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A Review of Retrofitting Techniques of Masonry Structures

Parnika Yadav[1], Salman Khursheed[2], Sushil K. Solanki[3] and Virendra Kumar Paul[4]

[1]Research Scholar, Department of Building Engineering and Management,

[2]Assistant Professor, Department of Building Engineering and Management,

[3]Associate Professor, Department of Building Engineering and Management,

[4]Professor, Head of the Department of Building Engineering and Management,

School of Planning and Architecture, New Delhi, India.

Email: parnikasingh.yadav@gmail.com, salman.khursheed@spa.ac.in, sushilsolanki@spa.ac.in & vk.paul@spa.ac.in

ABSTRACT: The masonry structures in India are the non-engineered buildings and are among the most vulnerable structures for damage against seismic loads but these structures are not even able to sustain against gravity loads majorly due to the effects of structural distress caused due to ageing. This paper gives us an overall view of the response of masonry structures response towards seismic loading and their failure modes, factors affecting decision to retrofit. Various local and global retrofitting techniques are identified through an exhaustive literature study and are presented in a form of a matrix for the ease of selection.

KEYWORDS: Masonry structures, Structural distress, Seismic response, Retrofitting techniques.

INTRODUCTION

Circular Load bearing brick wall structures are essentially box-type structures that withstand earthquake loading through the integral action of the walls and their cross walls. During an earthquake occurrence, the forces acting on brick walls in a structure are applied in both the in-plane and out-of-plane directions of the brick walls. To resist the earthquake forces, shear and flexural strength of brick masonry walls play an important role in load bearing masonry structures. Pathologies that are common in old load-bearing buildings are primarily related to their age. In the case of masonry, the most common pathologies are structural in nature and can manifest as desegregation, crushing, fracture, and cracking (Meireles & Bento, 2013) (Hemeda, 2019). Mostly existing load bearing structures that were built in accordance with previous design codes and standards are frequently discovered to be vulnerable to earthquake damage due to inadequate detailing, underestimated earthquake loads, corrosion of material with time, and other reasons. While solidification an old building, structural designer must first understand about the structural functioning of the building, as well as assess its performance against different loading conditions combinations as per the latest code requirement (Sarkar, 2014).

(Bedi, 2013) defines retrofit as a general term that encompasses a wide variety of structural treatments such as preservation, rehabilitation, restoration, and reconstruction. The major difficulty faced in the retrofit process is the choice of the appropriate treatment strategy and its procedure needs to be addressed in detail. Many existing structures do not meet the seismic strength criteria of current earthquake standards, according to (IS:13935, 2009) due to original structural weaknesses, material degradation or adjustments made during use over time.

Few authors reported that Indian construction industry is facing multitude challenges including construction quality, sustainability and quality benchmarking, (Anil Sawhney, 2014) and have focused on the use of benchmarking for selection of suitable techniques. (Seth, 2017) With the application of proper seismic retrofitting techniques, their earthquake resistance can be increased to the level required by contemporary requirements. However, in most cases, the cost of retrofitting vs the cost of reconstruction determines whether or not to retrofit. (-273, 1997) As a thumb rule, "if the cost of repair and seismic strengthening is less than about 30 percent of the reconstruction cost, retrofitting is adopted". The code mentions about the damageability assessment of existing masonry buildings through some retrofitting techniques corresponding to each damageability grade (C.P.W.D, 2007). The researchers have also suggested on the use of building performance as a criterion for selection of retrofit techniques and material. (Paul S. G., 2018) Retrofitting removes the seismic insufficiencies, improves the response of existing unreinforced masonry buildings to both gravity and seismic loads and further enhances the "box type" behaviour of the structure by increasing the flexural strength of the structural components by improvement in configuration, load path, redundancy, connections, ductility and capacity etc. falls under it. Retrofitting of structures can be done so as to enable it to sustain against maximum probable earthquake without collapse. For deciding retrofitting system for a particular building, seismic evaluation of building is essential. So, strengthening must be done to avoid future loss of life and property (Sabu, 2012).

Research Objectives

- To develop an understanding of seismic response of masonry buildings.
- To identify techniques of retrofitting suitable for the existing masonry structure.
- To develop a framework for identification of suitable retrofitting techniques.

Methodology

The present research work was carried out using the following methodologies.

Stage 1: Search for relevant literature: This stage involved a comprehensive search for available literature like published research papers, conference papers, books, codes, and standards, etc. Related to load bearing masonry structures for developing an understanding of their behavior. And to identify the research gap and need of the study.

Stage 2: Screening of identified works: This stage was focused on screening identified works by focusing on the title, abstract, and keywords related to seismic performance, structural distress, non-destructive testing, masonry structures, and retrofitting techniques. Further full-text analysis of the works was carried out to find potential literature, followed by an exhaustive review of references listed in the sourced out works.

Stage 3: Retrofitting techniques identification: The current stage involved decision analysis for the identification of all types of retrofitting techniques and the extent of retrofitting needed.

Stage 4: Framework development: This stage deals with the development of a framework for selection of suitable retrofit technique for masonry structures.

Literature Review

Seismic Response of Masonry Buildings

The masonry walls around the exterior, and sometimes similar walls in the interior, bear up under the weight that is delivered to them by floor or roof beams, that's why they are called the load bearing walls. Masonry being an orthotropic material possessing very high strength in compression but almost negligible strength in tension. It is also heterogeneous as it is composed of both masonry units (bricks or concrete) and mortar. As per (Ingham, 2011), the mechanical properties of the components vary greatly depending on the type of construction, location, and time of erection. The masonry tends to have a short elastic period before cracking and subsequent non-linear behaviour. (Bouchard, 2007) The structural configuration of masonry buildings also tends to have a major role in the response of buildings towards seismic loading like the no of storeys, whether it's a regular structure or an irregular structure (Bélec, 2016). The failure modes of masonry elements are difficult to predict as they are affected by a number of factors like, the direction of loading acting stresses, number of openings, size of the openings, and the compressive and flexural strength of the masonry mortar (Abdolhossein Fallahi, 2012).

Failure Modes in case of Masonry structures

After going through the available literature, the researchers like (Bouchard, 2007) (Meireles & Bento, 2013) (Chuanlin Wang, 2018), others have identified three major failure modes in cases of masonry structures. Few of the common mechanisms of failure identified through the literature are- Out of plane, in plane, connection, diaphragm, pounding, failure due to opening of walls, non-structural component failure, inadequate shear capacity, absence of collector elements in slab, inadequate detailing of connections in the frame, presence of soft storey, lack of proper confinement of beam- column joints etc. These all identified failure mechanisms can be broadly classified into these three failure mechanisms based on the available literature-

Plane failures

In-plane failure generally occurs when the load acts parallel to the wall which leads to generation of in-plane shear stresses. So, the major factor responsible for failure are the size and location of the openings, masonry mortar strength (Apaudel, 2022). If the direction of acting forces is perpendicular to the plane of the wall, then it leads to generation of out-plane stresses. Masonry buildings with light roofs, such as tiled roofs, are more susceptible to out-of-plane vibrations because the top edge can deform significantly due to a lack of lateral restraint.

Deformation controlled failures

The deformation - controlled failures possess less risk of sudden collapse. These failures generally have a more ductile nature when compared to force- controlled failure (Bouchard, A Performance-Based Approach to Retrofitting UnreinforcedMasonry Structures for Seismic Loads, 2007).

Force controlled failures

Masonry failures under vertical loads are always force-controlled because the blocks crush quickly. Toe crushing and diagonal tension are two common examples of force-controlled failure for in-plane lateral loads on URM shear walls (Bouchard, A performance-based approach to retrofitting unreinforced masonry structures for seismic loads 2007).

Seismic Retrofit Strategies

(Bedi, 2013) defines retrofitting process as a broad umbrella term comprising of treatments such as preservation, rehabilitation, restoration, and reconstruction. The major challenge faced while the retrofit process is the selection of an appropriate treatment strategy, and every project has some uniqueness so it must be determined individually for each project considering the suitability of the treatment strategy.

According to various researchers like (Chuang, 2005) (Y. Korany, 2001), (Chuanlin Wang, 2018), (A. Bradshaw 2011), retrofitting techniques for existing URM buildings have been studied in detail. The type and quality of masonry materials, existing structures strength, building occupancy, type of structure, use of the structure, structural layout etc., are important considerations when selecting a retrofit method. The method chosen must take into consideration the building aesthetics, function, and the structural strength requirements for strength, ductility, and stiffness. The following are the traditional retrofitting techniques found in various literature:

- Grout and epoxy injection
- Anchoring and tying
- Overlays
- Repointing
- Bracing
- Internal reinforcement
- External reinforcement
- Post tensioning
- Seismic damper
- Base isolation

Extent of retrofit

If seismic strength of an existing building is only 33% of that required for a new building as per the current standard design code the risk involved is about 20 times as high as that of a new building. If the strength is two-thirds of what is required by the current standard, the risk is reduced to three times what it is now. As a result, it is strongly advised that retrofitting be carried out if the existing building's strength falls below 70% of the capacity required by the current design standard. In the interest of public safety, when the risk is too high (more than ten times the standard risk), building authorities should prohibit human occupancy of the building. If a building is relatively old and has lived more than half of its design life, it should be retrofitted to withstand at least 70% of total design seismic loads, according to current standards. (C.P.W.D, 2007) as shown in Figure 1.

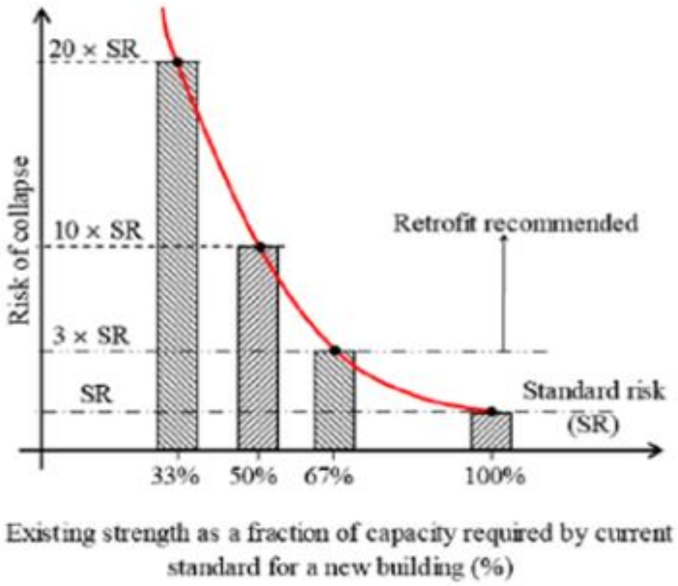

Figure 1: Extent of retrofit

General Issues to be Considered While Selecting Retrofit Technique

The international and national codes provide the technical criteria for retrofitting solution assessment solution but these also include few noon- technical issues also. As per (547, 2006), (A. Bradshaw, 2011), (Charleson, 2001), (Caterino, 2009), (Khursheed, 2017), (Seshadhri, 2017), (E Kapoor, 2021) six basic non-technical issues are of concern to building owners or users which help the stakeholders in decision to making to prioritize the decision making:

1. Construction cost: Overall construction cost is a very important aspect to decide whether to retrofit or not along with the client's expectation fulfilment.
2. Disruption to the building users during construction: In case of a partially or completely occupied building, the parameter of disruption of building occupants becomes a major challenge.
3. Aesthetics: In historic buildings, conservation of historic architecture also usually has a control on type of retrofit strategy.
4. Post-disaster importance of building: The post-disaster importance of a building refers to whether the building has any special usage after a disaster. For example, hospitals, airports, fire station etc.
5. Availability of workmanship/materials: Depending on the location of the project the availability of the required skillset of manpower as well as the material and equipment availability might also have an impact on the choice of retrofit.
6. Sustainability: For the purpose of retrofitting, sustainability concept includes: transportation of materials, amount of material and machinery required, and recycled content of materials.

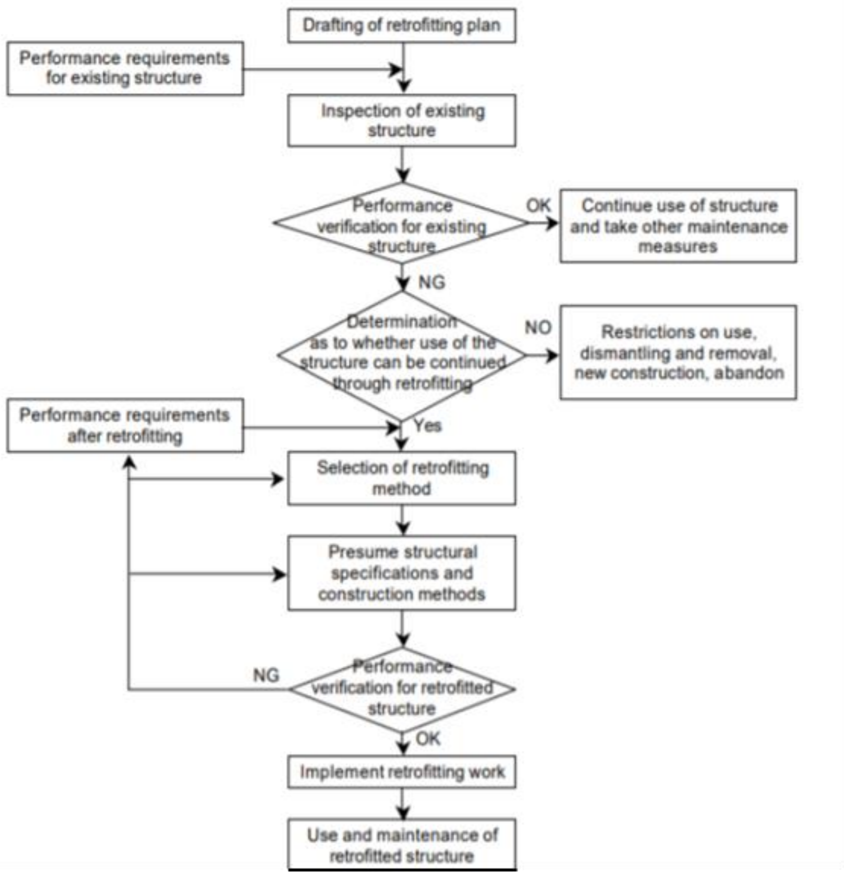

Figure 2: Retrofit framework plan

Table 1: Comparison matrix for effectiveness of retrofitting methods based on effectiveness and economic cost

<table>
<tr><th colspan="2">Methods</th><th>Effectiveness</th><th colspan="3">Economical</th></tr>
<tr><td rowspan="2">To decrease the seismic forces</td><td>Base isolation</td><td>Reduction of acting seismic forces by 5 to 6 times.</td><td colspan="3">It is one of the most expensive techniques to install. Ranging up to 5 to 6% of the construction cost. It’s advisable for new construction.</td></tr>
<tr><td>Seismic damper</td><td>Reduction of acting seismic forces by energy dissipation through seismic dampers</td><td colspan="3">It is also a very expensive technique and entails use of advanced equipment and techniques.</td></tr>
<tr><td rowspan="7">To enhance the strength of existing buildings</td><td>Surface Treatment</td><td>Shotcrete method enhances the stability of structure in case of out of plane failure</td><td colspan="3">It requires purchase of special equipment like pressurised hoses but it is cheaper as compared to base isolation and seismic damper.</td></tr>
<tr><td>Stitching & grout/epoxy injection</td><td>Repair work of existing cracks is carried out by stitching using steel ties and mortar. Although there is no significant increase in lateral strength, this aids in the restoration of the wall's initial stiffness.</td><td colspan="3" rowspan="2">Trifling costs for grouting technique as such products are readily available in the market and the application process is also very simple.</td></tr>
<tr><td>Mortar Joint treatment</td><td>The original strength and stiffness can be restored by injection grouting and repointing technique.</td></tr>
<tr><td>External reinforcement</td><td>Increases lateral in-plane resistance by 4.5 times.</td><td colspan="3">It is relatively costlier when compared with mortar jointing and epoxy injection techniques.</td></tr>
<tr><td>Re-pointing</td><td>There’s no significant improvement in the structural performance under dynamic loading conditions.</td><td colspan="3">Minimal costs is associated with repointing as main element is just strong mortar or any high strength bonding material.</td></tr>
<tr><td rowspan="2">Mesh reinforcement</td><td rowspan="2">It boosts lateral strength by a factor of 1 to 3. It also improves out-of-plane and in-plane stability by increasing shear and flexural strength while causing minimal structural disturbance.</td><td>Industrial geogrid</td><td>Mesh cost: $2/m^2$</td><td>Application cost: $19/m^2$</td></tr>
<tr><td>Soft polymer mesh</td><td>Mesh cost: $0.5/m^2$</td><td>Application cost: $4/m^2$</td></tr>
<tr><td></td><td>PP reinforcement</td><td>It increases the structural ductility and energy dissipation capacity. Suitable for up to 15 m high structures.
Few preventive measures are needed to be taken for protection of polypropylene from sunrays.</td><td colspan="3">US $ 2 per sq ft of PP band.</td></tr>
<tr><td></td><td>Steel mesh cage</td><td>Steel bar mesh are suitable up to 4 storeys, involving less architectural changes.</td><td colspan="3">The cost of steel reinforcement for a 1000-square-foot house is $400</td></tr>
</table>

To improve the integrity	Columns	Improves the lateral resistance of the structure by adding vertical structural elements	It involves activity of demolition and reconstruction. So, it's costlier to execute.
	Tie bars	Is effectiveness is similar to that of the steel bars in post-tension method.	The cost of this technique is similar to that of post-tensioning.
	Fibre reinforced mortar	By increasing the tensile strength of mortar, FRP improves both in-plane and out-of-plane capacity.	The cost of this technique is less costly as mortar and fibre are the main contributors towards cost.
	Post-tensioning (using rubber tyres)	It improves in-plane strength by a factor of 5-6 and improves both tensile and flexural capacity. It is appropriate for historical buildings with architectural value because it causes minimal disruption to aesthetics.	Combined cost of scrap tyres and connectors is ~ INR 45/ sqm.
	Cable wire system	Cable wire system comprises of wires or strands which are very light weight material possessing high tensile strength and are anti corrosive which enhances the in-plane capacity and ductility of the structure.	It involves high cost.
	Splint and bandage	This technique is suitable for up to 2 storeys and it leads to major architectural changes.	US $ 4-6 per sq ft. (RCC) US $ 3-5 per sq ft. (GI welded wire mesh)
	Shotcrete	Shotcrete increases in-plane strength by a factor of 3.6 while also improving out-of-plane stability by increasing ductility and energy dissipation. High mass, surface treatment required, affects architecture, finishing required, high disturbance	It's a low-cost technique.

The comparison matrix above has been drawn out by in depth literature review of previously carried out research works (A. Bradshaw, 2011), (Subhamoy Bhattacharya, 2014), (Chuang, 2005), (Hima Shrestha, 2012), (547, 2006), (Anil Sawhney, 2014), (Abdolhossein Fallahi, 2012), (Salman Khursheed, 2019), (Paul V. K., 2017).

CONCLUSION

The major conclusion drawn out from the current paper are that structural cracks are one of the major signs for structural distress due to ageing in case of load bearing structures. The overall seismic behavior of an unreinforced masonry building is very complex because of variability in the material properties and non-homogeneous nature of the material. In-plane walls (walls in the direction parallel to earthquake shaking), being the stiffest parts of the building, are considered as the lateral load resisting elements. The retrofitting technique selected should be such that increases the stiffness, ductility of the structure, by reducing the brittle failure behavior of masonry. The proposed retrofit techniques selection matrix can help as a tool is ease of selection of the relevant technique.

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