength of masonry panels using non-woven geotextile. They studied it experimentally and numerically. The strengthening was done on one side and different geometric patterns that is parallel, diagonal and cross were used. The wall panels were subjected to diagonal compression test. The study concluded that there was an increase in load carrying capacity, shear strength, in-plane strength and stiffness in the walls strengthened using geosynthetic. The cross pattern showed remarkably better performance compared to the other patterns. Strengthened walls showed a less brittle behaviour compared to the un-strengthened panels. Therefore, geosynthetic can be effectively used for strengthening masonry buildings in seismic prone areas.

2.4.2 Out-of-plane bending strengthened using geotextile

Khan [22] used geotextile in different patterns to strengthen the out-of-plane flexural strength of masonry wallettes. The wallettes were strengthened on both sides. Cross, parallel and diagonal patterns were used. Fig (2) shows the different patterns of geotextiles used. Both un-strengthened and strengthened wallettes were subjected to four point bending test.

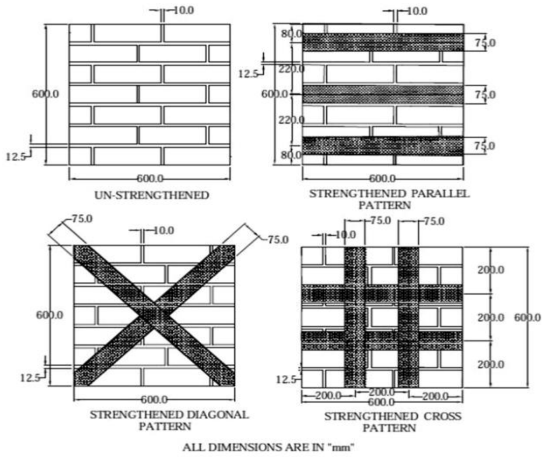

Fig -2: Patterns and specification of masonry wallettes

The study concluded that there was an increase in load carrying capacity, displacement, ductility, stiffness, flexural strength and energy dissipation capacity in walls strengthened using geosynthetic. Also, the cross pattern showed remarkably better performance compared to the other patterns. Due to its low cost, ready availability and high strength geosynthetic can be successfully used to strengthen masonry buildings against out-of-plane bending.

Khan [26] et al with the help of 3D finite element simulation in ANSYS conducted a numerical study using geosynthetic as strengthening material for brick masonry wall. The in-plane and out of plane performance of the masonry wall strengthened using geosynthetic was estimated. Therefore, from the results it was found that geotextile can increase both the in-plane and out of plane strength of masonry wall. Results obtained from the in-plane test showed a 72% increase in diagonal shear strength compared to the un-strengthened wall while the out of plane test resulted in an increase in flexural strength capacity to 129.23% when compared to an un-strengthened wall. A heritage masonry building too was retrofitted using geotextile and the strengthened model helped in controlling the stresses and deformation forces of earthquake. Thus, this retrofitting can be used to preserve heritage building.

3 CONCLUSION

It is said that the largest part of the existing building stock is made of one of the oldest methods of construction system that is masonry. Since a lot of historic structures too are made of masonry, it is really important to address the remediation, retrofit and seismic upgrading of such structures. It is also important to consider techniques that are less invasive in order to preserve the architectural and heritage values of the historic structures. This paper discusses different methods or techniques used to strengthen masonry structures. Fibre Reinforced Polymer (FRP), Engineered Cementitious Composite (ECC) and Geotextile were used to strengthen masonry walls in a less invasive manner. The application of different types of FRPs like carbon, glass and basalt fibre reinforced polymers were discussed and their contribution to the enhancement of the strength of the masonry structures were also dealt with. Geotextiles were used in the in-plane and out-of-plane strengthening of masonry walls. The above techniques were successful in enhancing the structural strength and seismic upgrading of the masonry structures.

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