Seismic performance of masonry-infilled RC frames and its implications in design approach: A review

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ABSTRACT

Predicting the seismic response of masonry-infilled (MI) reinforced concrete (RC) frames holds immense importance due to the significant influence of masonry on the structural performance. Despite numerous studies delving into the seismic behavior of these frames, their complex interaction of masonry infills and RC frame presents ongoing challenges for researchers, designers, and standards committees. Although numerous studies have been conducted to investigate the seismic behavior of masonry-infilled reinforced concrete frames, its complex behavior poses a challenge to researchers, designers, and the specification-making committees. In recent years several national codes (ASCE 2013, BIS 2016, EC 2018) have been revised to include the estimation of the stiffness of reinforced and non-reinforced masonry walls and have provided guidelines for the modeling and analysis of structures considering MI. This article aims to provide a comprehensive review of how infilled masonry walls impact the seismic performance of RC frames, drawing comparisons with the aforementioned codal provisions.

The focus lies on scrutinizing experimental, numerical, and analytical studies that explore in-plane and out-of-plane behaviors. Factors like masonry strength, stiffness, the area of openings, stiffness degradation, energy dissipation capacity, and damage patterns are thoroughly examined. Key findings with critical implications are highlighted, shedding light on potential future research directions in this crucial field.

Keywords: Infilled masonry, RC frames, stiffness, seismic behavior, macro-modelling, and micro modelling

INTRODUCTION

Reinforced concrete frames with reinforced or non-reinforced infill are commonly employed as structural systems in many countries. Fig. 1 illustrates the basic scheme of masonry infill walls. Despite a significant volume of experimental and numerical investigations into the seismic behavior of reinforced concrete (RC) frames with masonry infills, the authors are motivated to provide an extensive review of the influence of masonry infill on the seismic behavior of RC frames for the following reasons:

i. Contradictions regarding the impact of strong and weak masonry on the seismic behavior of RC infill frames.
ii. Contradictions concerning the most effective diagonal strut model for inclusion in seismic design codes.
iii. A scarcity of studies available on the combined in-plane and out-of-plane behavior of masonry infill frames in both experimental and analytical research.

The seismic analysis and design of masonry-infilled RC frames necessitate the incorporation of infill wall stiffness and strength into analytical models (Basha et al. 2020). Often, the consideration of infills is omitted in structural analysis and design, even though masonry infill significantly contributes to the building's stiffness, strength, and ductility. Therefore, there is a compelling need to emphasize special attention in structural design and analysis (Sigmund and Peneva 2012, Mohammadi and Nikfar 2013).

Infill masonry walls can alter both the local and global behavior of reinforced concrete frames. These walls experience compression and tension along both diagonal directions, and the high shear stress in the wall can lead to mortar and brick bond failure. These actions increase the complexity of the frame's behavior, which can be attributed to the compatibility issue between the bending-dominated frame and the shear-dominated infill walls (Lee et al. 2021). Further the strength of masonry infills plays a vital role in failure pattern of the masonry-infilled RC frames. Infill walls also play a significant role in enhancing energy dissipation capacity as they reduce energy dissipation demands on frame members and significantly decrease maximum displacement. In general terms, infills serve as the first line of resistance under moderate and strong motions (Nicola et al. 2015). The objective of this article is to provide a comprehensive review of research results, encompassing experimental and numerical investigations, and models developed for determining seismic design parameters such as stiffness, time period, and ductility of masonry structures. Consequently, the paper also delves into the behavior of masonry structures under seismic loads, as studied by various researchers.

REVIEW METHODOLOGY

In this study, a well-defined, structured, and systematic review methodology, as proposed by Kitcharoen (2004), was adopted to study the influence of masonry infill on the seismic behavior of RC frames and its implications on the seismic design approach. The structure of this paper is divided into four sections such as systematic review study selection, findings, and discussions on three aspects, critical findings, and possible future research (Fig. 2).

Systematic Review Study Selection

A systematic literature review was conducted on two international databases, such as Scopus and Web of Science (WoS), using the keywords: masonry AND (infill* OR infill*) AND (seismic* OR earthquake*) AND (reinforced AND concrete) AND frame). The electronic search identified a total number of 1303 articles (Web of Science=459 and Scopus=844). An initial screening was conducted based on the three inclusion criteria, namely (a) articles on engineering topics; and (b) articles in the English language. Therefore, of the remaining 1073 papers, 350 duplicate papers have been removed.

The remaining 723 articles were screened using a two-step review process (step 1: title and abstract review and step 2: full text review), and 75 articles were screened. Some important articles and important standards that were not identified in the above process were included in the literature review. Finally, 93 articles were selected for qualitative and quantitative analysis and critical discussion. Fig. 3 presents a summary of the study selection strategy.

A comparative source analysis of publications is presented in Fig. 4. The source includes peer-reviewed international standard journals, conferences, and recognized publishers of standards and codes. Journals with more than two publications were selected and presented in Fig. 4. Thus, more than 19 journals have publications of more than two. This paper presents a review of 93 articles, most of which focus on analytical and numerical investigations and experimental investigations (Fig. 5). Some important review articles were also included in this study. Fig. 6 shows the number of selected articles published in a specific year between 2000 and 2021. Of all articles, more than 75% of the articles were published in the last ten years. This data underlines how the importance of research on the behavior of RC frames with infill walls has recently increased.

VOS Viewer is a powerful tool for bibliographic analysis, developed by Nees Jan van Eck and Ludo Waltman (van Eck and Waltman 2010) at the University of Leiden. The co-occurrence keywords of the authors of the selected papers were analyzed with the help of the VOSviewer software (version 1.6.5), and the co-occurrence network analysis was presented in Fig. 7. For the analysis of the network, the author selected keywords based on the condition of at least four occurrences. Thus, 29 keywords met the criteria mentioned above and had the most occurrences. The analysis shows that there are 5 clusters with more than 5 elements, with a connection strength greater than 15. Some important keywords are reinforced concrete, masonry, infilled frame, and stiffness. Among the five clusters, the strongest relationships in terms of keyword occurrences are between “infilled frames” and “reinforced concrete”, “masonry infills”, “stiffness”, “cyclic loading” and “seismic performance”, and “seismic response”.

REVIEW OF EXPERIMENTAL STUDIES

Many researchers have conducted experimental campaigns to study various behaviors such as load deformation characteristics, hysteresis behavior, strength improvement/degradation, stiffness improvement/degradation, energy dissipation capacity, effect of infill openings and aspect ratio. Table 1 summarizes the materials used, the type of tests conducted by the researchers and other structural behaviors of the RC frames. The large amount of research has been broadly divided into two categories based on the load types, namely in-plane (IP) loading, and out-of-plane (OoP) loading and are reviewed in subsequent sections.

In-plane Test

Most researchers have studied the behavior of RC frames under lateral monotonic and cyclic loading (Alwashali et al. 2017, Bash & Kaushik 2016, Basha et al. 2020, Bergami and Nuti 2015, Bob et al. 2016, Char et al.2002, Jiang et al.2015, Kakaletsis and Karayannis 2007, Kakaletsis and Karayannis 2008, Maidiawati et al.2018, Misir et al.2012, Ning et al.2019, Pujal and Fick, 2010, Schwarz et al. 2015, Siddiqui et al. 2015, Sigmund and Penava et al. 2013, Tanjung et al. 2017, Teguh, 2017, Van and Lau, 2021, and Wang et al. 2020). Interesting conclusions have been drawn on the positive and negative contribution of infills in the RC frame system to the overall behavior of the system. The following paragraphs present an overview of these studies based on different controlling parameters.

Effect of infill strength

Some researchers (Kakaletsis and Karayannis 2007, Siddiqui, et al. 2015, Teguh, 2017, Wang et al. 2018) have shown interest in studying the effect of masonry strength on the seismic performance of RC frames. During an experimental program, Wang et al. (2018) used low-strength sintered porous bricks and high-strength sintered shale blocks for a comparative study and observed that the reinforced concrete frames with high-strength masonry perform better than those with masonry with low resistance. Similar observations were also reported in another study by Kakaletsis and Karayannis (2008). Siddqui et al. (2015) conducted a detailed investigation of the effect of infills on multi-span frames and concluded that low-strength masonry does not contribute to the damage of the RC infills.

Furthermore, Wang et al. (2018) also reported that high strength masonry does not affect the failure modes of RC filled frames. Teguh (2017) conducted a comparative study using confined concrete blocks and confined bricks. The shear strength resistance capacity of concrete block masonry and weak infill masonry is presented in Fig. 8. Contrary to the observations of Wang et al. (2018) and Siddiqui, et al. (2015), Teguh (2017) observed that strong infill walls resist the collapse of weak or flexible RC frames, as illustrated in Fig. 8. Kakaletsis and Karayannis (2008) conducted cyclic tests on masonry infilled RC frame, and the experimental results show that the loss of energy dissipation capacity of strong infill materials is substantially lower than in RC frames with weak masonry.

In a major investigation, Jiang, et al. (2015) reports that the RC frame with rigidly connected masonry poses high lateral strength, stiffness and energy dissipation capacity compared to the RC frame with the flexible connection. However, rigid connections drastically reduce the displacement ductility ratio. As with the construction methodology adopted for multi-storey apartment buildings, the connection between the masonry infills and the reinforced concrete frame is partly flexible and partly rigid in nature, therefore, more experimental studies are needed to conclude and develop a guideline on the effect of the flexible connection on the deformation and especially on the stiffness of RC frames.

Effect of Infill Stiffness

Numerous experimental investigations have been conducted on the improvement of the stiffness of RC frames at various levels of lateral drifts (Al-Char et al. 2003, Maidiawati et al. 2018, Basha et al. 2020, Ricci et al. 2018, Van and Lau 2020, Kakaletsis and Karayannis 2007, Tanjung et al. 2017, Risi et al. 2019, Akhaoundi et al. 2018, Schwarz et al. 2015, Wang et al. 2018, Misir et al. 2012, Jiang et al. 2015, Ning et al. 2019, Kakaletsis and others Karayannis 2008, Bob et al. 2016). The secant stiffness is defined as the slope of the line connecting the origin and the peak point of the envelope. Van and Lau (2010) observed that the presence of infill acts as a reinforcement resulting in an improvement in strength and stiffness compared to the bare RC frame (Huang et al. 2016, Tanjung et al. 2017).

Researchers have shown great interest in studying the effect of drift (%) on lateral stiffness. At large in-plane lateral displacements, the lateral force also increases significantly (Ning et al. 2019). The reinforcement provided in the masonry was found to have a negligible effect on the stiffness of the RC frame (Tanjung et al. 2017). In a major advance, Onat et al. (2016) experimented on frames with reinforced and unreinforced designs and observed that infills with reinforced joint carries 38% more load than the unreinforced types subjected to in-plane loading. Van and Lau (2020) investigated the strength and stiffness behavior of bare and infilled frames under monotonic and cyclic in-plane loading and found that the load carrying capacity of bare frames and infilled frames does not depend on the type of loading.

Stiffness degradation

Stiffness degradation is a phenomenon associated with an increase in lateral displacement. As stated earlier, the lateral stiffness of RC frames increases due to the reinforcing action of the infills, however, with an increase in lateral displacement, the infills experience diagonal cracking after a certain level of drift (Ning et al. 2019). Gradually the diagonal cracks are interconnected, and the reinforcing action is weakened resulting in a drastic degradation of stiffness (Van and Lau 2020). A typical stiffness degradation curve obtained from the experimental investigation is presented in Fig. 9.

Effect of Energy Dissipation Capacity

Energy dissipation capacity is a critical parameter for assessing the performance of infilled frames under dynamic events. It is associated with cyclic loading and is represented by the area enclosed by the loading and unloading phases in a hysteresis curve. Misir et al. (2012) calculated the total area enclosed by each hysteresis loop at the same target drift level.

Numerous cyclic studies on RC frames indicate that energy dissipation capacity decreases with successive loading cycles (Kakaletsis and Karayannis 2008). However, infilled RC frames generally demonstrate superior energy dissipation capacity compared to bare frames (Huang et al. 2016). In-depth investigations by Basha and Kaushik (2016) further revealed that ductile RC frames exhibit 20% higher energy dissipation compared to non-ductile RC frames.

The improvement in energy dissipation capability is quantified through the "Energy Dissipation Ratio (EDR)," which represents the ratio of infilled frame energy dissipation to bare frame energy dissipation. Table 2 provides a summary of energy dissipation ratios from studies conducted by various researchers. Notably, Bob et al. (2016) discovered that an RC infilled frame with ceramic blocks exhibits an energy dissipation capacity 2.65 times higher than the minimum requirement.

Moreover, the contribution of masonry infills to energy dissipation becomes even more significant under higher intensity ground movements (Siddiqui et al. 2015). This highlights the crucial role of masonry infills in enhancing the energy dissipation capacity of RC frames, particularly during intense seismic events. Overall, understanding and optimizing energy dissipation in infilled frames are vital for ensuring their resilience and performance under dynamic loading conditions.

Failure / Damage behavior

Infilled RC frames can exhibit various failure modes, as demonstrated by several researchers. Teguh (2017) identified diagonal cracking, horizontal sliding, corner crushing, or a combination of these failure modes. Allouzi and Irfanoglu (2018) conducted a study in which they observed critical shear failures and critical bending failures. These failures refer to structural vulnerabilities under shear and bending forces respectively. When a structure experiences shear forces, such as lateral forces or forces parallel to its plane, it can result in shear failure if the shear strength of the material or connections is exceeded. On the other hand, bending failures occur when a structure is subjected to bending moments, causing excessive deformation or failure in the material due to the applied bending stresses. The study by Allouzi and Irfanoglu likely investigated these types of failures in order to understand the behavior and failure mechanisms of structures under different loading conditions, and to propose design guidelines or improvements to enhance their structural performance. Similarly, Kakaletsis and Karayannis (2007) summarized the failure modes as plastic hinge formation, internal strut crushing, shear sliding at joints, shear sliding crack, and corner rocking crushing.

Furthermore, in-plane failure modes observed in these frames include creep shear failure, diagonal cracking failure, diagonal compression failure, and corner crushing failure, as depicted in Fig. 10. Understanding these failure modes is crucial for assessing the structural performance of infilled RC frames and devising effective measures for their strengthening and retrofitting, especially under seismic conditions.

In the literature, several notable observations have been made regarding the damage behavior of infilled RC frames. Ning et al. (2019) reported shear failure at the beam-column junction in their investigations. In situations where the infilled RC frames have rigid connections, the failure mechanism becomes more complex due to the interaction between the masonry and the frame, as highlighted by Jiang et al. (2015).

Additionally, Wang et al. (2018) found that the use of high-strength masonry does not significantly affect the failure modes of RC-filled frames. These findings emphasize the importance of considering different connection types and masonry material properties when analyzing and designing infilled RC frames to ensure their structural integrity and performance under various loading conditions.

It has also been observed that the boundary condition influences the failure modes, load bearing, deformation capacity, and the arching action mechanism. If the infill is bounded on all sides, bi-directional action (which includes horizontal and vertical arching) occurs, resulting in greater load bearing, and deformation capabilities. But if the backfill is bounded by three (infill-beam gap) or two sides (infill-columns or infill-beams gap), one-way action is observed (Anic et al.

2020). Along with it, the load-bearing capabilities are lowered in comparison to the fully bounded ones (Fig. 11).

Out-of-Plane Test

Fewer tests were performed for the out-of-plane seismic behavior of the infills than for in-plane tests. Loss of transverse (out-of-plane) strength in unreinforced masonry infill panels is caused by in-plane cracking that has already occurred. This noteworthy observation was observed by Angel et al. (1994). The out-of-plane strength of masonry panels is significantly affected by the slenderness ratio, with its dependence on the compressive strength rather than the tensile strength of the masonry. Notably, repetitive loads within the elastic region did not result in stiffness degradation for the specimens. Furthermore, the study found that the in-plane shear stress and panel gravity loads had only a minor impact on the initial out-of-plane stiffness, without affecting the out-of-plane strength of the panel.

In their comprehensive study, Lunn, and Rizkalla (2011) conducted 14 tests using Concrete Solid Block (CSB) as the masonry unit to evaluate the effectiveness of various strengthening strategies in improving the out-of-plane behavior of infill masonry walls. The results highlighted that the glass-fiber reinforced polymer (GFRP)-reinforced infill masonry walls showed significant improvements in their out-of-plane capacity. Furthermore, researchers advocated the use of steel rods as anchors between the masonry infill wall and the reinforced concrete frame, underlining its potential to reduce the risk of premature failure caused by shear creep in the masonry infill. reinforced. Previously, such failures were observed in the form of cracking or crushing. This novel approach offers promising benefits for improving the overall structural performance and durability of the infilled masonry system.

Butenweg et al. (2019) conducted a combined in-plane and out-of-plane experiment in full-size RC frames filled with high thermal insulation clay bricks. At the conclusion of the experimentation, the authors underlined that the boundary conditions in the connection area between the infill panel and the frame are crucial points for the seismic damage of the infill panels. It is also suggested to integrate the traditional installation of infill walls in full contact with the frame by implementing new innovative systems with which it is possible to reliably obtain the required seismic safety.

Anic et al. (2020) compared two studies by different researchers and came to a noteworthy conclusion, as illustrated in Fig. 12. The force-displacement curve in the figure demonstrates the relationship between the applied forces and the resulting out-of-plane deflection by considering the influence of boundary conditions. Their analysis revealed that a weaker connection between the infill and the frame leads to a significant decrease in both bearing capacity and deformation capabilities. Furthermore, comparing the force-displacement curves of Dawe and Seah (1989) and Di Domenico et al. (2018), substantial variations in initial stiffness and strain capacities were observed across different boundary conditions. In particular, both studies showed a significant reduction in deformation capacities. These discrepancies can be attributed to the slenderness of the samples, with Dawe and Seah (1989) employing thicker panels than those used in Di Domenico et al. (2018). Furthermore, it should be emphasized that samples containing gaps in the packing column interface exhibited brittle behavior, leading to crushing shortly after reaching peak loading.

The out-of-plane behavior of in-filled RC frames has attracted considerable attention among researchers, especially after experiencing some degree of damage or drift in in-plane loading. Table 3 provides a summary of the out-of-plane modulus or stiffness of masonry infills studied by various researchers. It includes specific equations used to evaluate important aspects of the behavior of masonry infills. For example, it presents the out-of-plane secant modulus equation proposed by Akhoundi et al. (2018) and the stiffness after the in-plane degradation equation introduced by Ricci et al. (2018). These parameters offer valuable information on the stiffness characteristics of masonry infills perpendicular to their plane and consider the impact of deformation or damage in the plane. Researchers can refer to these equations to inform their studies and better understand the behavior of masonry infill walls in structural analysis and design. (Akhoundi et al., 2018, Ricci et al., 2018).

The study by Angel et al. (1994) revealed that prior in-plane (IP) damage could lead to up to a 50% reduction in the out-of-plane (OoP) bearing capacity of thin panels. Several studies, including Akhoundi et al. (2018) and Furtado et al. (2016), point out that previous in-plane damage affects the deformation behavior of RC frames with infill walls. However, conflicting results come from researchers such as Henderson et al. (1993) and Flanagan and Bennett (1996), who investigated the impact of prior drift damage between OoP planes on in-plane (IP) bearing capacity (OoP + IP). Both studies concluded that prior OoP damage drifting between floors had a significantly smaller effect on overall in-floor performance, particularly in terms of capacity. This is in line with the results of a recent investigation by Anic et al. (2020). Again, High workmanship plays a vital role in the global behaviour of masonry-infilled RC frames, and it should be taken into account in the analysis of the frames (Fartudo et al., 2020).

Effect of Openings

The behavior of masonry structures is significantly influenced by the presence of openings, as practical considerations often require that the masonry have openings which are shown in Fig. 13. Consequently, conducting a comprehensive study of both types of masonry structures becomes imperative for a correct understanding of the behavior of reinforced concrete frames with masonry infill. Brief reviews of the behavior of both types of masonry structures are provided in the following sections to facilitate a better understanding of their characteristics.

Infilled masonry frames with openings have received less research attention than frames without openings. However, Kakaletsis and Karayannis (2008) conducted a remarkable study in which they explored the importance of different opening properties on reducing the strength, stiffness, and energy dissipation capacity of filled frames. The overall finding suggests that the openings actually decrease the lateral resistance of the infill frames and alter the load distribution within the infill panel. Consequently, understanding the behavior of infilled masonry frames with openings becomes crucial due to the significant influence these openings have on the overall structural response.

Kakaletsis and Karayannis (2007) conducted a study on masonry infill walls with eccentric openings and their influence on the seismic performance of RC frames. It has been observed that infills with openings tend to crack and separate from the surrounding frames at an early stage before failure of the column reinforcement occurs. In particular, when the opening was positioned close to the edge of the infill, it was found to be beneficial to the overall performance of the infill frame. Placing the opening close to the edge of the infill significantly improves the performance of the infill frames. This placement promotes a more effective mechanism of energy dissipation through friction, which occurs primarily through gaps in the filler and bounding frame. Larger columns facilitate better distribution of cracks throughout the wall, further aiding energy dissipation. Conversely, when the opening is in the center of the infill along the loaded diagonal, the tensile strength of the infill decreases internally, resulting in more stack deterioration at low drift levels. The energy dissipation mechanism described above is less evident in the case of smaller cells.

In a subsequent study, Kakaletsis and Karayannis (2008) investigated the lateral force of frames filled with openings compared to bare frames. They found that the lateral strength of the infilled frames with openings was 1.33 to 1.54 times higher than that of the bare frames. Furthermore, the strength of the weak solid and strong solid masonry infilled frame was found to be 1.84 and 1.65 times greater than that of the bare frames. These results highlight the significant impact of eccentric openings and masonry infills on the overall strength and performance of reinforced concrete frames.

Mohammadi and Nikfar (2013) conducted a statistical analysis of the experimental data to derive an empirical equation for the stiffness (Eq. 1) and strength (Eq. 2) of infilled masonry frames with a central opening. By analyzing the data, they aimed to establish a practical equation that could effectively predict the stiffness and strength of such frames with an opening in the center.

$$\text{Strength } (R_f) = \begin{cases} -1.085\frac{A_0}{A_p} + 1, \ \text{for} \frac{A_0}{A_p} \leq 0.4 \ \text{RC frame} \\ -2.122\left[\frac{A_0}{A_p}\right]^2 + 1, \ \text{for} \frac{A_0}{A_p} \leq 0.25 \ \text{Steel frame} \end{cases} \quad (1)$$

And,

$$\text{Stiffness } (R_k) = 1.1859\left[\frac{A_0}{A_p}\right]^2 - 1.6781\frac{A_0}{A_p} + 1, \text{for } A_0 < 0.4A_p \quad (2)$$

Where, R_f and R_k are the strength reduction factor and stiffness reduction factor respectively. Similarly, A_o and A_p are the area of the opening and infill panel respectively.

According to Al-Chaar et al. (2002), in situations where infilled masonry frames have central openings, the behavior may vary according to the size of the opening. The corners of an opening in a structure may have a strut mechanism when the size of the opening is suitable. This occurs when the geometry and size of the opening facilitate the formation of strong corner elements that effectively resist and distribute the applied forces. Research conducted by Al-Chaar et al. (2002) highlights that infilled frames with openings often exhibit cracking and detachment from surrounding frames in an early stage, occurring before column reinforcement failure. In particular, their observations point out that when the opening is located near the edge of the infill, it produces the most beneficial results for the overall performance of the infill frame. This implies that the specific placement of the opening can play a crucial role in improving the structural behavior and resilience of the infilled frame system.

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In the study conducted by Wardi et al. (2018), the impact of different types of openings on brick infill frames was investigated. For frames with one central opening and two openings each occupying 25% of the panel area, the lateral resistance of the infilled solid frame was reduced to 58%. Additionally, the stiffness of the infilled frame decreased by 70% and 40% for single and double openings, respectively. The opening ratio, which represents the ratio of the opening area to the infill panel area, showed an inverse relationship with frame capacity, indicating that as the ratio increases, the lateral resistance of the frame decreases. However, despite this reduction in frame capacity, the same opening ratio was observed to have a positive effect on ductility, as reported in a separate study by Schwarz et al. (2015). Al-Chaar et al. (2003) introduced a specific reduction factor (Eq. 3) for the in-plane, which can be used as a multiplier to account for the influence of the opening size in the analysis.

$$(R_1)_i = 0.6\left(\frac{A_{open}}{A_{panel}}\right)^2 - 1.6\left(\frac{A_{open}}{A_{panel}}\right) + 1 \qquad (3)$$

Here, the variable,$(R_1)_i$, is the in-plane reduction factor that accounts for the presence of infill openings.

The study conducted by Wang et al. (2018), it has been underlined that the presence of openings in the wall enhances the deformation capacity and ductility of the frames. In particular, it is noted that by comparing different types of openings, an eccentric opening in the wall has a lesser effect on the behavior of the frame than a concentric opening. Similarly, Kakaletsis and Karayannis (2008), in their investigation of single-span reinforced concrete frames with reinforced concrete walls containing door and window openings, also reported a similar observation. Both studies pointed out that the nature and location of openings play a crucial role in influencing the behavior of reinforced concrete frames, with concentric openings having a more pronounced impact than eccentric ones.

REVIEW OF ANALLYTICAL AND NUMERICAL MODELS

Many approaches have been developed for infill masonry modeling by which the possible failure mechanism in the infilled concrete frame can be identified. Two common approaches are the micro modeling approach and the macro modeling approach. Various types of macro and micro modeling approaches have been shown in Fig. 15. Table 4 presents several similar studies where analytical and numerical modeling is adopted. The studies are classified according to the type of modeling approach used, the types of masonry, the types of loads and the model used for infill, respectively.

Micro modelling technique

It is a detailed strategy in which all the elements that make up the wall are modeled. A neat approach within micro-modeling might be to reduce the number of elements by combining the brick with the surrounding mortar which is then connected to the rest using connecting models. All these approaches can be considered expensive both in terms of modeling and in terms of computational needs, especially when applied to dynamic and nonlinear analysis. This detailed modeling allows us to obtain a result that helps us understand the local-level behavior and cracking pattern of the panel, which can be useful for global model calibration and for performing parametric studies. Hence, it is an important advantage of micromodels over simplified macro-models. Likewise, this modeling procedure allows us to evaluate the influence of each parameter on the seismic response of the infill panel. Micro-modeling is believed to have begun in 1967 with work done by Mallick and Severn (Mallick and Severn 1967, Asteris et al. 2013, and Furtado and de Risi 2020).

Chen and Liu (2015) developed a finite element model to simulate the IP behavior of concrete masonry infills bounded by steel frames with openings. The authors demonstrated that the model had the ability to simulate experimental tests with high accuracy. The finite element model has clear advantages for describing the behavior of filled frames and local effects related to cracking, crushing and contact interaction. In order for the model to be realistic, the constitutive relationships of the different elements must be adequately defined and the non-linear phenomenon in the masonry infills and in the interfaces of the panel frames must be adequately considered (Crisafulli et al. 2000). Some other micromodels are the distinct element method, which was originally developed for fractured rock. It allows the study of articulated lorries subject to static or dynamic loads.

Macro modelling technique

Single diagonal strut pattern and double diagonal strut pattern are two popular techniques adopted in macro modeling approach. Macro modeling with equivalent diagonal struts was believed to have been originally developed to improve numerical analysis models of infilled frames with high shear stiffness. After its evolution with multi-struts designs, it was able to integrate shear and tensile stresses within the contact length between wall and frame. The models started to become more complex, with some considerations regarding stiffness and shear strength reduction under dynamic loads. The other equivalent approaches also consider shear slip at the center of the infill walls. One of the aspects that has not yet been developed is the out-of-plane (OoP) behavior itself, which is an even more important problem when combined with the diagonal cracking created by in-plane (IP) demands on masonry infill walls (Furtado et al ., 2020).

According to Murty and Jain (2000), the induction of masonry infills in the RC frame is responsible for the change of the lateral load transfer mechanism of the structure from predominant frame action to predominant truss action (as shown in Fig. 16) which reduces the bending moment and increases the axial forces in the frame member.

In the past, researchers have found simplified methods to simulate the lateral action of the infilled masonry wall. The most commonly used method is the diagonal strut method, which is connected diagonally to opposite compression corners of the frame.

Both Crisafulli (1997) and Fiore et al. (2012) conducted studies comparing different post designs in masonry-filled RC frames. From Crisafulli's investigation, it was concluded that the double strut method offered a balanced approach with accurate results, avoiding excessive complexity in evaluation and calculation. Fiore et al. compared single and double diagonal strut models in buildings with a soft ground level and found that the behavior of the double diagonal strut model better explained both global displacement and local bending moment with shear force. In summary, both studies support the idea that the diagonal double strut approach is favourable, providing a more accurate representation of the behavior of infilled masonry reinforced concrete frames without introducing unnecessary complexity into the analysis.

In addition to post models, another approach commonly referred to as "beam analogy" or standard elastic theory was considered to evaluate horizontal displacements in masonry filled RC frames. This method considers the contributions of the whole system and is based on the bond strength developed at the interface between the masonry infill panel and the surrounding frame (Crisafulli et al., 2000). The validity of the "beam analogy" model depends on the effectiveness of the bond between the infill panel and the frame. It offers an alternative way to evaluate the behavior of infilled concrete frames and can be a useful tool in cases where detailed modeling of posts may not be practical or necessary. However, it is important to ensure that bond strength is accurately considered to obtain reliable results using this approach.

Published literature (Madan & Hashmi, 2008; Allouzi & Irfanoglu, 2018) on analytical modelling of MI RC frames performs both static and dynamic analyses to assess the behavior of masonry infilled RC frames. Static analysis may involve pushover analysis to determine capacity curves, while dynamic analysis considers the response of the structure to ground motion.

Madan & Hashmi, 2008 shows that displacement based nonlinear analysis of MI RC frames will predict the response in a better way. In their analysis using the capacity spectrum method, it is observed that the MI RC frame is severely affected if the infill panels are discontinued in the ground storey. Their study shows that partial infill RC frames results in drastic reduction of seismic damage. Though Infills significantly contribute towards the bending moment (Fiore et al., 2012), the compressive strength, stiffness, and the connection of infills and RC frames plays a major role in the development of bending moment. However, Allouzi and Irfanoglu (2018) have found that weak infills results in critical flexural failure and strong infills results in critical shear failure. Inclusion of infills would significantly enhance flexural-controlled hysteresis loops of ductile RC frames without infills to concave-shaped shear-controlled loops (Yuen and Kuang, 2015). Fig. 17 shows a typical lateral load-displacement behaviour of bare frame, flexure critical and shear critical frame behaviour. Masonry infill walls results in substantial enhancement of base shear. Though the percentage increase depends on the ground motion frequency content and its amplitude. Abdelaziz et al. (2019) studied that the base shear of infilled frames increases by 1.5-4.5 times as compared to bare frames. Shear failures in masonry infills can lead to a sudden loss of capacity and a reduction in ductility. This can result in brittle behavior during seismic events, which is undesirable because it limits the structure's ability to dissipate seismic energy through inelastic deformation.

In the design of masonry infill concrete frames, the geometrical and mechanical properties of the infill materials play a crucial role due to the variability of infills used worldwide. To ensure accurate and reliable design, it is essential to consider key parameters such as infill properties when evaluating the period. This approach is commonly recommended in the literature (Crisafulli et al., 2020).

Perroni et al. (2016) investigated this modeling and highlighted that filler material properties should not be neglected. In this investigation it was pointed out that the Young's modulus of the infill material significantly influences the time period of the frames. Considering these properties in the design process is important to predict the dynamic response and overall behavior of RC frames more accurately with masonry infill. By considering the variability of infills and their mechanical characteristics, engineers can make informed decisions to ensure the safety and reliability of structures.

REVIEW OF CODES ON DESIGN OF MASONRY INFILLED RC FRAMES CODAL PROVISIONS

Country codes can be basically differentiated into 2 groups. One considers the role of masonry infill in the design of the RC frame and the other does not. IS 13920 (BIS 2016), Eurocode 8 (EC 2004) and ASCE 41 (ASCE 2013) consider the effect of masonry infill in the design of reinforced concrete frames. However, NZS-3101 (2006) recommends insulation of masonry infill walls and therefore masonry infill is not considered during the design and analysis. Most of the regulations allow static analysis methods for typical small buildings, while dynamic analysis is often recommended for other types of buildings. But many regulations often limit the use of the design seismic force obtained from the dynamic analysis as it does not deviate much from a minimum value based on the empirical estimate of the natural period prescribed by the regulations. This restriction prevents the design of buildings for unreasonably low forces that could arise from various uncertainties involved in a dynamic analysis (Kaushik et al. 2006). Basha and Kaushik (2016) reported that current regulations may not effectively prevent shear failure in reinforced concrete columns of infilled frames, particularly in cases where the infills are weaker than the surrounding frame. This underscores the importance of considering the interaction between the frame and the fill to prevent potential failure modes. On the other hand, Huang et al. (2016) conducted a detailed investigation and concluded that the design moment and shear values need to be improved in filled frames due to the local filling effect. This suggests that the presence of infills can significantly affect the distribution of forces within the structure and that adequate design adjustments are needed to ensure the overall structural integrity. In summary, both studies underline the importance of considering the behavior of infilled frames and of making the appropriate design modifications to guarantee their structural safety, each addressing different aspects of the same problem.

Brick masonry infill reinforced concrete frames are considered "dual" systems by Eurocode 8 and are classified in high, medium, and low ductility classes where the effect of infills is neglected for the low class. Three-dimensional models are recommended for analyzing the arrangement of infill walls which cause serious irregularities in the plan. In addition, there is a provision for accidental runout which is increased by a factor of 2 if the irregularities are not so severe. Similarly, the Indian Seismic Code (IS-1893 2016) recommends linear elastic analysis of bare frame excluding the effect of brick fill.

Various codes provide their own guidelines for dealing with masonry infill, tailoring their recommendations to the specific environmental and regional conditions they encounter. When it comes to calculating the natural period of masonry infill structures, several regulations offer empirical formulas that can be applied in their respective contexts.

According to ESCP-1 (1983), NBC-105 (1995), IS-1893 (2016) the empirical formula (Eq. 4) for the calculation of natural period of masonry infilled RC frame is given by

$$T_a = \frac{0.09h}{\sqrt{d}} \quad (4)$$

Where, T_a is in s and $\boldsymbol{h}$, d (height, base dimension) are in meters.

Code of standards like Eurocode 8 (2004), NSCP (2015), NSR-98 (1998) also recommends the Rayleigh formula (Eq. 5) for the calculation of natural period.

$$T_a = 2\pi \sqrt{\frac{\sum_{i=1}^{N} W_i \times (\delta ei)^2}{g \sum_{i=1}^{N} F_i \times \delta ei}} \quad (5)$$

Where, W_i is the seismic weight, δei is the elastic displacement, Fi is the seismic force and g is the acceleration due to gravity.

Alegerian code (2015) suggests the value of T_a (Eq. 6) to be taken as the smallest between the two-expression mentioned below,

$$T_a = \frac{0.09h}{\sqrt{d}} = 0.05h^{0.75} \quad (6)$$

Similarly, when it comes to openings in masonry infill walls, only a few codes have mentioned them and NBC-203 (2015) and Eurocode 6 (2006) are among them.

According to NBC-203 (2015), for one-story buildings, openings are limited to 30% of the total wall length, and openings are limited to 25% of the total wall length for two-story buildings. Likewise, they indicated that the openings should be located away from the internal corner at a clear distance equal to at least $1/4^{th}$ of the height of the openings, but not less than 600mm.

As per Eurocode 6 (2009), when breaks occur in a stiffening wall due to the presence of openings, specific guidelines are given to determine the minimum wall length between openings. These guidelines are illustrated in Fig. 18. Furthermore, Eurocode 6 emphasizes that the stiffening wall should extend at least $1/5^{th}$ of the storey height beyond each opening. This widening is critical as it ensures the continuity and effectiveness of the stiffening wall beyond the openings, thus improving the overall structural performance. Compliance with these provisions contributes to maintaining the structural integrity and stability of masonry structures with interrupted walls of stiffening caused by openings.

After reviewing the design criteria of IS 1893 Part 1 (2016), it is explicitly stated that the variation of stiffness and flat strength of URM (Unreinforced Masonry) infill walls should be carefully examined. If irregularities are identified, the necessary corrections must be made. The recommended approach for modeling URM infills is to use equivalent diagonals and consider the diagonal as a pin joint. Eq. 7 proposed within the code to calculate the diagonal strut properties.

Width of the diagonal strut,

$$W_{ds} = 0.17\alpha_h^{-0.4} L_{ds} \tag{7}$$

Where,
$$\alpha_h = h\left(\sqrt[4]{\frac{E_m \times t \times \sin 2\theta}{4 \times E_f \times I_c \times h}}\right) \tag{8}$$

Where, E_m and E_f are the modulus of elasticity of the materials of unreinforced masonry infill and reinforced concrete moment-resisting frame, I_c is the moment of inertia of the adjoining column, t is the thickness of the infill wall, θ is the angle of the diagonal strut with the horizontal and L_{ds} is the length of diagonal strut.

Similarly, in accordance with the design guidelines, the equivalent strut thickness should be considered as the thickness of the original unreinforced masonry infill. However, this only applies if the height to thickness ratio (*h/t*) and the length to thickness ratio (*l/t*) are both less than 12. Where h is the clear height of the non-masonry infill wall between the upper beam and the lower floor, *l* is the free length of the unreinforced masonry infill wall between the vertical RC elements between which it extends.

Similarly, many expressions have been derived for strut width calculation in the literature and are adopted by different guidelines. Some of these expressions are mentioned below.

The expression (Eq. 9) adopted by FEMA guideline for the calculation of the strut width (*w*) is expressed as

$$w = 0.175(\lambda h_{col})^{-0.4} r_{\text{inf}} \tag{9}$$

Where, λ is the parameter suggested to express the relative lateral stiffness of the frame to that of infill (Eq. 10), h_{col} is the column height in between the centre line of beams and r_{inf} is the infill's length of the diagonal.

$$\lambda = \sqrt[4]{\frac{(E_m t_{\text{inf}} \sin 2\theta)}{4 E_f I_{col} h_{\text{inf}}}} \tag{10}$$

E_m, t_{inf}, h_{inf} are infill young's modulus of elasticity, thickness, and height respectively. E_f and I_{col} is the young's modulus and moment of inertia of the columns respectively. And θ is the angle whose tangent is the infill's height to length aspect ratio. And the expression (Eq. 11) given in CSA S340.1-04 for the calculation of diagonal strut width (w) is

$$w = \sqrt{\alpha_h^2 + \alpha_L^2} \tag{11}$$

Where,

$$\tan\theta = \frac{h_{\text{inf}}}{L_{\text{inf}}} \tag{12}$$

$$\alpha_h = \frac{\pi}{2}\sqrt{\frac{4E_f I_{col} h_{\text{inf}}}{E_m t_{\text{inf}} \sin 2\theta}} \tag{13}$$

$$\alpha_L = \pi \sqrt[4]{\frac{4E_f I_b L_{\text{inf}}}{E_m t_{\text{inf}} \sin 2\theta}} \tag{14}$$

Examining the codal approaches concerning planimetric and vertical irregularities, Eurocode 8 (2003) provides specific provisions to address these problems in seismic design. For slight planimetric irregularities, the law recommends considering the effect by doubling the accidental eccentricity. This adjustment considers minor deviations from regularity in the horizontal distribution of mass and stiffness. However, in cases of severe planimetric irregularities resulting from significant asymmetrical placement of walls or other structural elements with mass and stiffness irregularities, a more comprehensive approach is warranted. In such situations, Eurocode 8 suggests performing a three-dimensional analysis that considers the stiffness distribution related to the uncertain position of mass irregularities (MI).

Similarly, in the Nepal code (NBC-201 1995), the eccentricity between the center of mass and the center of stiffness along each major direction is limited to 10% of the building dimension along that direction. As regards the vertical irregularity, the Indian seismic code (BIS, 2002) requires that the elements with average lateral stiffness of the upper three floors are less than 70% of those of the upper floor or less than 80% of the average lateral stiffness of the three upper floors.

SUMMARY AND FUTURE RESEARCH SCOPE

The motivation behind this revision work was to identify the outcomes of the existing research on the behavior of infilled masonry concrete frames with particular attention to the various available models used and the subsequent discussions and critical findings relating to the geometric and mechanical properties of the structural and non-structural members in the design. After a detailed review process, the following important findings are observed that needs further attentions from the researchers;

- Seismic design codes of many countries neglect the contribution of masonry infills in the resistance of lateral loads. But many research highlighted that it does have a positive impact too and hence suggested not to neglect the influence of masonry infills for the proper analysis of a structure.
- Inclusion of strong masonry infills results in high base shear and leads to shear critical failure behaviour. Shear failure can significantly reduce the lateral load resistance of the structure. Masonry infills are commonly used to enhance the lateral stiffness and strength of RC frames. When shear failure occurs, this enhancement is compromised, making the structure more susceptible to excessive lateral drift and displacement during an earthquake. Thus the response reduction factor of MI RC frames is found to be higher than bare frames.
- The presence of opening significantly affects the performance of masonry infilled frame structure under the lateral loading. It results in reduction of strength and stiffness of the MI RC frames. However, its presence was found to be beneficial to the performance of the infilled frame if it was near to the edge of the infill. Indian Seismic Code (IS 1893 (Part 1): 2016), do not address the effect of infills considering the irregularities and openings. The equation proposed by Mohammadi and Nikfar (2013) can be considered to assess the modified strength and stiffness of RC frames considering the opening of MI RC frames.
- The use of dowels bars while connecting the infilled masonry wall with the frame were found to be beneficial for minimizing the failure.

- Since there is a variability of infills utilized worldwide, the role of geometrical and mechanical properties of infills were found to have importance in the seismic behaviour of the structure.

Based on the above discussions, several future research possibilities can be proposed that can be considered for the seismic performance evaluation of RC frames with masonry infill, highlighted below;

- In-plane reduction factor can be considered for inclusion in the standards/codes to address the effect of the opening size for both in-plane and out-of-plane testing.
- Despite many efforts to study the behaviour of RC infilled frames, the inclusion of suitable models in specifications/codes/standards are still an open issue. As the double diagonal strut model has demonstrated its efficiencies to explain the global behavior RC buildings in terms of bending moment and shear force, this model can be encouraged to considered in the design codes.
- Combined in-plane and out-of-plane behavior of masonry infill frames needs attention in both experimental and analytical research.
- Several infilled frame strengthening techniques are available but cost-efficient and strengthening technique providing high seismic safety needs more attention.
- Various available techniques on seismic protections of infilled masonry frames using mass damper, fraction dampers, viscous dampers, yielding dampers, magnetic damper needs to be investigated and cost-efficient solutions to be proposed.

DATA AVAILABILITY STATEMENT

All data, models, and codes that support the findings of this study are available from the corresponding author upon reasonable request.

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Fig. 1: Basic layout of masonry infilled RC frame.

Fig. 2: Structure of the Review Paper.

Fig. 3: Systematic review study selection.

Fig. 4: Distribution of selected articles among journals.

Fig. 5: Types of research on seismic behavior of infilled RC frames.

Fig. 6: Year wise number of articles selected for the study.

Fig. 7: Co-occurrence analysis of authors keywords (minimum 4 occurrences).

Fig. 8: Envelope of hysteresis loop for RC frames with strong and weak infill (Teguh, 2017).

Fig. 9: Stiffness degradation curve (Van and Lau 2020).

Fig. 10: (a) frame failure, sliding shear and diagonal cracking; (b) corner crushing and diagonal compression for infilled RC frames under in-plane load (Nicola et al. (2015).

Fig 11: Types of arching action in relation to different boundary condition: (a) Two-way (rigid) arching action; (b) Gapped arching action; and (c) One-way (double-gapped) action.

Fig 12: (a) Pressure-displacement curves by Dawe and Seah (1989); and (b) Force-displacement curves by Di Domenico et al. (2018) considering different boundary conditions.

Fig. 13: Types of openings (partial openings, full openings, and no openings)

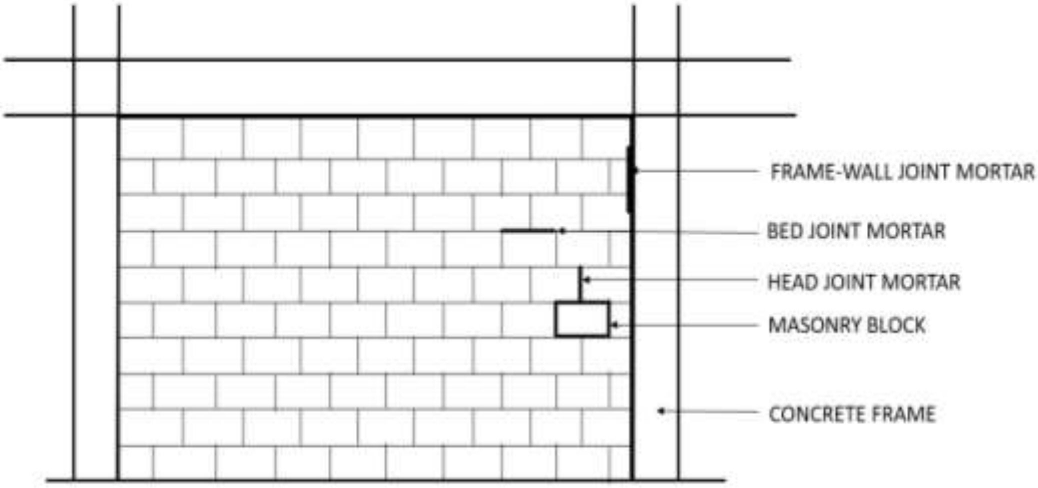
Fig. 14: Strut and tie approach for panels with central openings and partially infilled panels: (a) typical strut-and-tie approach for panels with central openings; and (b) for partially infilled frames (Al-Chaar, 2002).

Fig. 15: Approaches for numerical study of RC infill frames.

Fig 16. Change of lateral load transfer mechanism: (a) predominant frame action; (b) predominant truss action (Murty and Jain, 2000).

Fig. 17: Lateral load-displacement response curve of bare frame, frame with weak masonry infill and frame with strong masonry infill.

Fig. 18: Minimum length of the wall between the openings as per Eurocode 6.



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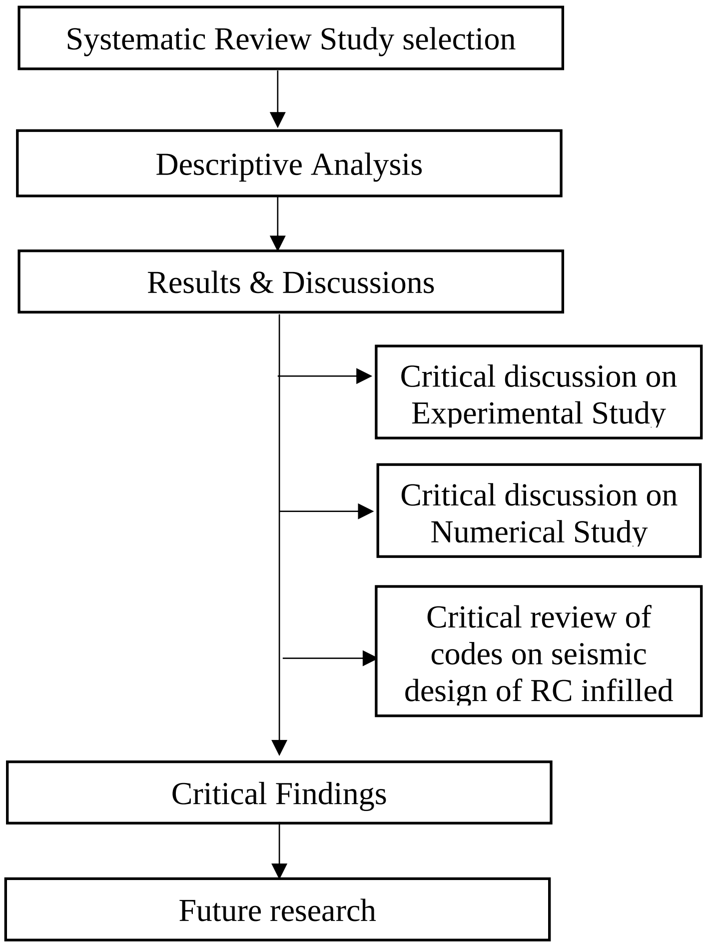

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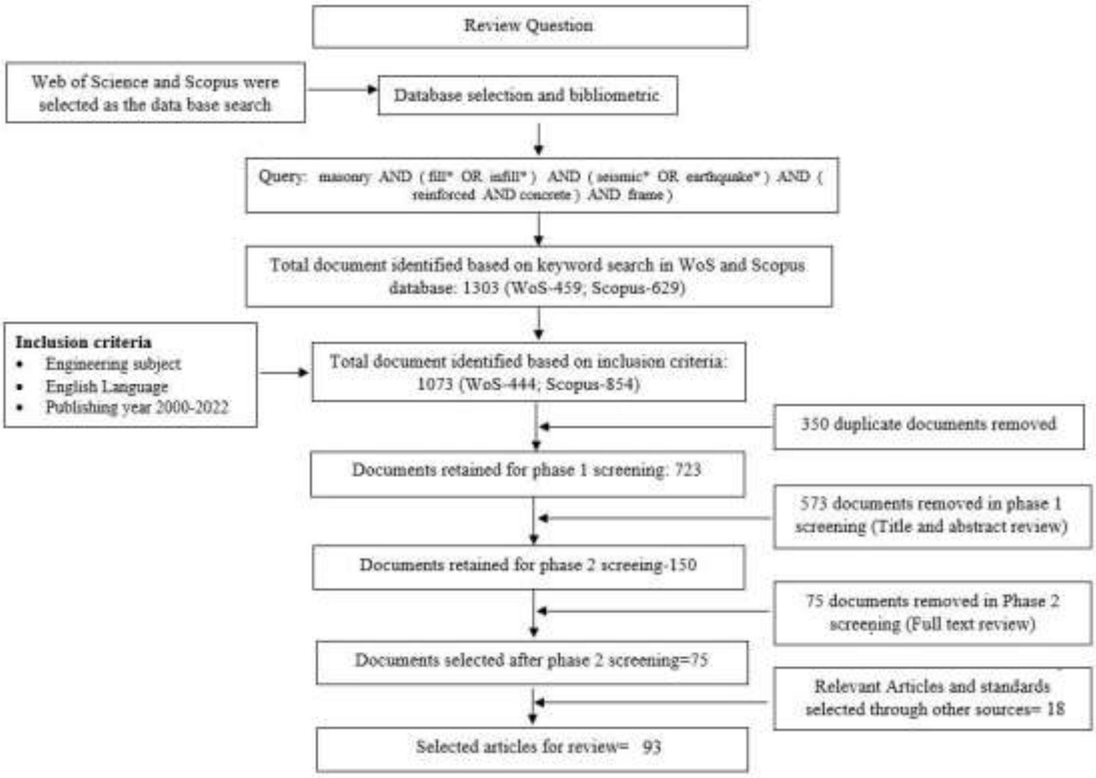

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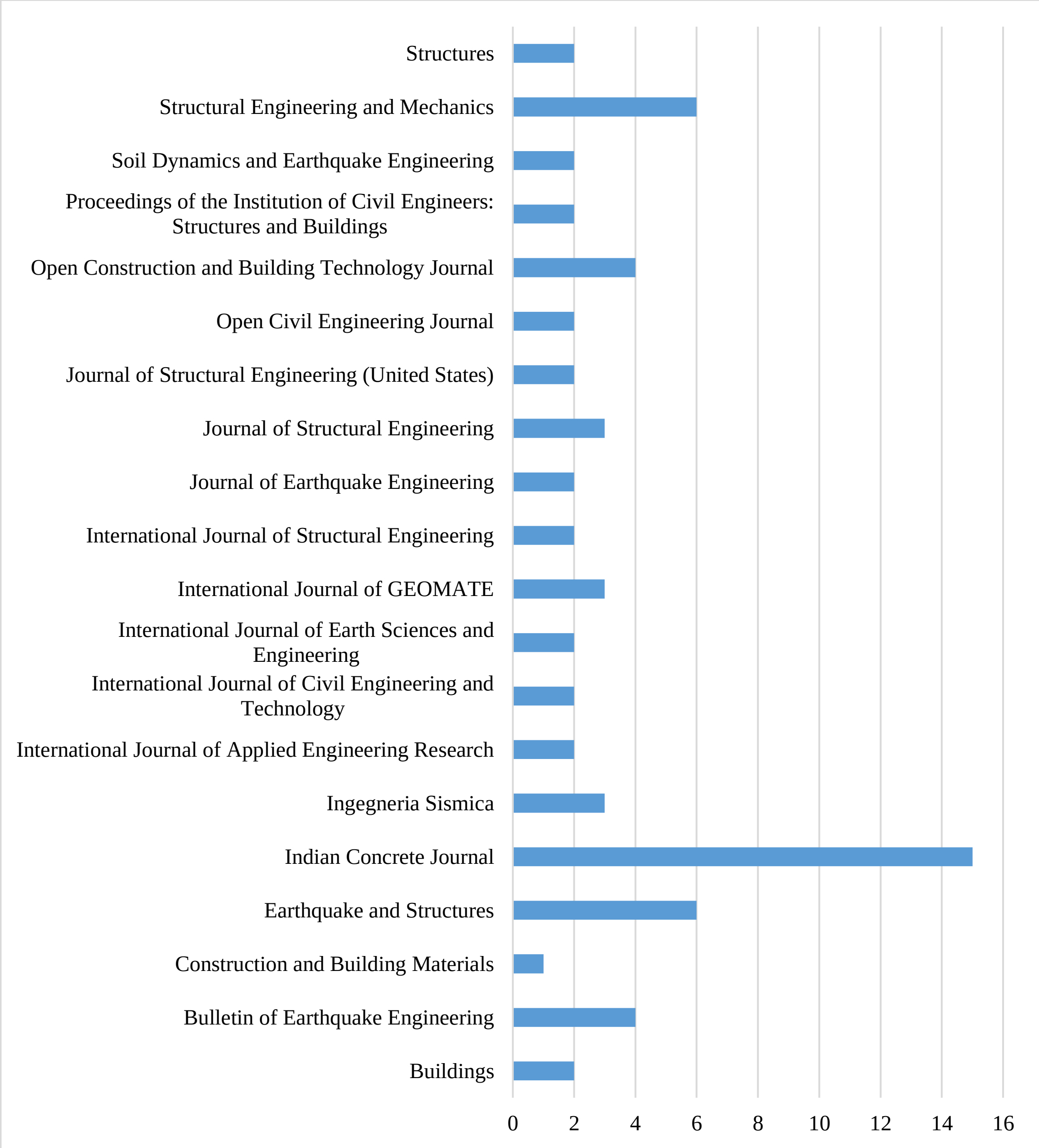

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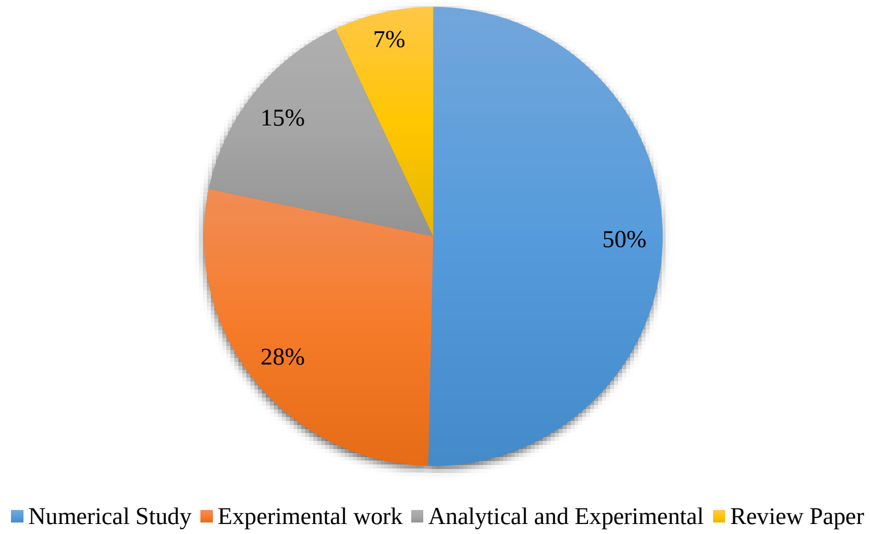

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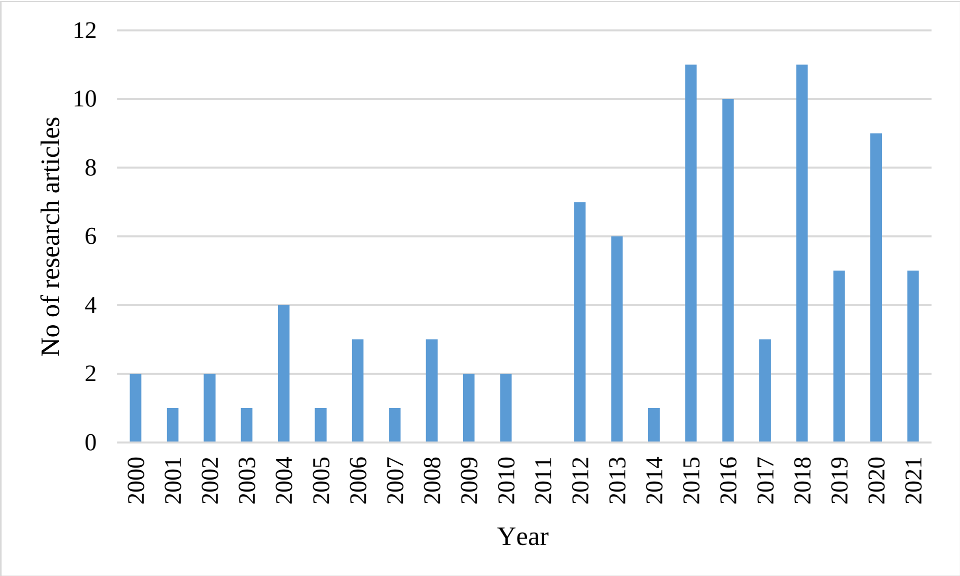

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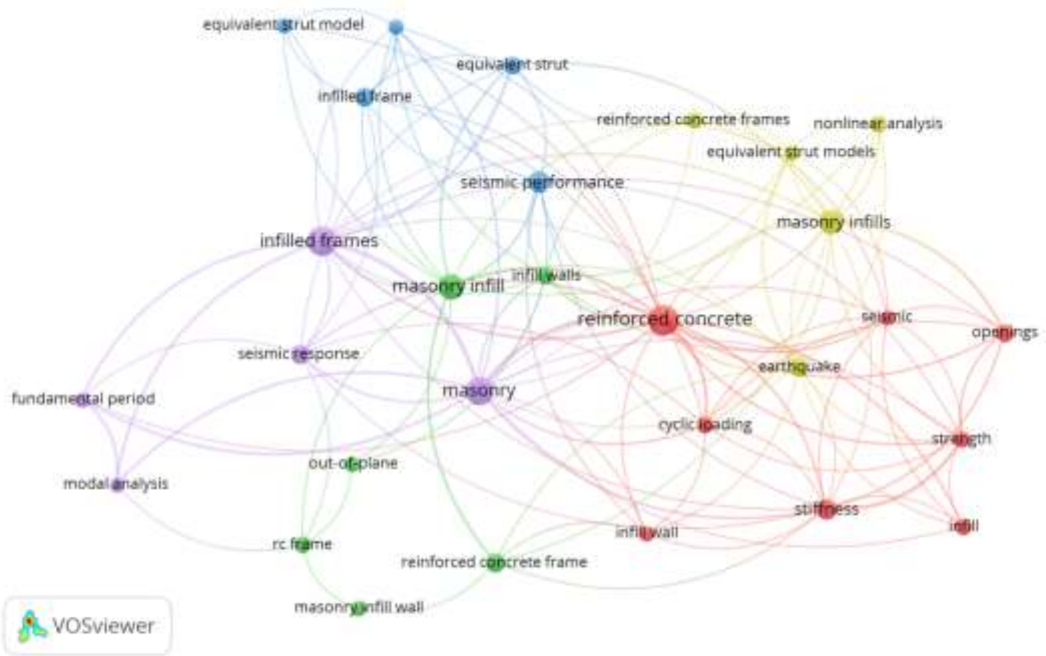

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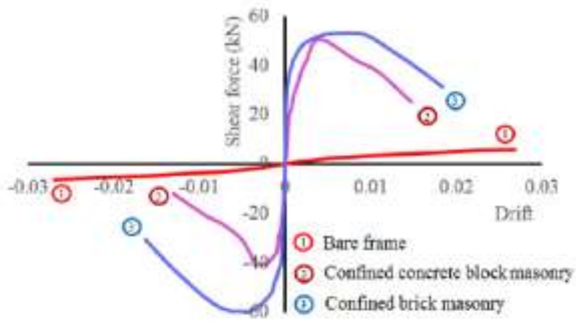

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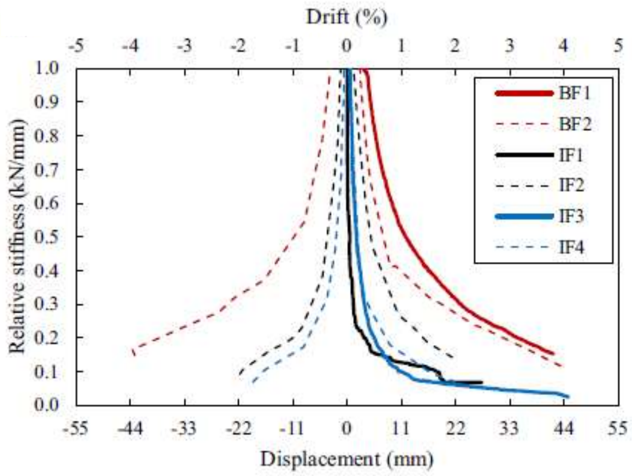
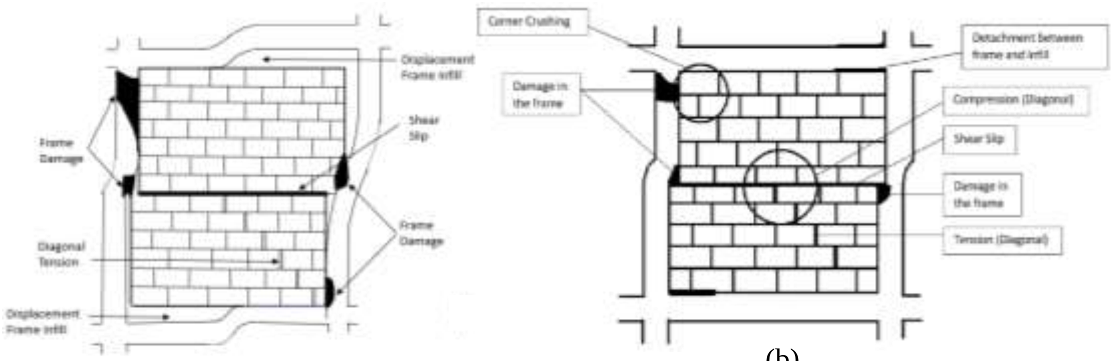


Fig. 9: Stiffness degradation curve (Van and Lau 2020).



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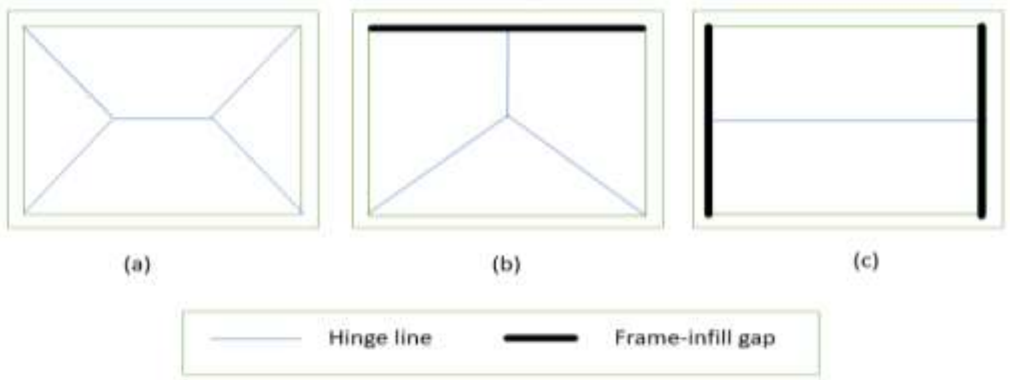

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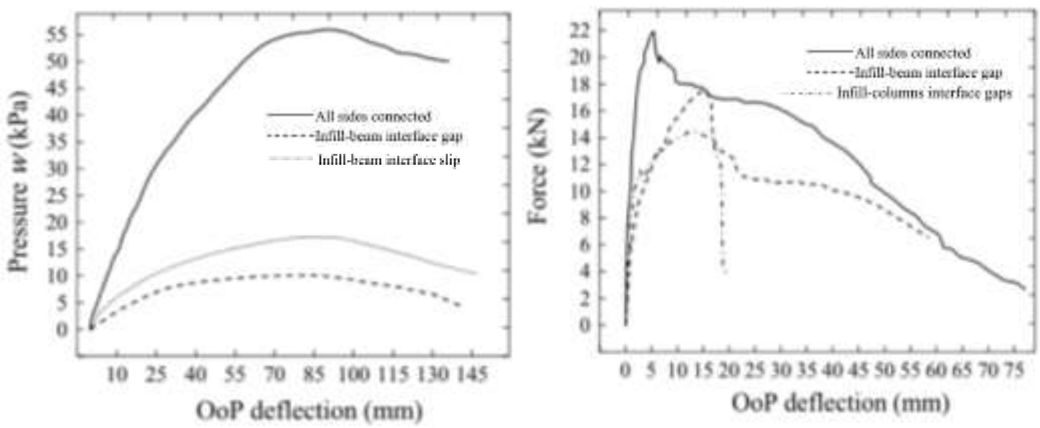

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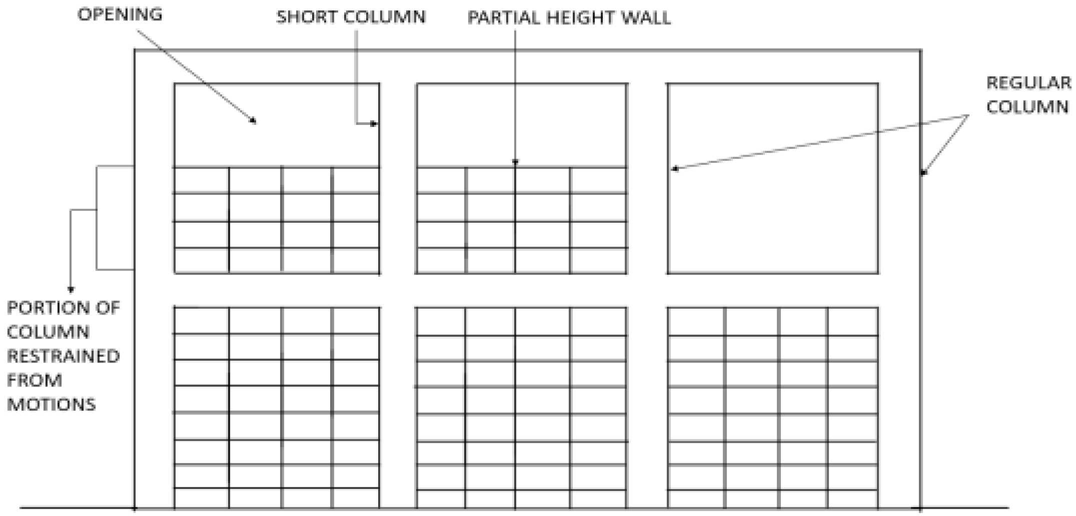

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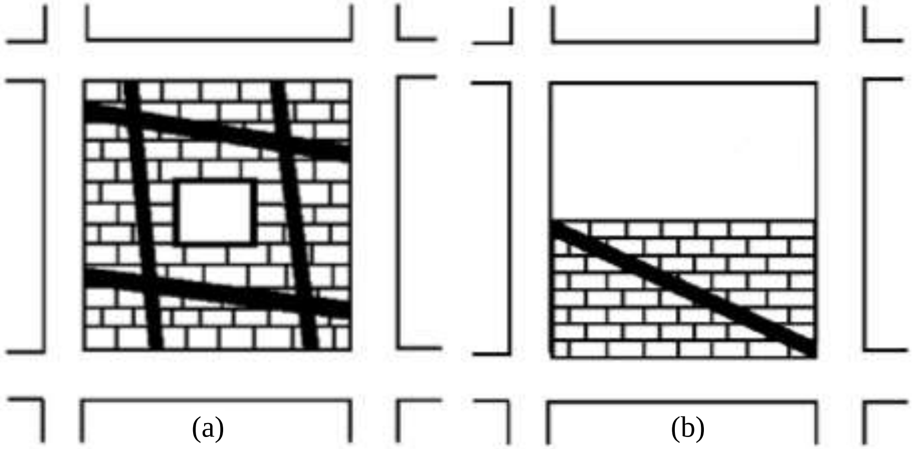

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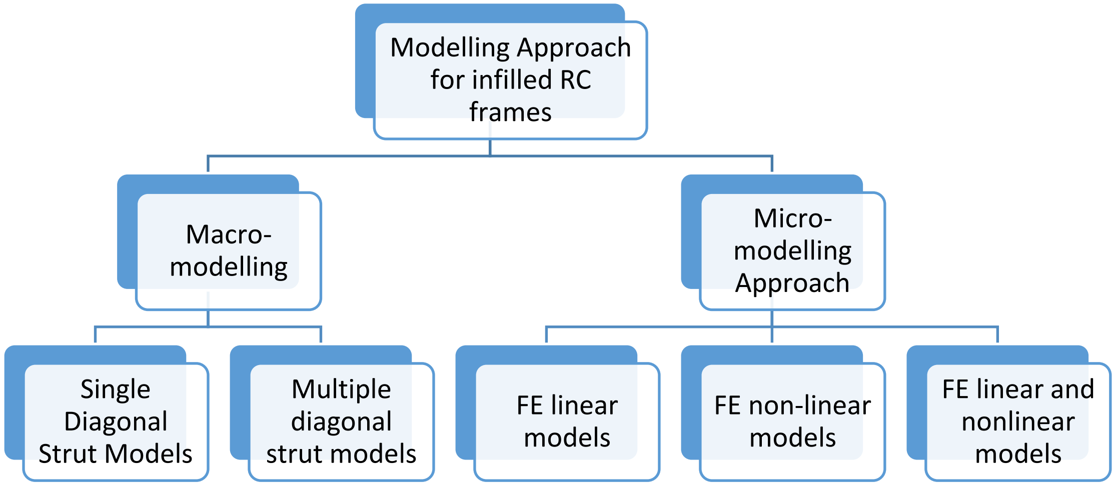

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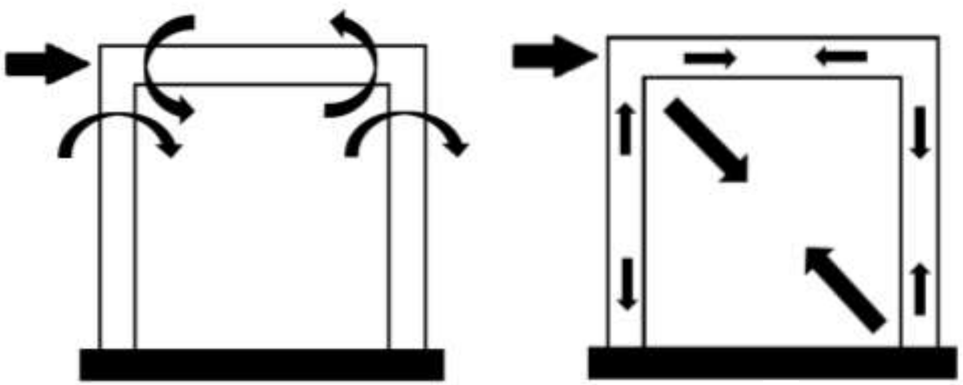

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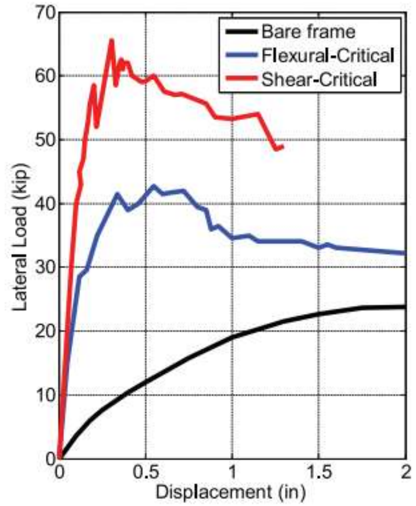

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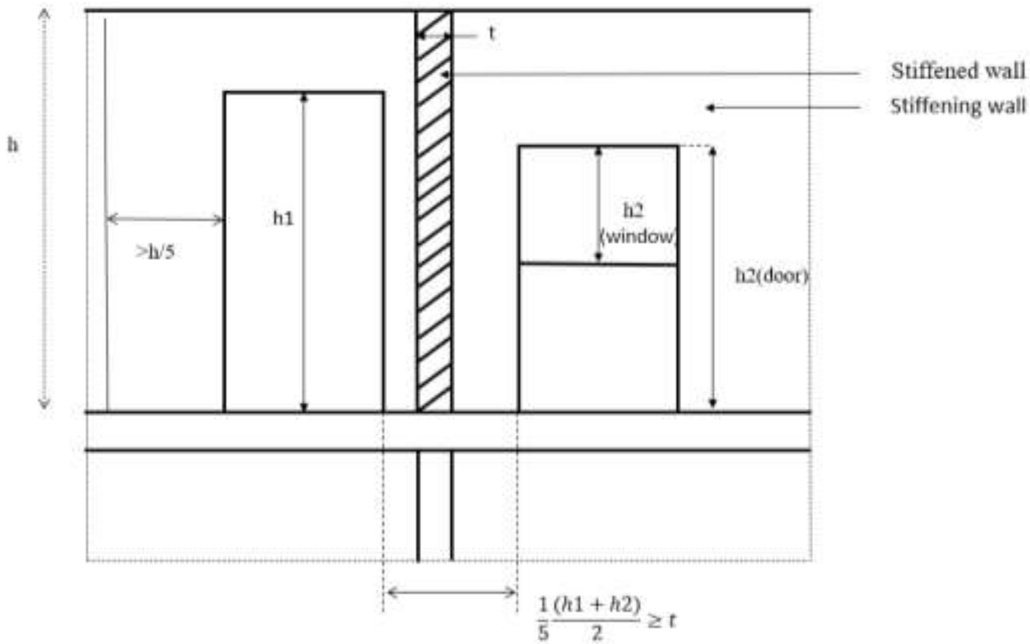

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Table 1: Literature review of experimental studies on infilled RC frames with in-plane and out of plane loading

Sl. No	References	Model size	R/UR	Infill Material	Loading type	IP/OOP	Effect of strength of masonry	Load displacement behavior	Strength enhancement	Stiffness enhancement/degradation	Energy dissipation capacity	Failure behavior	Effect of openings	Panel aspect ratio
1	Akhaoundi et al., 2018	Frames are of size 2.735mx2.135m	UR	Bricks	Static	OOP		Yes	Yes	Yes	Yes	Yes	Yes	
2	Al-Char et al., 2003	Frames are of size 1.5mx1.5m	UR	Concrete Masonry Unit (CMU)	Cyclic Loading	IP and OOP		Yes	Yes	Yes		Yes	Yes	
3	Alwashali et al., 2017	Frames are of size 2.2mx2.6m	UR	Brick masonry	Static and cyclic	IP		Yes				Yes	No	1 to 2
4	Bash & Kaushik, 2016	RC frame of size 3.2m x 1.5m.	UR	Fly Ash Brick	Dynamic	IP		Yes		Yes	Yes	Yes	Yes	1
5	Basha et al., 2020	Frames of size 1.5 m x 1.5 m	UR	Fly Ash Brick	Cyclic	IP		Yes	Yes	Yes	Yes	Yes	Yes	
6	Bergami and Nuti, 2015	Frames are of size 2.5mx1.885m	UR	masonry brick	Cyclic			Yes	Yes			Yes		

7	Bob et al., 2016	Frames are of size 2.5mx1.625 m	UR	Ceramic blocks with vertical hollows and solid bricks.	Cyclic	IP		Yes		Yes	Yes	Yes		
8	Al-Char et al., 2002	RC frame of of height 3.048m for prototype and 1.5m for model	UR	Concrete Masonry Unit (CMU)	Static Monotonic	IP		Yes			Yes	Yes		1
9	Furtado et al., 2016	Frames are of size 2.3mx4.2m.	UR	Hollow Clay Bricks	Cyclic and Monotonic	OOP		Yes				Yes		
10	Furtado et al., 2016	Frames are of size 4.8mx3.3m	UR	Hollow Clay Bricks	Cyclic and Monotonic	OOP		Yes				Yes		
11	Huang et al., 2016	Frames of size 2.25 m x 3 m	UR	Solid clay brick, hollow concrete block and aerated concrete block.	Cyclic Loading	IP and OOP		Yes			Yes	Yes		1.5 and 2

12	Jiang et al., 2015	Frames are of size 5.94mx3.175m	UR	aerated concrete block	Cyclic	IP		Yes		Yes	Yes	Yes		
13	Kakaletsis and Karayannis, 2007	Frames are of size 1.2mx0.8m.	UR	Clay Brick	Cyclic	IP		Yes	Yes	Yes	Yes	Yes	Yes	
14	Kakaletsis and Karayannis, 2008	Frames are of size 1.7mx1.5m	UR	Clay brick and vitrified ceramic brick.	Cyclic	IP	Yes	Yes		Yes	Yes	Yes	Yes	1 and 1.5
15	Maidiawati et al., 2018		UR	solid clay brick-masonry (IFSW)	Cyclic Loading	IP		Yes	Yes	Yes	Yes		Yes	
16	Misir et al., 2012	Frames are of size 2.5mx2.025m	UR	Standard and Lock Bricks	Quasi-static	IP		Yes		Yes	Yes	Yes		
17	Ning et al., 2019	double storey frame of size 2.44mx1.44m	UR	Aerated Lightweight Concrete blocks	Cyclic	IP		Yes		Yes	Yes	Yes	Yes	

18	Onat et al.,2016	RC frame of size 6.4m × 3.25 m.	R	Bricks	Static	IP and OOP		Yes				Yes	No	
19	Pujal and Fick, 2010	3 storey full scale frame	UR	Solid Clay Bricks	Cyclic	IP		Yes		Yes		Yes	No	
20	Ricci et al., 2018	Frame of size 1.83m x 2.35 m	UR	Solid clay bricks and concrete masonry units infill	Cyclic	OOP and IP		Yes		Yes	Yes	Yes		
21	Risi et al., 2019	Frames are of size 3.890mx2.50m	UR	Clay Hollow Bricks	monotonic and cyclic	OOP		Yes				Yes		Yes
22	Schwarz et al., 2015	Frames are of size 2.245mx1.8 m	UR	AAC Blocks	Cyclic	IP		Yes		Yes	Yes	Yes	Yes	Yes
23	Siddiqui et al., 2015	Three-story building frame	UR	Low strength autoclave aerated concrete Blocks	Pseudo-dynamic testing	IP		Yes				Yes		

24	Sigmund and Penava et al., 2013		UR	Hollow Clay Blocks	Quasi-static			Yes				Yes	Yes	
25	Tanjung et al., 2017	Frames are of size 1.025mx1.05m.	UR and R	Brick	Monotonic	IP		Yes		Yes		Yes		
26	Tanjung et al., 2017	Frames are of size 1.15mx1.15m	UR	Burnt clay brick	lateral static reversed cyclic loading	IP		Yes				Yes	Yes	
27	Teguh, 2017	Frames are of size 3.7mx3.75m.	UR	Clay Bricks and Concrete Blocks	Cyclic	IP	Yes	Yes				Yes		
28	Van and Lau, 2021	Frames are of size 1.7mx1m.	UR	Solid clay brick	Cyclic and Monotonic	IP		Yes	Yes	Yes	Yes	Yes		
29	Wang et al., 2018	Frames are of size 2.5mx1.885m	UR	high strength and low strength brick	Cyclic	IP	Yes	Yes	Yes	Yes	Yes	Yes	Yes	

R-Reinforced; UR-Unreinforced; IP-In-plane; OOP-Out of plane

Table 2. Energy dissipation of infilled frame/energy dissipation of RC bare frame

Reference	Energy dissipation ratio (EDR)
Bob et al., 2016	1.55 to 1.75
Huang et al., 2016	1.07 to 1.34
Bash & Kaushik, 2016	1.5 (ductile frames)
Bash & Kaushik, 2016	1.5 (non-ductile frames)
Kakaletsis and Karayannis, 2008	1.02-1.43 (frame with infill opening)

Table 3. Out of plane modulus or stiffness of masonry infills developed by few researchers.

Modulus	Equation	Reference	Reference
Out of plane Secant Stiffness	$K = K_{\inf}\left(e^{-3.3D}\right)$	K- Secant stiffness (kN/mm) after in-plane damage, K_{inf}- Secant stiffness (kN/mm) without in-plane damage, D- prior in plane drift.	Akhoundi et al., 2018
Stiffness after in-plane degradation	$\frac{K_{\deg,dam}}{K_{\deg,undam}} = \min\left(1; 0.33IDR^{-0.61}\right)$	IDR=Inter storey drift ratio $K_{deg,dam}$- Out of plane softening stiffness with in-plane damaged infill, $K_{deg,undam}$- Out of plane softening stiffness with in-plane undamaged infill,	Ricci et al., 2018

1062 Table 4. Literature review of numerical studies on infilled RC frames with in-plane

1063 and out of plane loading

Sl. No.	Reference	Micro modelling / Macro modelling	Reinforced masonry/ Unreinforced masonry	Static/ Cyclic	IP /OOP	Models for infill
1	Lee et al., 2021	Macro-modelling	UR	Monotonic	IP	Disturbed Stress Field Model for Masonry Element, Slip Model for Mortar Joint
2	Abdelaziz et al., 2021	Macro-modelling	UR	Cyclic	IP	equivalent strut
3	Zine et al., 2021	Micro-modelling	UR	Monotonic	OOP	nonlinear layered shell element
4	Akid et al., 2021	Macro-modelling	UR	Monotonic	IP	equivalent strut
5	Aragona et al., 2021	Macro modelling	UR	Monotonic	IP	equivalent strut
6	Mucedero et al., 2020	Macro-modelling	UR	Cyclic	IP	Six equivalent strut model
7	Mohamad & Romao, 2020	Micro-modelling	UR	Cyclic	IP	equivalent strut
8	Jalaeefar and Zargar, 2020	Macro-modelling	UR	Monotonic	IP	equivalent strut
9	Abdelziz et al., 2019	Macro-modelling	UR	Dynamic	IP	six strut members
10	Hashmi and Madan, 2018	Micro-modelling	UR	Dynamic	IP	rational nonlinear model
11	Hanoun et al., 2018	Macro-modelling	UR	Cyclic	IP and OOP	four elastic beam elements pinned to the joints of the RC frame elements and linked with a nonlinear axial link element,
12	Noui et al., 2017	Micro-modelling	UR	Static	IP	nonlinear layered shell element
13	Mohyeddin et al., 2017	Macro-modelling	UR	Static	IP	equivalent strut
14	Asterisi et al., 2016	Macro-modelling	UR	Static	IP	equivalent diagonal struct

15	Deng and Sun, 2016	Micro-modelling	UR	Static	IP	equivalent bracing
16	Zhai et al., 2016	Micro-modelling	UR	Monotonic	OOP	damage plasticity material models
17	Fiore et al., 2015	Macro-modelling		Monotonic	IP	equivalent strut
18	Tavakoli, Akbar poor, 2014	Micro-modelling	UR	Monotonic	IP	equivalent strut
19	Farghaly and Rahim, 2013	Micro-modelling	UR	Cyclic	IP	stress strain relation model
20	Sipos et al., 2013	Micro-modelling	UR	either static–monotonic or cyclic	IP	equivalent strut
21	Fiore et al., 2012	Micro-modelling	UR	Cyclic	IP	equivalent strut
22	Haldar et al., 2013	Macro-modelling	UR	Static	IP	equivalent strut
23	Haldar et al., 2012	Macro-modelling	UR		IP	equivalent strut
24	Asteris et al., 2012	Macro-modelling	UR	Static	IP	equivalent strut
25	Haldar and Singh, 2012	Macro-modelling	UR	Static	IP	equivalent concentric diagonal compressive strut element
26	Afefy et al., 2001	Micro-modelling	UR	Cyclic Triangular Load	IP	diagonal strut
27	Asterisis and Cotsovos (2012)	Micro-modelling	UR	Static loading and seismic loading	IP	27-node Lagrangian brick elements
28	Fiore et al., 2012	Micro-modelling	UR	Static	IP	Double diagonal strut model
29	Madam & Hashmi, 2006	Micro-modelling	UR	Cyclic	IP	smooth hysteretic model (based on equivalent strut approach)
30	Al-Muyed and Afrin, 2005	Micro-modelling	UR	Monotonic	IP	equivalent strut

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