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State-Of-The-Art Literature Review on Inelastic Behavior of RC Infill Brick Masonry Buildings

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Abstract: Brick masonry construction can be widely seen in Asian countries as well as globally. It is observed that the performance of these structures during past earthquakes is not very good and the same can be attributed to several factors. There is a need to understand the behavior of such buildings during earthquakes so as to save life loss during earthquakes. At the same time research is going on in several countries to understand the behavior of brick masonry buildings subjected to lateral shaking. In this paper, state-of-the-art review on vulnerability of brick masonry construction and on-going research on the same is discussed. This review consists of analytical and experimental research performed in past few years. Upon understanding the capabilities of numerical techniques available for numerical modeling of infill walls, Applied Element Method (AEM) comes out to be efficient model, where the level of damage by crack occurrences, their evolution, block separation and material loss before collapse and mitigation measures of retrofitting of weak buildings can be suggested.

***Keywords:** Numerical methods, applied element method, Brick masonry, nonlinear behavior*

1. Introduction

Brick being a traditional construction material can be seen widely in Asian countries, viz., India, Nepal, Pakistan, Bangladesh and China etc. Brick is widely used because of its aesthetic appeal, its strength, durability, and other desirable properties. But, experiences from past earthquakes like Kobe earthquake (1995), Bhuj earthquake (2001) and recent earthquakes like Chile (2010) Haiti (2010) and China earthquake (2010) clearly shows that most of the property and life loss was under infilled brick masonry structures.

1.1 Vulnerability of Brick masonry construction in India

In the Near East India, bricks have been in use for more than five thousand years. Brick masonry construction is widely used in western and southern India in rural and urban parts of India. Brick construction is specially used by middle class population in urban areas, and is becoming popular in rural area as well, this may be due to aesthetic appeal, strength and durability and most important is easily available material. In brick masonry type of construction, Brick masonry walls are the main load bearing element in buildings. Roof structure is a cast in-situ reinforced concrete slab. This type of construction is in practice from around 75 years. Major areas in Indian states contribute to brick masonry construction: Maharashtra contributes about 20% of housing units of this type i.e. approximately 3 million housing units in total. In Mumbai, 30% of houses are of brick masonry construction [1]. Good quality bricks are normally available in Northern regions of the country from the State of Punjab to west Bengal, whereas in other regions the strength of the brick is relatively less [2].

North eastern zone is basically a hilly region with heavy rainfall and falls under seismic zone V. Houses are built with soil blocks and ‘Ekra’ walling. Roofs are generally sloping, either of thatch or CGI sheets having timber or bamboo made rafters or purlins. Whereas the north zone covers hilly region as well as substantial part of indo-gangetic plain and falls under seismic zone IV. Houses are built with soil blocks, bricks, stone walls and roofs are CGI sheets, burnt clay tiles, reinforced brick concrete and R.C.C. On the other hand west zone contains sand dunes, marshy land, black cotton soil and hilly region. In this region brick produced have low compressive strength of 25-40 kgf-cm2 and less water absorption. Bricks made up of soil blocks are used for house construction and rainfall is low in this region but east zone consists of alluvial soil and lateritic soils. Good production of clay bricks is there due to abundance of alluvial soil. Houses are built with soil blocks, bricks, lateritic blocks and stone according availability of materials. In contrast South zone consists of poor quality soil for brick, red soil, lateritic soils, coastal marine soil and some hilly areas. In this region houses are made with soil blocks, lateritic blocks, bricks, stone walls, and the roofs are with RCC Mangalore tiles and RBC [3].

In view of above things which focus on different types of soil conditions in different regions throughout India and different construction types, there is a need to study the behavior and damage to brick masonry structures during earthquakes and to explore the mitigation measures of retrofitting of weak buildings.

1.2 prevailing seismic hazard of the country:

As per IS 1893 (Part1)-2002, 60% of Indian region comes under zone III, IV and V (see Figure 1) and construction practices in India need to refer IS standards to avoid possible damages to the buildings during earthquake.

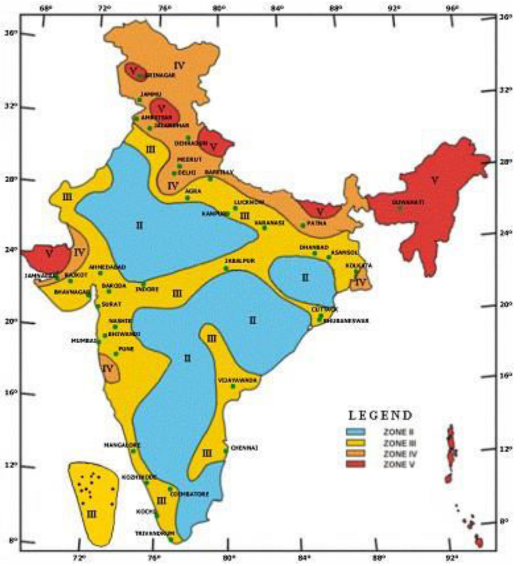

Figure 1 *Seismic Zone Map of India (IS: 1893 (Part1)-2002) showing four seismic zones- about 60% of India's land under seismic zone III, IV and V*

1.3 Performance of brick masonry buildings during past earthquakes:

Generally Brick masonry is mainly used for wall construction. Brick masonry is strong in compression and is controlled by the unit strength of the masonry but it is weak in tension which is associated with the bond between unit and mortar. Usually, the process of constructing a building from individual bricks laid in a specific pattern and bound together, by mortar. Though the common form of laying one brick over other with a cohesive material like mortar, construction of masonry varies through time runs and place to place. Structural property of the constituent materials, bonding patterns, workmanship, combination to other structural materials like timber, reinforcement bar and concrete frame greatly influence the structural behavior of masonry structure under given loading conditions. Though history of earthquake shows many major earthquakes worldwide. But this study focuses on performance of brick masonry buildings during past important earthquakes in India; which caused more damage and life loss to the society, also regional construction practices in the corresponding area is discussed below:

1.3.1. Bhuj, Gujrat: The powerful earthquake that struck the Kutch area in Gujarat on 26 January 2001 has been the most damaging earthquake in the last five decades in India. The M7.9 quake caused a large loss of life and property. The estimated economic loss due to this quake is placed at around Rs.22,000 Crores (~US$5 billions) [4].

Western Gujarat (Figure 2) is a hot and arid region. Mostly common man stays in bricks masonry buildings. During earthquake all these types of buildings were the mostly affected one. Brick being a traditional construction material which gives them a sense of safety, there are other climatic reasons to build thicker walls and floor. These types of constructions keep the room temperature down. Particularly roofs made of timber and overlaid with an inferior quality of thick lime terracing, offered respite from heat. These roofs do not possess structural integrity. Instead they add mass at the top level and collapse easily as their supports shift. Lintels are often a piece of stone or timber. Mortar used is a very weak layer of lime-kankar, which when dry provides some bond, but when wet it loses its strength drastically.

1.3.2 Uttarkashi in Western Himalayas

The typical construction consists of stone masonry walls on a shallow foundation (Figure 2). Stones being flat provide reasonable stability to walls, which are often without mortar joints. For protection against high rainfall in the hills thin stone slabs are used as sloped roof materials. Thicker slabs of sandstone are used in these parts. During earthquakes, these heavy stones get easily dislodged because of their own inertia and pose life hazards [5]. Most houses in the region are constructed solely by the masons without specific engineering inputs. Seismic performance of the structure is therefore a direct function of the knowledge, skill, experience and acumen of the mason. It is interesting to note that framed structures are non-existent in the region [6].

1.3.3 The Chamoli in Central Himalayas (Chamoli (Himalaya, India)): The Chamoli earthquake of 29 March 1999 in northern India (Figure 2) is yet another important event from the viewpoint of Himalayan seismotectonics and seismic resistance of non-engineered constructions. Several relatively new buildings in rural as well as urban areas are in burnt brick masonry in mud or cement mortar. The earthquake occurred in a part of the Central Himalaya, which is highly prone to earthquakes and has been placed in the highest seismic zone (zone V) of India. The earthquake caused death of about 100 persons and injured hundreds more; it caused extensive damage to property. Maximum MSK intensity was up to VIII at a few locations.

Figure 2: *Indian Map showing location of past important earthquakes*

Table 1: *Locations on Map*

1	Bhuj (Gujarat)
2	Chamoli (Central Himalaya)
3	Latur and Killari (Maharashtra)
4	Uttarkashi (Western Himalaya)
5	Assam

1.3.4 Latur and Killari, Maharashtra: Latur and Killari (Figure 2) are situated in the northern extremity of the planes of Deccan plateau. Engineered structures were relatively scarce in the affected area. The collapse of traditional stone-and-mud buildings in the mesoseismal area was nearly total. The wood-plank roofs of these single-story dwellings typically were topped with a 30-60 cm thick layer of clay to provide protection from rain and heat. All such constructions behaved very poorly due to the heavy mass at the roof and the poor strength of the supporting rubble masonry walls; such houses were the main cause for the high number of casualties. A few brick masonry houses in the area were found to have concrete lintel bands performed well [7].

1.3.5 Assam in eastern Himalayas: Assam - Tibet earthquake (Figure 2) of August 15, 1950, 14:09 UTC 8.6M (USGS). At least 780 people killed and many buildings collapsed in the Nyingchi- Qamdo-Zhamo (Rima, Zayu) area of eastern Tibet. Traditional timber constructions in eastern Himalayas are replaced by made brick masonry structures as timber is becoming costlier.

1.4 Typical failures observed and qualitative damage grading to the brick masonry buildings:

1.4.1 Vertical cracks at wall junctions or failure at connection: Figure 3 shows the damage to the brick masonry wall during earthquake in Killari (1993).

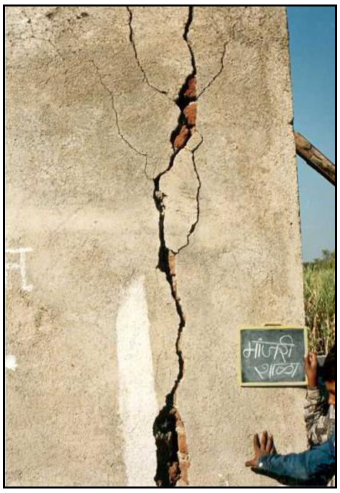

Figure 3: *Earthquake Damage - Wall Corner cracking (1993 Killari earthquake) (EERI, World Encyclopedia report, India, 6-5-2002)*

Almost a straight compression crack can be observed in the wall which may be due to flexural compression in the wall during earthquake. Magnitude of the earthquake was 6.4. This earthquake has a high PGA value of 0.11 g, a dominant frequency greater than 15 Hz and a long duration, which is a major cause to the structural damage [8]. According to Table 2, damage can be categorized as G3 as Moderate structural damage. Crack in the wall is deep.

1.4.2 Shear cracks or 450 bi-directional cracks in wall panels: Figure 4 shows the damaged structure during Killari earthquake. Horizontal crack can be seen at the wall-roof connection - Shifting of roof from the wall might have happened due to torsional movement of roof slab. Crack no. 1, 2 and 4 are shear cracks as earthquake ground motion acting as a shear force on the wall. Crack no. 3 is due to tension in the wall and crack no. 5 is due to the compression in the wall during earthquake. According to Table 2, damage can be categorized as G3 as Moderate structural damage, as widespread cracking of the wall can be seen.

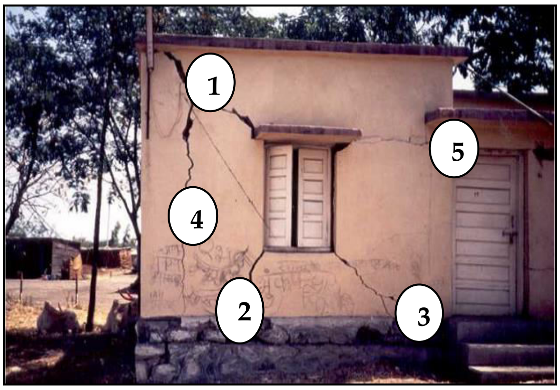

Figure 4: *Typical Earthquake Damage - Sliding Failure of Roof-Wall Connection Due to the Absence of Wall Reinforcement (1993 Killari earthquake) (EERI, World Encyclopedia report, India, 6-5-2002)*

1.4.3 Cracks due to in plane movement:

Figure 5: *Flexural & shear cracks alongwith separation of wall from wall connection (S. H. Farooq, 2006)*

An earthquake measuring 7.6 on the Richter scale struck Mansehra, Muzaffarabad, Islamabad, Lahore etc. on 8th October 2005 at 08:52 PST. PGA of the earthquake was 0.6g; Flexural as well as shear cracks were observed in most of the building due to excessive stresses induced by in plane vertical and horizontal forces. Figure 5 shows the horizontal flexural and shear cracks in brick masonry load bearing wall due to in plane movement caused by earthquake vertical and horizontal forces.

1.4.4 Out of plane (flexure) failure of wall leading to collapse: Collapse of buildings due to out of plane movement was also observed in the affected areas. All the walls having less flexural strength and minimum stiffness in the perpendicular direction of seismic waves were collapsed causing the failure of complete structure. Jabalpur earthquake occurred on May 22, 1997 at 04:22 am (local time) in the city of Jabalpur in Madhya Pradesh in central India. It caused significant damage to structures in the districts of Jabalpur, Mandla, Sivni and Chhindwada in the state of Madhya Pradesh [9]. Figure 6 shows collapse of wall adjacent to door, this is due to poor connection between wall and door frame. According to Table 2, damage can be categorized as G4 for Figure 6, wall portion is collapsed and major cracks can be seen. Door is also damaged heavily. The building is in dangerous state.

***Figure 6**: Out of plane failure in 1997 Jabalpur Earthquake (EERI, World Encyclopedia report, India, 6-5-2002)*

***Figure 7**. Shear failure in RC column (Jag Mohan Humar et. al., 2001).*

1.4.6 Shear failure in RC columns: Figures 7 shows shear failure in RC column in Bhuj earthquake in 2001. It has been observed that most of the building collapsed due to soft storey effect at first floor. Such types of failures are due to high shear imposed on first storey columns which caused a shear failure in some of the columns.

2. Past research on behavior of RC brick infill buildings:

Brick is easily available construction material in most of the Asian countries and widely in use due to its multifold effects such as durability, fire resistance, thermal and acoustic insulation and aesthetic appeal, but past earthquakes witness enormous loss to human life and property due to collapse of brick masonry buildings. Though frame structures with masonry infill are commonly used in regions of high seismicity but adequate knowledge of the behavior is required to design this type of structure in order to reduce the loss of life and property associated with a possible structural failure. Most of the rural India has construction of load bearing structures such as stone masonry, unreinforced brick masonry and confined masonry buildings which are lacking the seismic safety measures suggested by seismic code, so it becomes important to assess the behavior of such building under seismic loading.

A major goal of the current research was to understand the behavior of brick masonry buildings under seismic loadings. In past, several studies were carried out in the area of brick masonry buildings. In this paper, a review of the past experimental, analytical, numerical studies are presented. Damage estimation plays important role in predicting amount of damage in the buildings, in view of this existing damage model have been used in this study for qualitative damage analysis of structures (Table 2).

2.1 Analytical Studies: Modeling methods:

For the analysis of masonry buildings basically three approaches were considered, that is; detailed micro modeling, simplified micro modeling and macro modeling. Detailed micro modeling considers the two components of masonry, brick and mortar separately. The interface represents a potential crack/slip plane with initial dummy stiffness to avoid interpretation of the continuum [10]. This approach provides detailed insight of the structural behavior but it is computationally costly[11]. In the second approach, mortar and brick properties are considered as combined and so brick masonry thus considered as a set of elastic blocks bonded by potential fracture/slip lines at the joints. In this approach, brick arrangement is kept as input variable of the analysis and therefore walls with discontinuities such as windows and door openings can be analyzed [12,10]. The third approach is macro modeling, it uses homogenization techniques which considers masonry as a periodic media i.e. elements arranged in uniform pattern.

Two stages of homogenization are used, one for the orthotropic material and the other for smeared cracking of the material [13]. Macro models are capable to analyze large structures, but it cannot consider discontinuities and details. Regardless of the type of modeling adopted the important failure mechanisms, characteristic of masonry, considered by Lourenco [10] are (a) Cracking in the joints; (b) Sliding along bed or head joints at low values of normal stress; (c) Cracking of the units in direct tension; (d) Diagonal tension cracking of the units at values of normal stress sufficient to develop friction in joints; (e) Splitting of the units in tension as a result of mortar dilatancy at high values of normal stress.

2.1.1 Masonry structures (URM and RM) and loading (static and dynamic):

Review on macro model: Macro model approach use simplified model of frame and panel to get overall behavior based on the physical understanding. In past research work in analytical studies, macro model developed as a diagonal strut model for infilled frame, it was based on the analytical work conducted by Polyakov (as reported by Mallick and Severn, 1967) [14]. Later, Holmes (1961) proposed that the equivalent diagonal strut should have a width equal to one third of the length of the panel and later Stafford Smith, (1962) improved the approach based on experimental data [15, 17]. Some methods were also proposed for predicting the approximate lateral stiffness of single and multi-storey frames. The equivalent width of strut was found to lie between 1/4th and 1/11th of the diagonal length, depending on the span to height ratio of the frame, Smith (1968) [16]. A study on the effect of openings and shear connectors in infill frames concluded that opening should not be there at either end of a loaded diagonal as strength will be reduced, Mallick and Garg (1971) [18]. Openings should be located in the middle third of the panel instead of near end, as opening help in transferring gravity loads of the portion above the opening by arch action which also prevents progressive collapse in such infill frames (Smith, 1967). Further work was continued by many other researchers, who refined the model, mainly by considering several struts to represent the panel, Crisafulli (2000) [19].

Strength and stiffness degradation with respect to opening and closing of masonry gaps was studied by Madan et al (1997) [22] for static non-linear analysis as well as dynamic analysis. Effect of single strut and multi strut versus 4 node panel element was studied by Crisafulli (1997, 2007) [20,21] and it has been understood that If single strut is considered for the analysis, single strut resisting compressive and tensile forces cannot describe the internal forces induced in the members of the frame properly but when a 4 node panel element allows lateral stiffness of panel and strength of masonry panel, particularly for a shear failure along mortar joints or diagonal tension failure is expected. Equivalent braced frames with infill walls were studied by Diptesh Das and C.V.R. Murty (2004) [23]. For the analysis and design of infilled frame subjected to in plane forces, a method is proposed based on equivalent diagonal strut approach by considering a single strut approach though it cannot capture local effects but at the same time it is useful for the analysis of large structures. So, the RC frames with unreinforced masonry walls were modeled as equivalent braced frames with infill walls replaced by "equivalent struts". Reduction factor for effective width of diagonal strut was studied by Goutam Mondal and Sudhir K. Jain (2008) [24]. They proposed a reduction factor for effective width of diagonal strut to account for the central window opening in the infill reinforced concrete frame. Parametric study has been done to obtain lateral stiffness of infill frame with varying window opening. Two types of analysis methods considered, first is finite element method and single equivalent diagonal strut method. Finally, the width of equivalent diagonal strut for the single equivalent diagonal strut method is estimated so as to obtain the same lateral stiffness as estimated from the finite element method.

Review on micro model: Modeling of units as Elastic continuum elements were done by Page (1978) [25], initially units were modeled as elastic continuum elements, bonded with interface elements. Based on experimental study elastic interface (σ, τ) was developed. In the yield surface contains two compressions and one tension branch. The marked change in slope in compression corresponds to a change in the failure mode from pure shear failure in the joint to combined joint/unit failure.

Strain softening model for compression with a tension cut-off was proposed by Arya and Hegemier (1978) [38]. A von Misses strain softening model for compression with a tension cut-off was used for the units of a masonry considered. Joints were modeled with interface elements by incorporating cohesion and friction angle in softening and tension cut-off for brittle behavior. Experimental results on shear walls were checked with the collapse load obtained from the model. Analytical work has been done by Lourenco (1996, 1997) to incorporate all types of failure related to brick masonry [10, 26]. All the damage was concentrated in the relatively weak joints. The joint interface yield surface considered to include all the failure mechanisms except tensile cracking. Interface cap model was developed. The interface model includes a compression cap in which the complete inelastic behavior of masonry in compression is considered. Around same period, a continuum model has been developed by Gambarotta et al in 1996 for brick masonry [12]. In plane stress condition, the constitutive equations were developed. Brick masonry is considered as a stratified medium with two layers i.e. the mortar head joints and brick unit's representative layer and bed mortar joint layer.

In detailed study of brick joint action, a standard compressive test was performed by J.G. Rots, 1991. It has been observed that horizontal compressive stress arise in mortar and horizontal tensile stress arise in bricks and the later stresses govern ultimate failure under compression; also it has been studied that the mortar joint, the peak stress in brick amounts to 6.5 times the average stress and is likely to initiate cracking and spalling of brick and / or delamination along the brick / joint interface. (J. G. Rots, 1991) [27]. Later, a new homogenization technique to investigate the elastic-brittle behavior of masonry panels subject to incremental lateral loading has been investigated by Lee and Pande et al (1996) [28]. First brick units were homogenized with perpend joints to give equivalent elastic properties of a stacked system and then these stacked systems was then homogenized with the bed joints to obtain equivalent material properties for masonry. Jahangir Bakhteri et al (2004)[29] considered composite material for brick msonry which showed accurate stress distrubition for the prism considered.

Around same period, in numerical modeling using AEM, Bishnu Pandey (2004) [39] observed that principal crack is dependent on the imposed displacement and not on the pre compression load. Also, when the mortar strength is higher; then the load carrying capacity of the wall also increases at all stages of loading. Effect of lintel band was also been studied. A significant effect in wall behavior was observed due to lintel especially on crack pattern. Crack appeared in wall without band is disappeared in wall with band. In case of transverse loading out of plane failure can be withstand by avoiding crack using lintel band. (Bishnu Pandey, 2004)[39]. Earthquake loading and effect of retrofitting was studied by Paola, 2006 [11]. The behavior of wall under monotonic lateral loading was studied by considering earthquake loading and sustainability of masonry building was studied after retrofitting. In their work as an advantage of AEM they could study the crack initiation, crack propagation till full collapse of building. Around same period Guragain et al [40], did the numerical simulation by AEM for brick masonry wall under lateral loads and especially cyclic loads in order to understand the behavior of brick masonry building in earthquake. Material model considered by him was the damage model proposed by Gambarotta et al (1997) [12] for cyclic loading case [12]. The constitutive equation was based on damage mechanics and takes into account the mortar damage and the brick mortar decohesion which are considered to take place during crack opening and friction sliding along the interface. (Guragain et al, 2006)[35] also different failure behavior with respect to wall aspect ratio was observed.

In a research study by author [43], brick masonry infill wall was modeled using AEM (Applied element method) and parametric study was done by considering different parameters such as, effect of mortar volume, effect of span ratios and effect of opening on strength of wall. It was seen that more span ratio is responsible for less strength and vice versa. For the case of opening in wall, it becomes difficult to form a strut action which causes its strength to degrade. Effect of mortar thickness causes a weaker zone in masonry wall, so mortar thickness used in construction should be appropriate as per IS code.

2.1.2 Qualitative damage assessment: To study the behavior of masonry buildings after an earthquake; to get insight into the performance of various kinds of brick masonry structures and types of failures occurred; the extent of damage to the structure for particular earthquake; qualitative damage model was used in India. Typical Brick Masonry failures occurred during past earthquake and damage assessment is given in Table 2. Damage Assessment GICEA (Gujarat Institute of Civil Engineers and Architects) under the guidance of Dr. A. S. Arya, IIT Roorkey. Damage classification is as per MSK intensity scale and modified for Load bearing masonry buildings and wooden frames, RC frame buildings as well. Table 2 explains the category and assessment of damage assessment for the Masonry structures.

Table 2: *Damage Assessment by GICEA*

0	None	No damage	Building need not be vacated. Seismic strengthening is advised
G1	Slight non-structural damage	Thin cracks in plaster, falling of plaster bits in limited parts	Building need not be vacated. Seismic strengthening is advised
G2	Slight structural damage	The load carrying capacity of the structure is not reduced appreciably	Building need not be vacated. Seismic strengthening is advised for long seismic safety.
G3	Moderate structural damage	The load carrying capacity of the structure is reduced little.	Building needs to be vacated. It can be reoccupied after restoration and strengthening.
G4	Severe structural damage	Gaps occur in walls; inner or outer wall collapse. The building is in a dangerous state.	Building needs to be vacated. Extensive restoration and strengthening need to be done before reoccupation.
G5	Collapse	A large part or the entire building collapses	Cleaning the site and reconstruction.

2.2 Experimental studies:

In past many experimental studies were done to understand the behavior of brick masonry buildings and collapse pattern and crack occurrences in the building and brick and mortar joints during earthquake. Masonry wall can be considered in two ways depending on their functional use. First is bare wall and second is Infill wall. Different types of loading conditions considered in past experimental studies i.e. in-plane and out of plane loading, cyclic and dynamic loading, pseudo dynamic loading, quasi static loading etc. whereas in this study in-plane lateral loads are considered as research interest.

2.2.1 Quasi-Static Testing: Armin B. Mehrabi et al (1996) [31] investigated the influence of masonry infill panels on the seismic performance of reinforced concrete (RC) frames that were designed in accordance with code provisions. In monotonically applied loading, load carrying capacity of bare frame was increased when brick infill considered. Pires and Carvalho (1992) [46] in their experimental study considered seven models of single storey and single bay frame. A quasi static horizontal cyclic loading was used. During the test crack have been observed in the infill due to loss of stiffness and maximum strength was recorded at 0.1% drift. Different cases under Quasi Static loading are discussed below: Multi-bay Multi-Storey building frames with URM Infills: Many experimental studies were conducted on multi bay multi-story building frames with URM infill to understand the interaction between frame and masonry infill wall panels. Bertero and Brokken (1983) [36] in their experimental model of 3 bay of 3 storey RC frame infill building and under quasi static monotonic and cyclic loading understood the complex interaction between frame and infill. Later, Zamic and Tomazevic [46] (1984) through their experimental study observed that at 0.2% of storey drift cracks were observed in the infill wall whereas a RC infill frames showed a satisfactory behavior till 2% of drift. In another experimental study of concrete frame with infill wall conducted by Valiasis and Stylianidis (1989) [37], it has been observed that the infill increased the building strength by 50% but it could remain for small drifts only. In order to understand the seismic behavior of RC frames with masonry infill Manos et al (1995) [47] considered two cases of RC frames without infill and RC frames with infill. It has been observed that bare frame could reach maximum strength at 1% of drift whereas with infill maximum strength was observed at 3% of drift.

GM Calvi et al (1996) carried out experimental evaluation of strength, deformability and energy dissipation capacity of the structure [30]. They have described problems and the relative merits and roles of several experimental techniques, including quasi-static, dynamics and pseudo dynamic loading in full and reduced scale. GM Calvi et al [41] in 2004 studied seismic performance of infilled R.C. frames, both for global in-plane response and local out-of-plane response. They have also highlighted some issues related to observed interaction between masonry infills and bounding frames and some analytical methods summarized. Calvi observed in experimental and numerical results that, frames with slightly reinforced masonry infills generally perform better than bare frames as it enhances lateral capacity of the building and energy dissipation provide a significantly better behavior in terms of operational limit states and cost of repair.

C.V.R. Murty and S. K. Jain (2000) [42] did experimental studies on RC frames with masonry infills under cyclic loading. It was seen that the masonry infills contribute significant lateral stiffness, strength, overall ductility and energy dissipation capacity. They considered twelve single-bay single-storey RC frames of 1:2.7 reduced-scales were experimentally studied under reverse cyclic displacement-controlled loading. Frame columns were detailed to yield in flexure before shear failure. The specimens tested include (a) bare frame, (b) frame with unreinforced masonry (URM) in full- and reduced-scale bricks, and (c) frame with unanchored and anchored reinforced masonry (RM) in full- and reduced-scale bricks. The main conclusions drawn from these tests were, Initial stiffness of infilled RC frame was 4.0 times more than bare frame was 4.3 times more when masonry was reinforced. Strength for URM infilled frames had 70% higher strength than bare frame. Under cyclic loading, the yield displacement of infilled frames was much smaller than that of the bare frame, and hence, the infilled frames had considerable larger ductility. Further, addition of reinforcement in infills increased the ductility of infilled frames. The average energy dissipation in unreinforced infill frames was about 22% higher than that in the reinforced infill frames. That was because of the localization of sliding along the few mortar bed joints along which reinforcements were placed.

Multi-Storey buildings frames: Govindan et al (1986)[35] considered a seven storey RC frame with brick infill and compared it with bare frame and it has been observed that the infill strength was double than that of a bare frame and at 3.7% of drift observed at its maximum strength whereas maximum strength for bare frame observed at 1%.

2.2.2 Psuedo-Dynamic Testing: Mosalam et al (1998) considered a 2-storey, 2-bay steel frame with concrete block masonry as infill. In this study pseudo-dynamic testing has been considered in order to get an acceptable approximation of the dynamic. It has been observed that at 0.5% drift; major cracks were observed in infill. Felice Colangelo [45] (2004) considered single-story single-bay half-scale reinforced-concrete frames of which two specimens tested bare and five specimen considered infilled by perforated brick and mortar masonry. It has been observed that initial stiffness due to infill wall increases by one order of magnitude when compared with the bare frame whereas maximum strength doubles compared to bare frame. In energy analysis it has been observed that infilled frames are prone to a greater input, and absorbed, energy. Later, H.

Ozkaynaket al (2010) [33] in their experimental study considered twelve 1/3-scaled RC frames. Frames have been tested as bare frame and infill frame and also by considering CFRP retrofitting and cross diamond bracing scheme. In this study, a cross diamond-bracing scheme appears as an effective retrofitting technique that brings the bare frame from collapse prevention to life safety performance levels.

2.2.3 Dynamic shake table testing: Much experimental work has been done using Shake table test in order to study the seismic performance of brick masonry building during earthquake. Shake table is a device for shaking structural models or building components with a wide range of simulated ground motions, including reproductions of recorded earthquakes time-histories. While modern tables typically consist of a rectangular platform that is driven in up to six degrees of freedom (DOF) by servo-hydraulic or other types of actuators, the earliest reported uses of shake tables date back more than a century as reported by Omari (1900). Shake table study by past researchers focused on various aspects like effect of reinforcement on strengthening of wall, effect of scaling bricks, Effect of PP band etc.

Mihail Garevski et al [44] (2004) considered 1/3-scale specimen of RC frame structures with infill walls under real earthquake excitations in experimental dynamic shake table study, to verify the validity and applicability of the proposed retrofitting technique. The experiments have shown that using the CFRP strip technique for retrofit of such kinds of structural systems, the overall behavior under seismic excitation can significantly be improved. Later, Alidad Hashemiand Mosalam (2006) [32] considered a prototype of three bay stilt four storied structure. Shake table experiment was conducted on middle bays of the first storey. In this study, unreinforced infill wall played a significant role in terms of strength and ductility of the test structure. Presence of infill wall increased the stiffness of structure globally by a factor of 3.8 whereas natural period of the test structure shortened by 50% and there was increase in dampening coefficient depending on the level of shaking. Due to above effects displacement demand on the structure generally reduces attributed to change in demand forces. Later, P. Benson Shing et al. (2010) in their shake table study considered a 2-bay 3-storey building with full infill wall at one bay whereas window opening at other bay. It has been observed that Infills can significantly increase the lateral strength of a non-ductile frame, thus improving seismic performance. Retrofit using ECC overlay increased the resistance of the infilled frame, however it may not always be possible to increase ductility. Mohan M. Murudi et al (2011)[34] in his study observed that a lowest peak displacement to the engineered infill framed wall due to more energy dissipation whereas infill wall with opening showed a highest peak displacement among other infill wall attributed to reduction in stiffness due to opening.

3. Conclusions

In this state of the art literature, past research in analytical and experimental study related to behavior of RC brick masonry infill building under different loading conditions were considered. Though experimental studies are important, it becomes expensive and time consuming whereas a numerical study using Applied Element method is capable of considering detailed stages of loading and it can simulate crack generation, expansion of cracks and total collapse of the building under different loading conditions.

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