Retrofitting and strengthening of masonry structures with advanced composite fiber wrap system

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Abstract:
A large number of masonry structures exist all over the world. These structures need strengthening due to many reasons such as lack of strength, stiffness, ductility and durability. Generally the old structures are not designed for earthquake loads, and hence many such important structures have suffered during the past earthquakes all over the world. Along with loss of human lives and socio-economic problems, damages and collapse of historically important structures take place due to earthquake. Apart from earthquake requirements, buildings need strengthening due to modifications done in existing structure or change in use of the building. Deterioration of material strength on aging is another significant reason for need of strengthening or retrofitting. There are various methods for strengthening of Masonry Structures among which the use of FRP has received increased attention due to the advantages of FRP, mainly lower specific weight, resistance to corrosion, ease of application and cost effectiveness. One of the important features of FRP that makes it suitable for Masonry is its adaptability to curved and rough surfaces. The use of FRP material for strengthening of reinforced concrete material is well established. As compared to concrete less work has been done on masonry. A large number of masonry structures including historic monuments are required to be strengthened or retrofit in India and FRP can be a better option; however research work is required in this context. Effectiveness of FRP wrapping to masonry structural elements to enhance the performance, is required to be assessed experimentally. The present work focuses on the experimental investigations of FRP wrapped masonry load bearing members. The experimental program consists of testing on FRP strengthened masonry columns and FRP retrofitted masonry walls. The enhancement in load carrying capacity of masonry columns due to confinement by FRP strips has been found. An ‘Advanced Composite Fiber Wrap System’ with combination of vertical and horizontal FRP strips has been proposed. Behaviour of un-strengthened and FRP strengthened masonry columns subjected to uniaxial compression has been studied. The contribution of FRP anchors in enhancement of load carrying capacity has been quantified. In the next phase six masonry walls have been tested.

Finite element analysis for un-strengthened masonry elements and FRP retrofitted walls has been done using the ANSYS software. The experimental and analytical results are compared. CNR-DT-200 42 provides guidelines for the strengthening of masonry structures using FRP. As no Indian Standard code is available till now for the application of FRP on masonry structures, the applicability of CNR-DT-200, for the experimental work carried out in present study was checked by evaluating the results as per provisions of CNR-DT-200 and comparing with experimental results. A mathematical model has been proposed using the experimental results for predication of compressive strength of brick masonry column confined with FRP for Indian conditions. Further the estimation of load carrying capacity of FRP confined masonry columns with different strip widths has been done by using proposed mathematical model. The same model has been used to compare performance of ‘Advanced Composite Fiber Wrap System’ and ‘Continuous Wrapping System’. This study reflects, FRP wrapping is an effective strengthening and retrofitting technique for the load bearing members of brick masonry structures. ‘Advanced Composite Fiber Wrap System’ is found to be is more effective and economical as compared to Continuous wrapping system. Substantial increase in load carrying capacity of masonry columns was obtained by proposed discontinuous fiber wrap system. FRP anchors were effective in delaying the failure of specimens as well as enhanced the load carrying capacity of columns by 16-18% in case of both the composite materials; GFRP and CFRP. In case of masonry walls, different failure modes were observed for different FRP patterns. In case of Masonry Walls, lateral load carrying capacity was increased significantly due to discontinuous wrapping technique using composite materials. The results of Finite Element Analysis using ANSYS for masonry columns and masonry walls are in line with experimental results.
Keywords

 Finite Element Analysis, Retrofitting, masonry structures, composite fiber wrap system, FRP.

1. Introduction

Masonry structures are one of the oldest forms of construction though not obsolete and are still in practice all over the world. The Egyptian Pyramids, the Colosseum in Rome, the Taj Mahal in India and the Great Wall of China are some of world’s monuments that have been built in masonry. The smallest residential buildings, built by Romans in the first four centuries A.D., consisted of masonry walls, that supported a timber roof and roof covered with fired clay tiles. A multi-storeyed version of the small domestic dwelling was also built by the Romans during first century A. D. 1 ‘Mondanock Tower’ is an example of multistoried masonry building which is 16 storey high constructed in 1893 in Chicago. Through civilization, engineers and architects adopted masonry construction for residential buildings, churches, temples, forts and bridges.

The masonry consists of two different materials; masonry units and mortar joint. The common masonry units are stone, clay bricks, calcium silicate bricks and concrete blocks. Stones are the first masonry units used for construction. Stone structures are most durable and stand for centuries. Clay bricks are the most common masonry units and have been in use for at least last 10,000 years. By 3000 BC the bricks were being made by hand in a mould with cattle dung or straw added to increase the strength. The mechanical production of bricks started in 1858 with introduction of the Hoffman kiln 1. Calcium silicate bricks were made by moulding lime mortar in brick shape and air drying. Concrete units were introduced in mid 1800s. Now hollow concrete blocks are used for reinforced masonry construction. During ancient period mortars were made up of mud, clay, bitumen or clay-straw mix. Egyptians used calcined gypsum a few thousand years ago while the Greeks and Romans added lime, water and crushed stone or bricks to make mortar 1. In eighteenth century much research work was carried out on cement all over the world and their after the use of cement mortar started. Cement-lime mortars are also used to combine advantages of cement and lime.

After more than 6000 years, masonry is still used today for construction due to its advantages such as aesthetics, heat and sound insulation, fire resistance and economic considerations. Although masonry is very strong in resisting compression but very weak in resisting tension it is used in case of load bearing as well as framed structures and a large inventory of masonry structures exists all over the world. In masonry structures the load bearing elements are columns or piers, walls and arches.

‘Strengthening’ means the act of increasing strength of something and ‘Retrofitting’ means the process of modifying something after it has been manufactured. Hence both terms are most of the times used as synonymous in context of structures. Also the term ‘Retrofitting’ is usually referred for upgrading the seismic resistance of an existing structure so that it becomes safe under the recurrence of likely future earthquakes 2, hence used as ‘Seismic Retrofitting’.

A large number of masonry structures exist all over the world. It has been reported by Arya 3 that as per data of Indian Census 2001, the masonry houses constitute 84.7% of the total housing units whereas concrete and other units constructed using materials such as wood, metal/asbestos sheets and bio-mass material put together constitute 15.3%. The data of past earthquakes have shown that masonry structures are most vulnerable to earthquake forces. During the last century, human casualties during earthquakes were mainly caused by structural damage, being the failure of unreinforced masonry structures responsible of more than 60% of them 4. More than 15 lakh people have died due to collapse of buildings during earthquakes in last 100 years, all over the world. In 1976, earthquake in China caused loss of approximately 2.4 lakh lives mainly due to collapse of brick masonry structures 5.

More than 2000 deaths during Killari (Maharashtra) earthquake in 1993 and more than 8000 deaths in Bhuj (Gujrat) earthquake (2001) is attributed to collapse of masonry structures 6. Along with loss of human lives and socio-economic problems, damages and collapse of historically important structures takes place due to earthquakes. Preservation of Monuments is important as these are identification of culture, region, country and having artistic value. Seismic retrofitting of Historic Monuments is a specialized task because many conventional techniques cannot be applied, as, prime objective of this type of retrofitting is to preserve aesthetics of these structures. Archaeological Survey of India has reported that there are at present more than 3650 ancient monuments and archaeological sites in nation. Generally the old structures are not designed for earthquake loads and hence need retrofitting. Even in some cases due to subsequent updating of code and design practice or subsequent upgrading of seismic zone, retrofitting of structures is essential for survival of structures in next earthquake. Prior to the introduction of modern seismic codes in the late 1960s for developed countries (USA, Japan etc) and late 1970s for many other parts of the world including India, many structures...
unreinforced masonry structures were designed. Hence these structures were definitely not designed to resist seismic forces and are not safe during earthquake.

The existing masonry structures need strengthening or retrofitting due to many reasons such as lack of strength, stiffness, ductility and durability. Apart from earthquake requirements, buildings need strengthening due to modifications done in existing structure or change in use of the building. Deterioration of material strength on aging is another significant reason for need of strengthening or retrofitting. The building evaluation showed that 96% of the unreinforced masonry (URM) buildings in California needed to be retrofitted. Also in a study, it has been observed that retrofitting an existing building makes it 30% more efficient, and makes a better case environmentally than building a new structure with the same efficiencies. Thereby, the development of effective and affordable retrofitting techniques for URM elements is needed.

2. Experimental setup and Results

Experimental investigations have been carried out on Fiber Reinforced Polymers (FRP) strengthened masonry columns and FRP retrofitted masonry walls. The experimental program has been presented in two parts: first part on masonry columns and second part on masonry walls. The enhancement in load carrying capacity of masonry columns due to confinement by FRP strips has been found out. An ‘Advanced Composite Fiber Wrap System’ with combination of vertical and horizontal FRP strips has been proposed.

Behaviour of unstrengthened and FRP strengthened ceramic columns subjected to uniaxial compression has been studied. The contribution of FRP anchors in enhancement of load carrying capacity has been quantified. In the next phase masonry walls has been tested. The behaviour of un-retrofitted and FRP retrofitted masonry walls subjected to in-plane lateral load along with pre-compression has been studied experimentally. Evaluation of performance of various FRP strip patterns for masonry walls has been carried out.

Masonry column specimen:

Specimen sizes were finalized considering the provisions given in codes and sizes of bricks and mortar joints. As per IS 1905:1987, a masonry column has been defined as a vertical member, the width of which does not exceed 4 times the thickness. The same definition is also given by British Standard CP III: Part2: 1970. National Building Code of Canada and Recommended Practice for Engineered Brick Masonry 1969 defines the columns as a member whose width does not exceed 3 times the thickness. Considering the mortar joint thickness as 10 mm and size of bricks 210 x 100 x 70 mm, total 15 brick masonry solid column specimens of 210 mm x 210 mm in cross section and 480 mm of height were cast.

Figure 1.1: Research Methodology

Figure 2.1: Masonry Column Specimens

Figure 2.2: Columns in Existing Masonry Buildings

Three column specimens were tested without FRP wrapping to serve as control specimens under
uniaxial compression load till failure. Twelve column specimens were strengthened using FRP and tested for the enhancement in load carrying capacity. These specimens were first subjected to uniaxial compression load of about 80% to 90% of ultimate failure load, obtained in case of control specimens; to create experimental conditions very close to reality.

**Proposed FRP Strengthening Scheme: ‘Advanced Composite Fiber Wrap System’**

But in case of brick masonry structures, the continuous wrapping changes the nature of original material totally. Even it has been mentioned in CNR-DT200 42 that, FRP reinforcement that completely encases the strengthened member may prevent migration of moisture, such FRP systems shall not be applied continuously to ensure the migration of moisture. FEMA 547, 2006 19 points out the disadvantage of continuous FRP wrapping, it states that Fiber composites are impermeable, if continuous overlays are used, moisture transmission through the masonry wall will be stopped at the fiber. Eventually, the concern would be the moisture would build up and begin to delaminate the fiber bond and lead to general building concerns with excessive moisture. Also the discontinuous wrapping will be economical as compared to continuous wrapping. Hence discontinuous wrapping technique by using FRP strips has been adopted for all specimens.

A new discontinuous FRP wrap system is proposed for all columns. The system consists of combination of horizontal and vertical strips. Horizontal strips are necessary for the confinement of column whereas vertical strips should be provided to avoid the failure of masonry between two horizontal strips. Literature review conforms that such combination of horizontal and vertical FRP strips was not used in previous research. The wrapping technique with horizontal and vertical FRP strips, proposed in this work is named as ‘Advanced Composite Fiber Wrap System’. This system is explained in detail below.

The vertical strips are proposed at two locations; at corners and at the location of vertical splitting cracks which are at the middle portion on all faces. Hence for each column, four vertical strips (one at each corner) of width 50 mm, four vertical strips (middle of each face) of width 30 mm and three horizontal strips of width 80 mm were fixed.

**Types of FRP Material**

The strengthening of masonry columns with ‘Advanced Composite Fiber Wrap System’ has been done by using following two different FRP materials.

1. Glass FRP (GFRP)

2. Carbon FRP (CFRP)

Both FRP materials are available in market and comparison of experimental results for these two materials will be useful in selection of appropriate material while application in field.

**Strengthening Procedure**

All the columns were first loaded under uniaxial compressive load up to around 80 to 90% of ultimate capacity of control column. Vertical splitting cracks were observed on all four faces.

Figure 4.1 shows all stages in application of FRP on masonry columns. These cracks were first filled with ‘Lime Surkhi’ (Figure 4.1B). Lime Surkhi was prepared by mixing Lime and brick powder properly with water to form a paste. Instead of cement mortar or grout, Lime Surkhi was used to fill the cracks to avoid contribution of filling material in increase of load carrying capacity of the specimen. The crack filled specimens were kept for 24 hours, after which the specimens were made smooth by using the grinder machine (Figure 4.1C). The corners of the column were rounded and made smooth. This is very essential so the FRP material gets properly bonded to the surface.

**FRP application was done as follows:**

- Application of Primer: Primer was prepared by thoroughly mixing Resin Primer Base and Hardener in the proportion of 1:0.5 (kg). This solution is applied all over the column surface as base coat (Figure 4.1D). The specimens were kept for 24 hours.

- Marking for the locations of FRP strips was done on the columns. Mixture of Base, Hardener and aggregate powder was prepared. The proportion for this mix was 1:0.5:3.5. This mixture is termed as ‘Putty’. The putty was applied at locations of FRP strips, (Figure 4.1E) which were marked previously.

- On the putty, epoxy was applied (Figure 4.1F). Epoxy solution was prepared by adding Matrix base and hardener in the proportion of 1: 0.35.

- The vertical strips at corners and middle portion were carefully placed at the locations and then fixed by pressing with roller (Figure 4.1G). After fixing all vertical strips, horizontal strips were applied at marked locations.

- For the specimens with anchors, holes of 12 mm diameter and around 100 mm length were drilled at the location of anchors. For each specimen, three anchors were used. The anchors were inserted at the overlap of each horizontal strip in staggered manner.
For GFRP wrapped specimens, GFRP anchors were used and for CFRP wrapped specimens, CFRP anchors were used.

The FRP wrapped specimens were kept for four days and testing under uniaxial compressive load was carried out.
The experimental work on masonry walls showed that the FRP retrofitting enhanced the overall performance of wall specimens. The FRP strip patterns were decided after studying the behaviour and failure pattern of control wall. Three different retrofitting patterns were adopted with two FRP materials (GFRP and CFRP) and five retrofitted wall specimens were tested for in-plane lateral load.

The minimum increase was obtained to be 2.7 times or 177% of the load taken by un-retrofitted wall; which was in case of ‘Only Vertical Strips’ of GFRP. The maximum load was carried by the wall retrofitted with CFRP ‘Vertical and Horizontal Strips’ pattern, which was 5.85 times or 485% of the load taken by un-retrofitted wall. The comparison of GFRP and CFRP materials for the same pattern of retrofitting showed that CFRP wrapped wall exhibited little higher performance in terms of strength as compared to GFRP wrapped walls.

The strains in masonry and FRP were more in case of GFRP as compared to CFRP specimens.

3. Finite Element Analysis

The experimental work is further supported with analytical work, which has been done in the following three parts:

- Finite Element Analysis (FEA) using ANSYS.
- Mathematical Modelling for Masonry Columns Confined with FRP.

The objective behind carrying out FEA for experimental work is to observe whether FEA can correlate behaviour of un-strengthened and FRP strengthened masonry members. ANSYS is being used for steel members successfully. The masonry being heterogeneous material and masonry members are cast in alternate layers of bricks and mortars, it becomes more complex to analyze. Hence initially, validation of FEA by using ANSYS has been carried out for two different research works on brick masonry columns. The FEA has been carried out in following phases

1. Validation of FEA using ANSYS.
2. FEA for Un-strengthened Masonry Members: Column and Wall.
3. FEA for FRP Retrofitted Walls.
4. Conclusion

This thesis has explored various topics like, characterization of brick masonry, behaviour of masonry columns, walls and application of FRP for strengthening of masonry elements; columns and walls. To accomplish goal of the study, experimentation was conducted on FRP strengthened masonry columns and FRP retrofitted masonry walls, finite analysis was carried out and finally modified model for Indian conditions has been proposed.

Behaviour of unstrengthened and FRP strengthened brick masonry columns subjected to uniaxial compressive load was studied experimentally. New discontinuous wrapping technique consisting of combination of horizontal and vertical FRP strips has been proposed and tested for masonry columns; this technique is termed as ‘Advanced Composite Fiber Wrap System’. The effectiveness of FRP anchors was determined experimentally.

The behaviour of un-retrofitted and FRP retrofitted masonry walls subjected to in-plane lateral load along with pre-compression was studied experimentally. Three different wrapping techniques were adopted for masonry walls. GFRP and CFRP composite materials were used for columns as well as walls.

Finite Element Analysis of masonry columns and walls was performed using ANSYS software. Validation of FEA using ANSYS was carried out first considering two different experimental research works from literature. Mathematical model has been calibrated for predication of compressive strength of FRP confined brick masonry columns for Indian conditions. Validation of proposed model has been done by applying the model to experimental research works from literature. The proposed model was further used for predicting the enhancement in load carrying capacity of masonry columns strengthened with Advanced Composite Fiber Wrap System for different values of width of horizontal CFRP strips.

5. Future Scope

In order to establish FRP as strengthening or retrofitting material for masonry structures in India, more experimental research work is required to be carried out.

More experimental work in this context will also be useful to form IS codes or guidelines for application of FRP for strengthening or retrofitting material for masonry structures.

In the present study, mathematical model for FRP strengthened masonry columns has been developed for Indian conditions. Development of mathematical model for FRP retrofitted masonry walls subjected to in-plane lateral load considering the available experimental results can be done on similar lines. A complete testing setup, including testing frame can be developed which will be instrumental in increasing experimental studies on FRP strengthened masonry elements.
6. References


