Synopsis on

Seismic Assessment and Retrofitting of 16th Century Historical Structures of Northern India

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1.0 Introduction

Numerous failures of brick masonry monuments due to earthquakes have been reported in references[1][2][3][4]. Therefore a need arises for developing a cost efficient and easily executable retrofitting strategy compatible with historical clay brick masonry structures cited in references[5][6][7]. Retrofitting means structural strengthening of a building to a Pre-defined performance level, whether or not an earthquake has occurred. The seismic performance of a retrofitted building is aimed higher than that of the original building. Retrofitting of heritage structures is a need of an hour as heritage clay brick structures are vulnerable against seismic forces and the problem has been further aggravated because there are no international codes available for heritage structures.

For this study performance based design is going to be used specifically in an extensive manner and hence required to be explained in brief for the understanding of research community which has been done in subsequent sections.

Why Performance-Based Design?

• Evaluate the probable seismic performance of historical monuments/buildings.
• Design frame buildings for alternative performance capabilities and also to quantify the ability of a specific design to achieve desired performance objectives.

PB methodology in simple words…

Design for the achievement of specified results rather than adherence to prescribed means.

Performance-based Design

The basic concept of performance based seismic design is to provide engineers with the capability to design buildings that have a predictable and reliable performance in earthquakes.
Thus the Performance-based seismic design is a process that permits design of new buildings or upgrade of existing buildings with a realistic understanding of the risk of life, occupancy and economic loss that may occur as a result of future earthquakes.

Performance-based design begins with the selection of design criteria stated in the form of one or more performance objectives. Each performance objective is a statement of the acceptable risk of incurring specific levels of damage, and the consequential losses that occur as a result of this damage, at a specified level of seismic hazard.

Performance Objectives

- Fully Operational,

- Operational,
- Immediate-occupancy,
- Life-safety and
- Collapse-prevention

Definitions

- Operational
  Negligible impact on building
- Immediate Occupancy
  Immediate Occupancy – building is safe to occupy but possibly not useful until cleanup and repair has occurred
- Life Safety
  Building is safe during event but possibly not afterward
- Collapse Prevention
  Building is on verge of collapse, probable total loss

Determination of Performance Point

- Generally, a team of decision makers, including the building owner, design professionals, and building officials, will participate in the selection of performance objectives for a building.
- Once the performance objectives are set, a series of simulations (analyses of building response to loading) are performed to estimate the probable performance of the building under various design scenario events.
- If the simulated performance meets or exceeds the performance objectives, the design is complete otherwise it has to be redesigned.

Advantages of Performance Based Seismic Design

- Systematic methodology for assessing the performance capability of a building.
- Design individual buildings with a higher level of confidence.
- Design individual buildings to achieve higher performance and lower potential losses.
- Design individual buildings that fall outside of code-prescribed limits with regard to configuration, materials, and systems to meet the performance intended by present building codes.
- Assess the potential seismic performance of existing structures and estimate potential losses in the event of a seismic event.
- Performance-based seismic design offers society the potential to be both more efficient and effective in the investment of financial resources to avoid future earthquake losses.

Differences between traditional approach and performance based approach

1. Conventional limit-states design is typically a two-level design approach having concern for the service operational and ultimate-strength limit states for a building, performance based design can be viewed as a multi-level design approach that additionally has explicit concern for the performance of a building at intermediate limit states related to such issues as occupancy and life-safety standards.
2. The deformation or strains are better quantities to assess damage than stresses or forces. Since the deformation are expected to go beyond the elastic values.
3. The performance based analysis gives the analyst more choice of 'performance' of the building as compared to the limit states of collapse and serviceability in a design based on limit state method.
4. Traditional designs are based upon on Elastic behavior of structure whereas Performance based design uses inelastic behavior of structure.

2.0 Literature Review

After review of literature it was found that for this study the research will be focusing on two important parameters via Performance Based Design and Nonlinear Material Model and hence while reviewing the literature these two research domains have only been considered presently for literature review under this study. Reviewed papers in Indian and International seismic research scenario in the research domains have been reviewed and the findings of it are given below;-.

2.1 Indian Scenario

2.1.1 Indian Masonry

Jain et al. (2000), discusses the earthquake technology issues in detail regarding gap widening between state-of-the-practice of earthquake engineering and research in advance countries against India[8].

Pore et al. (2005), authors of this paper were deputed by department of earthquake engineering of IIT Roorkee to observe damages caused to monumental buildings after Kashmir (Muzaffarabad) earthquake of 8th Oct. 2005. It was found that mostly damaged structures were non engineered structures constructed in rural areas, traditional construction such as Dhajji-Diwari performed better and least damaged. Damage in the monumental buildings found to be less as compared to other constructed structures[9].

2.1.2 Indian Brick Masonry

Jai Krishna et al. (1969), research paper includes information about brick masonry properties with different mortars and strengthening of shear walls and brick houses using different reinforcing method[10].

Performed a site specific time history analysis on a Khusro Tomb built in 1622 A.D. by Sultan Nisar Begum. A 3-D finite element model is prepared on ANSYS Workbench. Gravity analysis results show the behavior of Tomb due to its geometry and stress variation is plotted in a form of contour. Time history analysis results shows that the Khusro Tomb's geometrical configuration is adequate to withstand the earthquake due to nearest Allahabad fault[11].

2.1.3 Indian Clay Brick Masonry

Sarangapani et al. (2002) investigates properties characterization of bricks, mortars and masonry. The obtained results reveal low module compared to cement mortar for bricks around Bangalore region. This situation leads to masonry where lateral tension develops in mortar joints while lateral compression develops in brick which further leads to brittle nature of mortar[12].

Kaushik et al. (2007) Compressive stress–strain relationships, analytical expressions to estimate young’s modulus of elasticity for masonry was determined based on the experimental tests conducted on masonry prism specimen constructed with bricks from four different manufacturers using three different grades of mortar. Also propose an analytical model for plotting stress–strain curves for masonry and a simplified analytical model which can be appropriately used in FE analysis programs[13].

Tomar et al. (2017) has done exhaustive testing on Historic Unreinforced Brick Masonry (HUBM) in contemporary lime masonry. The tests revealed the design, yield, ultimate strength and feasible inelastic material properties suitable enough to characterize the cyclic behavior of historical brick masonry in India. Compressive strength has been evaluated as 2.15MPa which is comparable for same mortar and brick combinations evaluated in India and is quite low in comparison to clay brick masonry of western countries.
Elastic modulus, shear modulus and Poisson ratio have been evaluated to be on the lower side as compared to contemporary mortars constituted masonry. Elastic modulus range evaluated from $40f_m$ to $75f_m$ is quite low as compared to $250f_m$–$1000f_m$ suggested nationally and internationally for contemporary brick masonry evaluation. Parameters such as damping, hysteresis behavior, energy dissipation and stiffness degradation characterizing the seismic behavior in elastic and inelastic range suggested the improved performance of brick masonry with increase in compressive strength of lime mortar[14].

Tomar et al. (2017) a massive historical lime mortar brick masonry building: Forest Research Institute Dehradun has been analyzed in an uncracked form. A multifaceted assessment in the form of historical investigation about the building, geometrical reconnaissance survey, foundation soil characterization has been done. Material identification by laboratory testing, structural assessment using finite element method along with non-linear static pushover analysis has been carried out and the results were compared with existing in situ cracked conditions prevailing in the building. Comparisons of the expected seismic demand of uncracked structure with in situ existing damages were close and the vulnerability of such buildings to pervasive damages and a possibility of collapse against seismic loading[15].

Tomar et al. (2018) selected Forest Research Institute building Dehradun which suffered extensive damages during the Uttarkashi earthquake has been considered for seismic vulnerability assessment and achieving a generalized retrofitting strategy for the region which can be extrapolated globally. Structural assessment by non-linear static analysis has been carried out for FRP retrofitted and an un-retrofitted building using FEM. Different types of FRP has been modeled numerically as wrapped around the piers of huge brick masonry structure and analyzed under site specific earthquake loading which reported in an improved performance of strengthened structure[16].

2.2 International Scenario

2.2.1 Clay Brick Masonry

Paret et al. (2008) in this study the strengthening of a 100 years old multi story brick masonry historic monumental synagogue in San Francisco using traditional and innovative approaches is presented. Despite the historical record showing that the building survived the Great 1906 Earthquake with relatively little damage. The solution consisted of a combination of intervention techniques. These interventions include a system of tension ties in the attic that interconnect the four perimeter walls, yet circumvent the domed sanctuary; center-cored reinforcement of the masonry walls; and fiber-wrap of a few critical piers. The tension ties contain super-elastic nitinol wires and were designed to be lightweight, easy to install, and to restrain the walls from falling outward while maintaining the modal separation and inherent flexibility of the system that enabled the structure to survive the 1906 earthquake[17].

Tonks et al. (2007) emphasis that designers should work effectively through a detail of check list for any URM building and the progress of developing a hierarchy of critical detailing for each topology. Preliminary architectural studies indicate that the topologies should be differentiated based on size of building, percentage openings, connections between beam and floor assemblies with walls, brick wall masonry construction quality, date of construction. Based upon the above points of considerations, the structural engineers must focus on brick and mortar strength[18].

Chena et al. (2008), studies macro element capable of simulating the in-plane response of unreinforced masonry (URM) piers and spandrels formulation and validation is presented in this research. For this study, the modeling approach was extended to explicitly address the in-plane failure modes unique to URM. Study shows 67% failure modes that macro element properly simulated and 19.1% of average absolute error for estimated strength. It was reduced to 11.9% after ‘calibration’ of the default diagonal tension strength of masonry. Finally, parametric studies of boundary conditions, vertical stress, aspect ratio, can be done by proposed macro element[19].

Ismail et al. (2009) considered and evaluated an earthquake prone building with inside and outside cavity walls constructed using solid clay burnt bricks and a lime mortar with procedure suggested by New Zealand Society of Earthquake Engineering (NZSEE) and by homogenized finite element (HFE) computer model. As a result of Initial evaluation building was declare earthquake prone in transverse direction further result declared under out-of-plane loading the walls were unstable and further concluded that the structure requires a retrofit and the most suitable seismic retrofit post-tensioning solution (Grade 500E with nominal yield of 500 MPa and tensile strength of 680 MPa @900mm and a minimum edge distance of 220mm threaded steel Post tensioned tendons) was recommended and meets 100% NBS requirement after retrofit application. Due to least architectural impact, corrosion deteriorated veneer ties are replaced by self drilling stainless steel ties[20].

Ufuk et al. (2012) studies the performance assessment of two unreinforced clay brick masonry historical buildings located in Istanbul built in 1869 and 1885, respectively exposed to Ms = 7.0+ Istanbul Earthquake in 1894 is estimated to be 60% within the next 30 years is probably the highest hazard level in entire Europe. Further proposes structural rehabilitation solutions by Cement jacketing of main load bearing walls and application of FRP bands to secondary walls[21].

Mahini et al. (2012), a heritage brick vault with adobe piers at Yazd (Ighbal heritage complex over 75 year ago built with masonry locally available), Iran, built in 1935 is investigated for lateral resistance and structural behavior under lateral loading using nonlinear finite element analysis program (ANSYS). Macro modeling using smeared model for masonry was modeled. FRP retrofit is considered in this study for improving load carrying capacity based upon pushover FE analysis. Comparison of their failure mechanisms and lateral strength is done before and after retrofitting. Finally, Carbon Fiber Reinforced Polymer (CFRP) laminates with two retrofit schemes, one FE strips of 20 cm width was used as retrofitted material at extrados for the vault and the piers which increases resistance capacity by 27% and by increasing width composite by 40 cm in second scheme the total load carrying capacity was about 0.69 KN which is not considerable and thus is uneconomical[22].

2.3 Material Model and Damage Model

Akbarzade et al. (2010) have proposed and evaluated the performance of an interface elasto-plastic constitutive model for the analysis of unreinforced masonry walls by means of micro-finite element modeling. It is concluded that the suggested model is suitable for assessing the behavior of masonry walls under vertical and horizontal loading. The proposed model is suitable for linear and nonlinear analysis of unreinforced masonry walls with no limitation on the consideration of various variables such as geometrical dimension and material properties. Based on micro consideration in the analysis the localized cracking and failure could be predicted accurately. The tensile and compressive behavior of brick and mortar and that of interface element would be easily considered in all state of behavior up to collapse. The proposed model is capable to recognize the failure mode of the URM walls[23].

Maria et al. (2011) has proposed a new constitutive model for the Finite Element Method (FEM) nonlinear analysis of masonry structures and the use of nonlinear static procedure in order to estimate the seismic performance of masonry buildings. In this paper, the new CoDIC model is defined through an appropriate intersection of a modified concrete model domain with plasticity Drucker-Prager domain and by means of the definition of a new compression surface. The conclusion drawn was that the new model is able to better represent the masonry mechanical behavior because it takes into account both the cracking in the tensile region that the material plasticity in the compression[24].

Kamal et al. (2013) has done nonlinear analysis of historic and contemporary vaulted masonry assemblages and adopted modeling and nonlinear solution were done using a commercially available computer program (ANSYS), which renders the approach applicable by a practicing engineer. The conclusions drawn were, (1) the ultimate capacity of wall bearing masonry structures is considerably under-estimated if linear analysis is carried out. Nonlinear analysis gives a much better representation of the structural behavior of masonry elements regarding ultimate capacity and cracking pattern. (2) The limit for masonry tensile strength determined experimentally and numerically was 0.565 MPa, representing a ratio of 0.13 of compressive strength, which is within the range found in text books and reported by researchers[25].

Vindhyashree et al. (2015) conducted computer simulation of the prism tests (experiment) Numerical Simulation of Masonry Prism Test using ANSYS/ABAQUS and reveals that there is reasonable agreement between the experimental and the simulation values of the compressive strength of masonry. The value predicted by ANSYS is closer to the experimental result compared to that predicted by ABAQUS. The crack patterns observed during the masonry prism test (experiment) and predicted by ANSYS resemble each other to a good extent[26].

Miccoli et al. (2016) investigated the non-linear behavior of rammed earth by taking into account both the macro- and micro-modeling approaches. Based on the test results of investigations the macro-modeling approach comes out to be sufficiently accurate to simulate the global shear behavior of the rammed earth wallets tested. The use of the micro- modeling approach is justified where an additional computational effort is required and when specific collapse mechanisms involving failure of the interfaces between layers are expected[27].

Barberoa et al. (2018) proposed a novel methodology to determine the material parameters for Progressive Damage Analysis (PDA) in ANSYS and explain the procedure in detail. It is observed that adjusted material parameters F2t; F6;Gc; can be used to predict damage initiation and evolution in laminated composites using ANSYS and that good comparison with available experimental data can be achieved with certain restrictions[28].

2.4 Performance Based Design

Huang et al. (2008) has done a nonlinear static pushover analysis using the displacement coefficient method, as described in FEMA 356, was used to evaluate the seismic performance of the existing hospital building in California, US. Based on the proposed pushover analysis the results showed that the life-safety target performance of the upgraded building was achieved. In addition, the performance based retrofit scheme was compared to a different seismic retrofit scheme based on a prescriptive code design approach. The comparison showed that the performance based approach lead to a better understanding of the nonlinear behavior of the structure during severe earthquakes. During severe earthquakes, performance based approach provides a more efficient and cost effective strengthening solution for this building[29].

Pujades et al. (2010) has studied the Seismic performance of a block of buildings representative of the typical construction in the Eixample district in Barcelona (Spain). Four non-null damage states are considered: slight, moderate, severe and extensive-to-collapse. The buildings are described by their bilinear capacity spectra, which are defined by their yielding point (Dy, Ay) and by their ultimate capacity (Du, Au). The two most relevant results of this study are;
(1.1) the old unreinforced masonry buildings of Barcelona are extremely vulnerable, in such a way that they may cause catastrophic effects in case of earthquake.
(1.2) for type II soil (intermediate quality soil) and in the Ux direction (parallel to street), the aggregate does not improve significantly the seismic behavior of isolated buildings; rather the aggregate seems to inherit the shortcomings of seismic strength of the individual buildings from which it is compounded.
In any case, the expected damage depends on the geometry of the building as well as on the soil quality. All the buildings perform better on hard rock soils than in other soil types, but as it can be seen, this effect is more relevant in the Uy direction (Transverse to street). In both directions,

Ux and Uy, this effect relative to the soil quality is more notable for the deterministic scenario than for the probabilistic one[30].

Bilgin et al. (2012) investigated capacity evaluation of the residential buildings using damage limit states suggested by Calvi (1999). Pushover analysis data and performance criteria were used to determine inter-storey drift ratios and damage limit states according to Lagomarsino and Penna (2003) of each building in both directions. From this study following conclusions were drawn;

- As per the study the sudden reduction in wall thickness cause deficiencies for the upper part of the building as it is observed in this study. Excessive inter-storey drift and inadequate shear strength may result in moderate to severe damage to these brittle structures. As a conclusion, wall thickness should be reduced in a gradual manner for new buildings.
- This study shows that the number of openings decreases energy dissipation capacity by around 50% and therefore increases the sustained damage for this type of buildings. This might cause a deficiency in a probable future earthquake and preventive measures should be taken urgently.
- Shear failure of masonry piers seems the most frequent failure mechanism of URM buildings in the past earthquakes and the pushover analyses results support this fact. Non-ductile behavior of weak piers could be improved by means of adequately distributed bed joint reinforcements[31].

Khan et al. (2012) has discussed earthquake impact assessment of the city of abbottabad. Based upon the measured data, different performance levels have been established. The damage pattern of the test structure was a combination of shear and flexural cracks. However, the predominant failure mode was shear. High compressive stresses developed at the two ends of the in-plane walls due to overturning moments, resulting in vertical splitting at the wall corners[32].

Nolle et al. (2013) has proposed methodology for fragility analysis, it can easily be applied to other building types provided that damage state drift thresholds and material properties are available. It has several advantages, such as in the use of simplified mechanical models for capacity curve generation, which proved particularly effective for carrying out analyses of uncertainties with significantly reduced computational time, and in the use of experimental displacement-based damage criteria instead of relying on expert opinion[33].

Julián et al. (2015) has summarized and discussed the approach in the seismic design provisions for buildings in US and Mexico. It is concluded that earthquake-resistant design in Mexico has evolved in refinement and complexity. It is also demonstrated that the procedure prescribed by such design codes allows the assessment of the design strengths and displacements in a more rational way, in accordance not only with the present stage of knowledge but also with the contemporary tendencies in building codes. In contrast, the procedures used in US codes may not provide a clear view for seismic response assessment of buildings[34].

2.5 Retrofitting Based

Gilstrap et al. (1998) discusses the potential benefits, liabilities, and architectural considerations regarding the use of high-performance fibers for reinforcing masonry structures are discussed with an emphasis on out-of-plane bending. Examples are provided of structure reinforcement and repair by the use of fiber based systems[35].

Sheth et al. (2004) discusses the evaluation and design procedures to recommended for exeuction to seismically retrofit an important historic monument 'The Mani Mandir complex' present in the town of Morbi in the western state of Gujarat, which suffered significant damage during the M7.7 Bhuj earthquake of 2001 in India. A detailed condition survey was carried out and measured drawings were prepared. A comprehensive retrofit program was formulated. Conservation principles, minimum intervention and consonance with the heritage character of the building were important considerations in selecting the retrofit program. The complex was modeled using finite elements and behavior was studied of the existing structure as well as retrofit structure. The retrofit measures recommended included discriminate use of internal reinforced concrete skin walls, providing a rigid diaphragm behavior mechanism in existing slabs, introducing stainless steel reinforcement bands in the existing masonry walls, cross-pinning and end-pinning in walls and pillars, and strengthening of arches and elevation features[36].

Sengupta et al. (2004) study evolve methodologies to assess the seismic vulnerability of reinforced concrete three- to ten-storied, residential and commercial buildings and to propose retrofit measures for the structurally deficient buildings in India. The paper also presents a review of the existing retrofit strategies that are applicable for multi-storied residential reinforced concrete buildings addressed in the project. It also presents a case study of a three storied building, located in an urban area in earthquake zone III[37].

Bastianini et al. (2005) presents the results of a real-scale experimental work regarding innovative seismic retrofitting technique for masonry walls and vaults by epoxy-bonded composite strengthening's. Palazzo Elmi-Pandolfi in Foligno (Italy), an historical building dated 1600 that was seriously damaged in the earthquake of 1997, has been repaired and retrofitted including carbon FRP (CFRP) strengthening's, whose effectiveness has been evaluated through dynamic and static tests. In this work, preliminary tests were performed in order to assess Brillouin monitoring effectiveness in real applications for strain monitorage and crack detection[38].

Cimellaro et al. (2011) discusses technical issues pertaining to the seismic retrofit of the Santa Maria di Collemaggio Basilica and in particular, the limitations of the last (2000) retrofit intervention. Considerable damage was caused to the church because of questionable actions and incorrect and improper technical choices[39].

Bose et al. (2012) reviews the results of a study on the behavior of unreinforced confined masonry walls in RC frames subjected to out-of-plane uniform pressures and shake table loading. It was found that the maximum pressures and failure cracking pattern for the walls with three-side supports were similar to those with four-side supports. Retrofitting the confined brick walls with carbon fibre reinforced plastic (CFRP) enhanced the peak lateral strength and residual strength in tested specimens. The proposed analytical model satisfactorily predicted the load–displacement relationship of all specimens[40].

Brar et al. (2012) studies the various aspects of retrofitting of heritage buildings, new techniques being evolved worldwide and scenario of conservation in India. In the end policy regarding retrofitting to be adopted is evolved. Final conclusion of the study is that historic and older buildings can be seismically upgraded in a cost-effective manner while retaining or restoring important historic character-defining qualities. Seismic upgrading measures exist that preserve the historic character and materials of buildings. However, it takes a multi-disciplined team to plan and to execute sensitive seismic retrofit. It also takes commitment on the part of city, state, and central leaders to ensure that historic districts are protected from needless demolition after an earthquake so that historic buildings and their communities are preserved for the future.[41]

Ashraf et al. (2012) presents experimental results of quasi-static load test conducted on two full-scale brick masonry walls, one unreinforced and the other confined, to investigate their in-plane lateral load behavior before and after retrofitting. The test results after retrofitting indicate that the applied retrofitting scheme significantly enhanced the lateral load capacity of the unreinforced masonry wall; however it was marginally beneficial in the confined masonry walls. The test results are also compared with American Society of Civil Engineers (ASCE) standards in terms of stiffness, strength and acceptable deformations. It is concluded that the guidelines provide reasonable estimates of the test observations[42].

Evrard et al. (2014) provides a vision of integrating the possibilities of Renewable energy in today´s society with respect to the cultural and architectural aspects of the buildings. It stresses the role of renovation and implementation of renewable energy strategies in historic residential buildings in Brussels as the main element to achieve energy efficiency targets. In addition, it will elaborate on the need to develop a methodology to assure success during the renovation of historical residential buildings from design phase. Resulting from the respect for the historical elements of the buildings, this paper will be divided into the exterior and interior changes of the building[43].

Chmielewski et al. (2015) presents a study on the cracked brick masonry dome of the historical church of St. Annain Wilanów (Poland), founded in 1772 and entered in the Polish register of monuments in 1965. The use of a three-dimensional structural model of the masonry dome allowed a detailed determination of the internal force distribution and the adoption of an appropriate repair and strengthening regime for this load-bearing structure. The correctness of the design solutions and calculation assumptions is reflected in the fact that, after a period of more than three years, no damage to the repaired elements of the masonry dome occurred[44].

Sayin et al. (2017) focuses on retrofitting of historical masonry structures from the point of seismic resistance based on failure analysis. It is aimed to determine the main principles by using conventional and modern techniques within the scope of laboratory tests and numerical approaches in recovering the historical structures. Further it is concluded that the retrofitting process is suitable as a practical tool for retrofitting applications Accuracy of retrofitting methods depends mainly upon analyses of examined structures and classification techniques. The efficiency of the retrofitting for historical masonry structures is directly related to the suitability of the used methods or techniques with retrofitting principles. Moreover, needless to say that in addition to the retrofitting of the structures, maintenance and repair of the structures also plays a major role in its service life.[45]

Milani et al. (2017) presents some numerical results on a Romanesque masonry church located in Emilia-Romagna (Italy), a region recently stricken by a devastating seismic sequence on 20th - 29th May 2012. A full investigation of the damages and their comparison with advanced FE analyses, in both linear and nonlinear range are carried out. FE limit analyses are performed through non-commercial software proposed by one of the authors. A remarkable consistency is found among limit analysis results, real performance of the structure under seismic excitation and advanced nonlinear dynamic analyses. A seismic upgrading by means of CFRPs composite materials is proposed, designed and analyzed quantitatively using FEs, finding an optimal fit between the required performance and the invasivity reduction. The interaction between CFRP strips and masonry substrate is accounted for assuming the behavior of the reinforcement in agreement with Italian Guidelines for r.c./masonry strengthening with composite materials (CNR DT200). It is found that, with a targeted design, it is possible to prevent premature collapses of the macro-elements, strongly increasing the load carrying capacity of the structure[46].

Milani et al. (2017) provides an insight into the possible applications of FRP on three masonry churches damaged by the 2012 Emilia seismic sequence. Several different linear and non-linear analyses are carried out, including standard response spectrum analyses, limit analyses with both pre-assigned failure mechanisms and Finite Elements (FE), pushover and non-linear dynamic analyses. A remarkable consistency is found between the real seismic performance of the churches and the results obtained through both limit and advanced non-linear dynamic analyses. In particular, both the damage distributions and the active failure mechanisms derived from the numerical analyses are consistent with those observed on the churches after the seismic event. A seismic upgrading of the churches through the application of FRP is proposed. It is found that through a rational design procedure of the FRP strengthening intervention it is possible to prevent the premature collapse of the macro-elements, considerably increasing their load carrying capacity[47].

Gupta et al. (2017) reviews the change of Reinforced concrete structural components which are found to exhibit distress because of earthquake loading. Such unserviceable structures require immediate attention. Analytical approach is adopted by using the shear wall mechanism in STADD Pro v8i software. It was determined that load carrying capacity for beam-column joint retrofitted with shear wall is increased[48].

Hamdy et al. (2018) addresses numerical modeling and nonlinear analysis of unreinforced masonry walls and vaults externally strengthened using fiber reinforced polymers (FRP). The aim of the research is to provide a simple method for design of strengthening interventions for masonry arched structures while considering the nonlinear behavior. Application is made on a historic masonry dome and the numerical analysis managed to explain its structural behavior before and after strengthening. The modeling approach may thus be regarded a practical and valid tool for design of strengthening interventions for contemporary or historic unreinforced masonry elements using externally bonded FRP[49].

Asikoglu et al. (2019) studies a seismic performance assessment of historical Kütahya Kurşunlu Mosque in Turkey is presented before and after it has been retrofitted. Site investigations were carried out to identify structural conditions, in which severe cracks, especially on the dome, were mapped. Regarding damage conditions, the Mosque has undergone several interventions, including retrofitting actions, in order to improve its seismic performance and global structural behavior. Effectiveness of seismic retrofitting of the Mosque was investigated by using the finite element method. Two representative structural models of the Mosque, namely non-retrofitted and retrofitted, were generated as a three-dimensional finite element model using advanced structural analysis software. Ambient vibration measurements were performed to identify modal properties of the Mosque. Thus, the finite element model was calibrated and improved according to the experimental modal data. Nonlinear pushover and dynamic analyses were conducted to evaluate the seismic performance of the historical Mosque. This paper aims to demonstrate the effectiveness of the adopted retrofitting by comparing the models (before and after retrofitting) and, also, to validate the nonlinear behavior of the model by comparing it with the existing damage on the Mosque.[50]

3.0 Justification for Research

3.1 Motivation

Based on existing literature reviewed it is observed that:

- Mostly experimental work has been reported on vulnerability assessment and retrofitting of huge historical structures built worldwide especially in Europe and America, however very less literature is available on vulnerability assessment and retrofitted of standalone historical structures in India.
- It is further observed that most of the study has been reported on historical structures built using stone masonry, whereas clay brick historical monuments have not been investigated.
- Generally, lime was used as a mortar for construction in most of the historical clay brick structures worldwide previously.

  Hence, a heritage lime surkhi mortar clay brick masonry structure is preferred for this research work to recommence.
- Therefore, present study emphasis on seismic vulnerability analysis and retrofitting of historical clay brick masonry structures constructed with lime surkhi mortar in the region of Fatehgarh Sahib, Punjab, India.
- The results obtained from this research in the region of Fatehgarh Sahib, Punjab, India, may further be applicable worldwide.

3.2 Research Gaps

- Material characteristics of Indian clay brick masonry are different as compared to the other countries[19] where mostly the research related to present study is concentrated and hence the properties corresponding to clay brick masonry documented elsewhere can't be used directly (see ANNEXURE I). Soil properties in Punjab (India) vary because of its geographical location and a versatile soil profile variation can be seen within kilometers. As clay brick masonry depends upon the locally available soil, therefore, it is required to investigate its proper characterization.
- Numerical assessment of various heritage structures across the world exists both in brick and stone masonry but the numerical assessment of retrofitted masonry is neither available in brick and nor in stone.
- Proper usage of material model and damage model for clay brick masonry across the world has never been given in the past for world in general and India in particular.
- No simplified damage model is given for Indian clay brick masonry in general for north Indian historical clay brick masonry.

Keeping this in view, the objectives of the proposed work are laid down in the succeeding section.

4.0 Problem Statement

To study the unstable behavior of fragile heritage clay brick masonry and to implement retrofitting of such structures accordingly. For aforementioned reason, first and foremost thing is to evaluate the mechanical properties of clay brick masonry. Generally, lime was used as a mortar for construction in most of the historical clay brick structures worldwide previously. Hence, a heritage lime mortar clay brick masonry structure is preferred for this research work to recommence. Therefore, present study emphasis on heritage clay brick masonry structures constructed with lime mortar.

The potential of prevailing unstrengthened heritage clay brick structures will be evaluated by numerical analysis using material properties of extracted clay brick samples historical monuments tested under uniaxial compression as well as from wallets constructed using clay bricks having same compressive strength as that of extracted clay brick sample. Assessing worldwide variation in structural properties contributing remarkably against seismic action for arches, large walls and domed vaults is not feasible with compromised boundary conditions. Therefore, a heritage clay brick masonry building is analyzed in succession to replicate the seismic behavior of efficient building with a value that is nearly to the actual.

So, to further safeguard our heritage building or to strengthening of existing vulnerable massive heritage clay brick structures, a retrofitting strategy is required. Based upon the categorization of clay brick structure, number and type of unguarded structural elements, retrofitting technique is essential to be decided for strengthening and further analyzing the strengthened structure.

Due to paucity of old fashioned retrofitting methods and latest technological advancement associated to retrofitting laminates, the evolution of CFRP, GFRP and FRP had already occur extensively all over the world. Some simple assumptions are required for modeling of structural elements and retrofitting laminates without compromising with accuracy level of simulation. The aim of present study is study these factors are needed to be studied for cost and time effectiveness of simulation time. Seismic response of vast ancient clay brick masonry structures are quite complicated and hence concurrently together with the assessment of structural capacity, mode shapes and periods along the two perpendicular directions are also required to be analyzed. Taking into consideration all above mentioned factors, an efficient retrofitting technique for seismic strength enhancement of the structure is needed to be discovered.

4.1 Objectives

The aim of the current study is to investigate the seismic vulnerability analysis and retrofitting approach for the historical clay brick masonry monuments of Fatehgarh Sahib, Punjab, India.

The prime objectives of the proposed study are summarized as follows:

1. To identify and evaluate mechanical properties of historical clay brick masonry of Punjab constructed in lime mortar and lime surkhi mortar under uniaxial compression.
2. Validation of non-linear material and damage models of clay brick masonry being used for numerical solution.
3. To evaluate the vulnerability and the seismic capacity of the one historical monument using numerical solution and identify the locations of distress.
4. To propose an appropriate retrofitting strategy for preserving historical monuments.

4.2 Methodology

The literature survey will be done extensively for damages regarding the historical clay brick masonry and their respective retrofitting techniques. Historical buildings are subjected to various adverse conditions throughout their life span such as material deterioration, metal fatigue, wood deterioration, heavy dead load stresses developed over a long duration and earthquakes. Somehow historical buildings can resist with time the other types of deterioration due to their massiveness but very much vulnerable to earthquakes (lateral loads) as these are capable to resist only gravity load effectively. Further prior to seismic retrofitting of the structure, existing deteriorated state may need restoration for which reconnaissance survey of the case study building is required. Hence in process of evaluating the structure for the deteriorated state, a complete knowledge database is required concerning the problems and typologies of historical clay brick masonry buildings. Hence visit to some of the 17th century historical monuments will be made and documented subsequently mentioning vulnerable macro elements of the structures.
Assessable Clay brick samples from historical monuments are collected and tested under uniaxial compression to find the engineering properties like compressive strength, Poisson ratio, Modulus of elasticity, stress strain curve, total strain, overall deformation, etc. Study corresponding to determination of mechanical properties of historical clay bricks as a unit and brick masonry as a whole under uniaxial compression is required to be carried out. Further characterization of Lime mortar using methods such as XRD/XRF/SEM analysis is required to be carried out for preparation of masonry wallets. Then contemporary clay bricks having same compressive strength as that of extracted samples will be prepared and tested under uniaxial compression for engineering properties like compressive strength, Poisson ratio, Modulus of elasticity, stress strain curve, total strain, overall deformation, etc. Further clay brick masonry wallets using contemporary clay bricks having same compressive strength as that of extracted samples will be constructed and tested for various engineering properties. This experimental work can give us the damage model.
Then clay brick masonry wallets (same as used in experimental work) will be modeled and analyzed using suitable commercial code for validation of experimental work. Further validated engineering properties will be used for material model and damage model. Hence whole

procedure will give us the required parameters for suggesting and further analysis for the historical clay brick monuments.

The emphasis will be on performance based design using pushover analysis based on IS code compatible time history spectrum for seismic acceleration load at the base of the building. Using the reliable data from above procedures such as engineering properties, vibration characteristics and soil conditions and already developed damage typologies, a vulnerability assessment procedure will be developed for clay brick masonry buildings. Then modeling of a real historical brick masonry building will be done using either FEM or any other suitable method and after applying an earthquake load of predefined intensity, the building will be damaged following a step by step evaluation procedure. The results of the above procedure are going to validate the developed vulnerability assessment procedure.

Using the developed vulnerability assessment procedure, the seismic capacity of the building can be easily evaluated. Based upon the literature review best feasible alternatives with suitable modifications and some new technologies will be considered for further analysis keeping minimum intervention. Analysis of the building will be done incorporating these retrofitting techniques and reanalyzing the retrofitted structure, results will be studied. The best feasible alternative will be decided based on the criterion of increased strength of the structure disturbing the aesthetics, architecture and cultural values associated with it to a minimum level[51].
(Refer ANNEXURE II) for flow chart showing working methodology of research.

5.0 Expected Outcomes

The expected outcomes and the significance of potential results of the research which can contribute to the research community are as follows:

1. To prepare a data base of damage typology, macro elements and behavior of historical clay brick masonry structures of India.
2. To evaluate compressive strength, Poisson ratio, elastic modulus and stress strain characteristics of unit (clay brick), mortar and wallets.
3. To give a generalized material model and damage model which can be used for evaluation of historical clay brick masonry structures having properties similar in nature to north Indian clay brick masonry.
4. Depicting critical over stressed regions of the case study monument based on seismic numerical assessment.
5. To give a proper feasible strengthening methodology (local as well as global) using FRP based on locations of critically stressed regions evaluated using numerical assessment.

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ANNEXURE - I

Explanation: -

Existing relevant study available close to this study cannot be exactly used in Indian scenario because brick masonry constituent properties are different in India from the rest of the world because in several western countries, the bricks are relatively stronger (where the compressive strength has been usually found to be in the range of 15–150MPa or 30–50MPa) and stiffer than the mortar which introduces a different type of uniaxial compression behaviour in accordance with elastic sandwich model. Whereas in India, often the mortar used is relatively stronger and stiffer than the bricks which results in relative compression of bricks and relative tension of the mortar in contrast to the scenario in western countries. It has been found that the bricks used in India are of comparatively low compressive strength (3–20MPa, 7–10MPa [BIS, 1991]) as compared to other parts of the world such as Greece, Germany, Italy, Barcelona and Poland. Bricks in India have been found to be low on elastic modulus as compared to western countries. A similar pattern of low compressive strength of bricks (yet close to compressive strength of bricks for this study) in India has also been found out by Rai and Dhanapal in 2015. The unit properties vary hugely within India due to large variation in soil conditions geographically from southern part to northern part varying from 2 to 24MPa which further necessitates the need to evaluate exhaustively the masonry properties in the northern part of the country.[14]

ANNEXURE – II

FLOW CHAT SHOWING WORKING METHODOLOGY OF RESEARCH: -