Research Article

Sustainable housing using confined masonry buildings

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Abstract

Much of India is prone to substantial earthquakes, and vulnerability associated with both unreinforced masonry (URM) and improperly built reinforced concrete (RC) frame constructions has been unmasked by past earthquakes. URM structures present a severe hazard in earthquake-prone regions. And non-engineered RC structures can lead to devastating consequences. Housing for families in the economically weaker sector and the lower-income group is undoubtedly challenging to such events. Regardless of residing in a city or village, everyone desires a house with masonry walls and RC roof, just like the buildings in larger urban areas. Confined masonry (CM) construction, which is a popular building system in many countries, can fulfil this need of society. Though CM building started informally, the seismic performance is found to be really well in several destructive earthquakes. This type of construction combines the advantages of URM and RC structures and does not need sophistication required in RC construction. In this paper, the seismic response of URM, infilled RC frame and CM buildings is compared using past seismic performance and literature. It is concluded that confined masonry is a better alternative for sustainable housing in seismic-prone regions of India.

Keywords Unreinforced masonry · Reinforced concrete · Confined masonry · Seismic response

1 Introduction

In recent years, earthquakes occurring in India and other countries have unveiled many weaknesses associated with both unreinforced masonry (URM) and reinforced concrete (RC) frame construction. Both URM buildings and non-engineered RC frame buildings continue to be the major cause of human and economic losses during past earthquakes as observed during Bhuj (2001), Kashmir (2005), Sikkim (2011) and Nepal (2015) earthquakes. Confined masonry (CM) has emerged as an improved masonry structural system, where the unreinforced masonry walls are confined with nominally reinforced concrete tie-elements (tie-columns and tie-beams) at the perimeter and other salient locations. Because of these small tie-elements, the ductility of the structure under lateral load improves compared to the URM structure, which translates into better seismic performance. Though a finished CM building looks like an RC frame building with infill walls, CM building does not need sophistication required in RC construction [1]. Here, the confining elements are not designed to act as load-bearing elements as in case of RC frame buildings with masonry infill; however, these are provided to tie together the walls, floors and roofs as well as to strengthen walls with openings. To study the economic aspect, Marques and Lourenço [2] estimated the costs associated with the construction of dwellings with RC, URM and CM typologies. Increase of 33% in the total cost was observed for the CM structure when compared to the URM structure. However, it allows a total cost reduction of 16% when compared to the RC structure. Medium-rise CM building had its first formal application in India in the form of a large-scale project involving the construction of 36 CM buildings in the new campus of IIT Gandhinagar, Gujarat. Preliminary cost estimates indicated that adoption of CM technology resulted in a cost saving of 10–15%

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over alternative RC frame construction [3]. The cost savings were mainly due to a smaller amount of concrete and steel because of smaller member sizes in CM buildings compared to RC frame buildings. Therefore, the CM structure combines the advantages of URM and RC structure, and the structure provides an economic advantage utilizing the masonry strength in the main load-bearing element. The past seismic performance of CM structure in comparison with other types is described in the next section.

2 Past seismic performance

The first reported use of CM construction was in the reconstruction of buildings destroyed by the 1908 Messina, Italy, earthquake of magnitude 7.2. After that, its practice started in Chile and Colombia in the 1930s and is currently widely used for housing construction, from low-rise (one-to-two storey) dwellings to multistorey (up to six storeys high) apartment buildings in several countries of high seismic risk [4]. CM structure has been subjected to many devastating earthquakes. Table 1 includes some countries where CM buildings have been used for housing construction and the history of remarkable earthquake experienced by them [5–17]. As mentioned in the past literature, the overall performance of the CM building in these earthquakes was very satisfactory. For example, in the earthquake performance report of 1939 Chile earthquake, 1999 Tehuacan earthquake, 2003 Tecomán earthquake and 2007 Pisco earthquake, CM structures showed far better performance than URM structure. Majority of CM buildings remained undamaged while the adjacent URM building (especially adobe construction) damaged severely or collapsed in these earthquakes. Also, in 1985 Guerrero–Michoacán earthquake, CM buildings showed better performance than even infilled RC frame buildings. Several reports of the past earthquakes have identified the out-of-plane collapse of URM and infilled RC frame wall as one of the predominant modes of failure. In the infilled RC frames due to construction difficulties, loose fitting of masonry beneath the concrete beam is quite common, which resulted in the out-of-plane collapse of these panels during the past earthquakes. However, a superior integration between the masonry and adjacent RC tie-elements is naturally developed in CM walls because of the construction sequences. As the concrete is cast after the masonry wall, a good bond is developed between the wall and surrounding frame in CM building. Therefore, in these earthquakes, CM buildings were less vulnerable in the out-of-plane direction compared to URM or infilled RC frame buildings.

Table 1 CM building performance during past notable earthquakes

Country	Year	Earthquake location	Magnitude
Chile	1939	Chillán	7.8
	1985	Llolleo	7.8
	2010	Coast of Maule	8.8
Mexico	1985	Guerrero–Michoacán	8.0
	1999	Tehuacan	6.5
	2003	Tecomán	7.6
Peru	1970	Chimbote	7.8
	2007	Pisco	8.0
Colombia	1983	Popayan	5.5
	1999	El Quindio	6.2
Iran	1990	Manjil	7.6
	2003	Bam	6.6
El Salvador	2001	Offshore El Salvador	7.7
China	1976	Tangshan	8.2
Indonesia	2004	Northern Sumatra	9.3
	2005	Northern Sumatra	8.7
	2007	Bengkulu	8.4
Haiti	2010	Port-au-Prince	7.0

In general, because of the main concept, i.e. load-bearing masonry wall tied by small RC elements, CM structures showed excellent resistance to seismic events occurred in worldwide. A few CM buildings suffered severe damage, especially high-rise buildings but most low- and medium-rise dwellings did not experience any damage. The damage in CM buildings was found to be mainly due to the omission of tie-columns, discontinuity in tie-beams, poor diaphragm connections and inappropriate structural configuration. Therefore, if it is properly constructed, it can sustain earthquake effects without collapse. As a result, the CM structure has attracted considerable interest in the research field. Studies have been carried out to understand the behaviour of the CM building system in order to transform it into a proper engineered construction. In the next section, the behaviour of the CM structure under experimental study is discussed.

3 Review of past literature

Seismic behaviour of CM structure has been a subject of experimental studies from many years. Past experimental studies have contributed to the comprehensive understanding of the seismic behaviour of CM walls in terms of their damage pattern and failure modes. From the investigation of experimental test studies and past earthquake damage reports, the general failure modes of CM structures can be broadly categorized into in-plane failures, out-of-plane failures, diaphragm failures, connection failures and non-structural failures as shown in Fig. 1 [18]. Among these, the in-plane performance of CM walls has

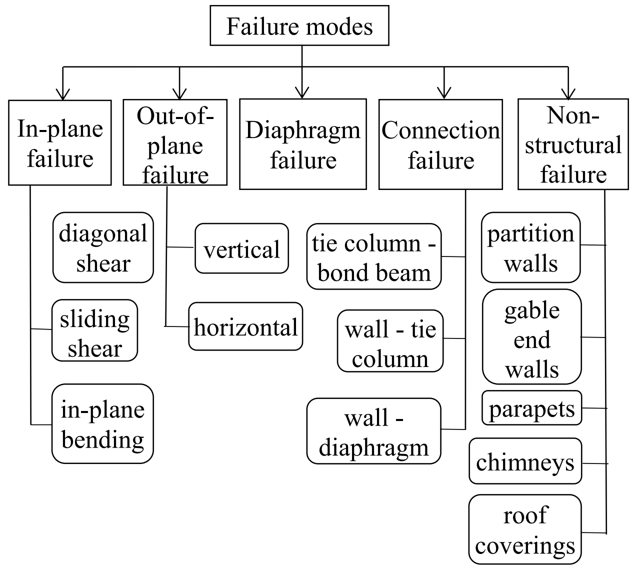

Fig. 1 Different failure modes of CM structure

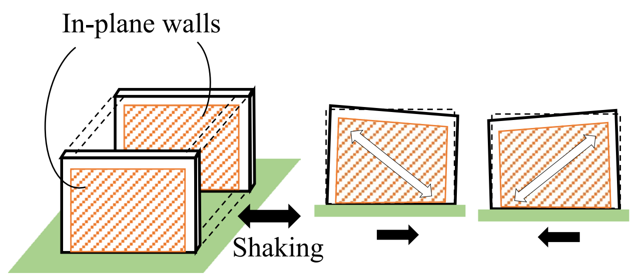

Fig. 2 CM wall subjected to in-plane loading

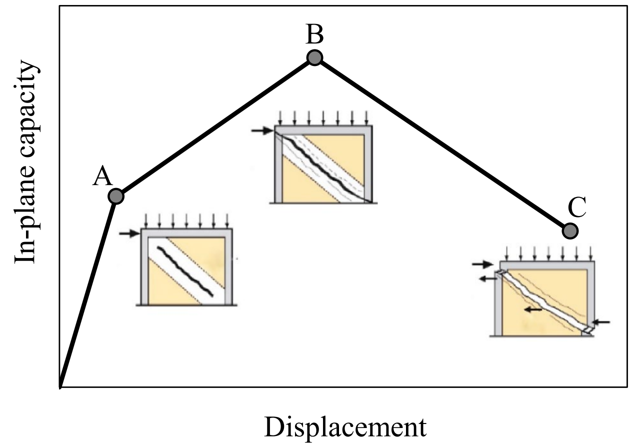

Fig. 3 Idealized in-plane load-deformation envelope curve for CM wall [1]

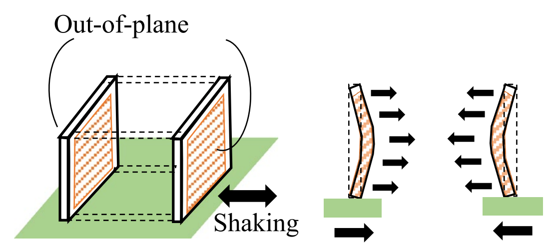

Fig. 4 CM wall subjected to out-of-plane loading

attracted considerable interest in the seismic research, as it is the primary load path for transferring lateral seismic forces to the foundation.

The summary of experimental studies conducted to understand the in-plane behaviour (Fig. 2) of CM walls in the past three decades is presented by Meli et al. [1]. It was observed that initially in a CM wall, the masonry panel resists the effect of lateral earthquake loads while the confining elements do not play a significant role (Fig. 3). Once the cracking takes place in masonry units or mortar joint, the panel becomes less effective in transferring the forces (Point A). If the lateral force continues to increase, the masonry panel typically begins to lose strength, and at this stage, the vertical reinforcement in tie-columns becomes engaged in resisting tensile and compressive stresses. Thus, even if the lateral loads on the wall exceed its capacity, because of tie-elements, the walls will stay together and continue to deform or stretch until the lateral loads lessen. In this way, the wall got significantly higher strength and considerably higher deformation capacity than URM walls and is prevented from collapse (Point B). These additional deformations cause further damage in the masonry and tie-columns. In many cases, ultimate failure occurs when the tie-columns completely fail in shear by the extension of diagonal shear failure of the panel (Point C). Meli et al. also concluded that the maximum in-plane resistance of CM wall could be considered as the sum of the shear resistance provided by the plain masonry wall and the tie-columns. Further, the load-deformation behaviour depends on various factors, such as wall aspect ratio, material strength, type of wall-to-tie-column interface, detailing of tie-columns, wall openings and overburden pressure. [19–27].

During lateral loading, masonry walls may be subjected to out-of-plane lateral loading and vertical compression due to self-weight and overburden loads (Fig. 4). Out-of-plane lateral loading creates bending and shear stresses in the wall, and because of the low tensile strength of masonry, cracks may appear in walls leading to possible collapse by overturning. Overturning or out-of-plane failure mode is very common in URM and infilled RC frame structure. In case of URM structure, walls are constructed without any reinforcement, and in case of an infilled RC frame structure, walls are constructed inside stiff

RC frames. However, in CM structure, the walls are constructed with flexible small RC confining elements around their perimeter and a superior integration between the masonry and adjacent RC elements is naturally developed due to the different construction sequences. As the masonry panels are tightly attached with the RC frame elements in case of CM structure, it exerts thrust on the beams and columns and forms effective arching mechanism [1]. Therefore, CM walls, in general, did not experience out-of-plane collapses in comparison with URM and infilled RC frames during past earthquakes. Several guidelines on CM emphasize on providing toothing or dowels at the wall-to-tie-column interface for satisfactory out-of-plane performance [1, 28, 29]. Very few experimental studies have been carried out on the out-of-plane behaviour of CM walls [29–34]. Several factors, such as, wall aspect ratio (height/length ratio), slenderness ratio (height/thickness ratio), type of floor diaphragm (rigid or flexible diaphragm), support conditions, stiffness of the surrounding RC frame, material characteristics, overburden pressure, etc., affect the out-of-plane capacity of wall [30–44].

The improvement in the in-plane performance of CM walls in comparison with URM and infilled RC frame walls was confirmed by different researchers [25, 45–47]. Yoshimura and Kikuchi [45] tested nine different specimens to compare the behaviour of CM wall with unreinforced masonry wall without any confining column and with infilled RC ductile moment-resisting frame having the same cross-sectional details as that of the CM specimen. As the CM wall specimen showed higher strength and ductility than the unreinforced masonry and infilled RC frame specimens, it was concluded that CM construction is the excellent structural system. Tomazevic and Klemenc [25] tested three specimens of confined and plain masonry walls with height-to-length ratio equal to 1.5, made at 1:5 scale, under the application of constant vertical load and programmed pattern of cyclically acting horizontal displacements. From their study, it was observed that by confining the wall with RC tie-columns, lateral resistance of a URM wall is improved by more than 1.5 times and deformation capacity by almost five times in addition to enhancing the energy dissipation capacity by six to seven times as shown in Fig. 5a. Yoshimura et al. [46] tested different types of unreinforced and confined concrete hollow block masonry wall specimens (2D and 3D specimens, walls with or without reinforcing bars or *U*-shaped connecting bars) under repeated lateral force (lateral load application point considered was at a height of 0.67 and 1.1 times the height of the wall measured from the top of the foundation beam), and constant axial stress (0.48 MPa and 0.84 MPa). From the study, it was concluded that the seismic performance of CM wall is better than the conventional URM system. The CM walls with *U*-shaped connectors and horizontal wall reinforcements developed moderately higher ultimate lateral strength with the increase in axial load and showed better ductility as compared to the URM wall specimens. Figure 5b shows the shearing stress-versus-storey drift plot for 2D URM and CM wall specimens without wall horizontal reinforcement under axial stress of 0.48 MPa and lateral load at the lower application point. As shown in the figure, CM specimen with *U*-shaped connecting bar improved the performance in terms of lateral load-carrying capacity and ductility. Goveia and Lourenço [47] tested nine URM (four with unfilled vertical joints, three with filled vertical joints and two with light bed joint reinforcement) and seven confined block masonry walls (two with unfilled vertical joints, three with unfilled vertical joints and light bed joint reinforcement and two with unfilled vertical joints and light bed joint reinforcement anchored to the confining elements), made at 1:2 scale, for constant vertical and horizontal cyclic load. From their study, it was observed that by confining the wall with RC tie-elements, the lateral capacity of standard URM wall is improved by 1.17 times and deformation capacity by 1.43 times.

Tu et al. [30] conducted shaking table tests on two full-scale single-storey structures to investigate the out-of-plane behaviour of CM walls of different thicknesses. The out-of-plane performance of these confined walls was also

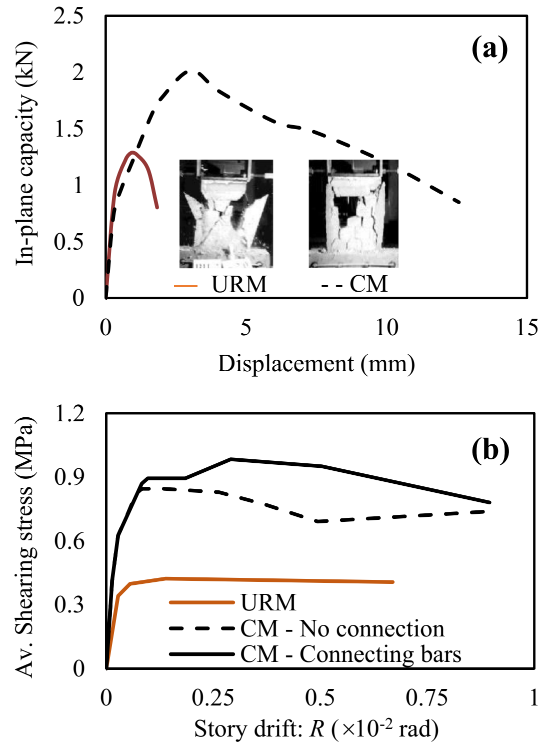

Fig. 5 Comparison of the in-plane response of CM and URM walls tested by: **a** Tomazevic and Klemenc [25], **b** Yoshimura et al. [46]

compared with infilled RC frames. The test results suggest that CM walls can sustain significant out-of-plane loads. The composite action between the wall and confining frames prevented the masonry panels from falling out of the frame and helped to reduce the influence of inertia forces caused by their self-weight. On the contrary, infill panels separated from the boundary frame and collapsed due to the out-of-plane inertia forces.

Practically, a seismic event can cause a masonry panel to experience both in-plane and out-of-plane loads simultaneously. The in-plane force causes damage to the wall by forming diagonal cracking, shear sliding or bending depending on the geometry of the wall. The in-plane damage of the wall affects the arching mechanism and reduces the out-of-plane capacity of the wall. Hence, the combined effect of in-plane and out-of-plane forces aggravates the extent of the damage. Singhal et al. [22, 23] tested half-scaled CM wall specimens with the different connections at the wall-to-tie-column interface (Fig. 6) and considered the successive applications of out-of-plane and in-plane loading. The seismic performance of CM wall in comparison with that of a typical infilled RC frame wall was also studied. It was observed that the CM walls with or without toothing exhibited improved in-plane and out-of-plane responses in comparison with the infilled RC frame wall, as shown in Figs. 7 and 8, respectively. The increased density of toothing caused significant improvement in post-peak behaviour under in-plane loads (Fig. 7). However, it did not have significant effect on out-of-plane behaviour up to the moderate level of damage (1.0% drift) (Fig. 8). At higher in-plane drift, CM walls with toothing were more effective in controlling the OOP displacements than with no toothing. Under lateral loads, CM walls acted as shear walls, and due to the composite action between the wall and the tie-column, the out-of-plane failure was delayed, and the wall could safely sustain large in-plane drifts up to 1.75%. However, the RC frame with infill masonry showed a separation of the wall panel at its interface with the framing element at in-plane drifts as low as 0.5%, which led to excessive out-of-plane deflection and increased risk of dislodgement from the frame.

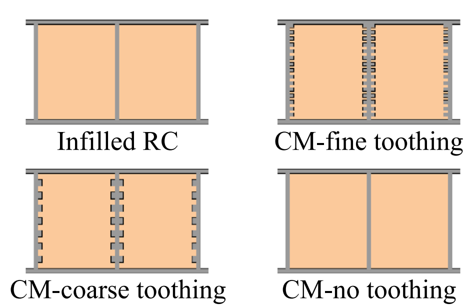

Fig. 6 Wall specimens prepared for the experimental investigation [22, 23]

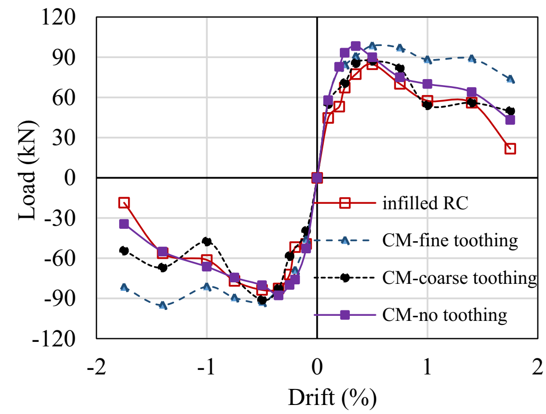

Fig. 7 Comparison of seismic response of infilled RC frame and CM walls [22, 23]

4 Conclusion

In this paper, seismic performance of CM building in comparison with URM and RC frame building with infill walls is examined. From the study, it is clear that low-rise CM structure exhibits better in-plane and out-of-plane resistance in comparison with URM and infilled RC frame structures under any seismic event. URM structures provide very less lateral strength in comparison with CM structures, and because of the brittle behaviour, they have no reserved strength after cracking. Again to construct a proper RC frame building with infill walls requires technical skills and finances. Much of India is prone to substantial earthquakes

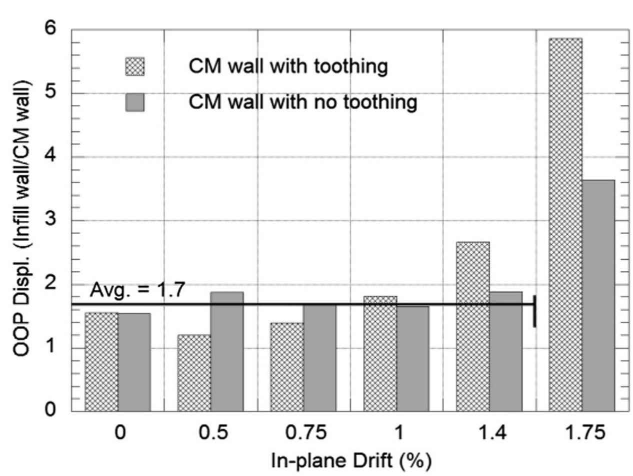

Fig. 8 Normalized out-of-plane displacement of infill wall with respect to CM walls at different in-plane drift (damage) levels [22, 23]

and construction of earthquake-resistant housing for families in the economically weaker sector, and the lower-income group is undoubtedly challenging. Confined masonry can be a useful construction technology because this practice does not require new or advanced construction skills or equipment. Same materials are used which are available in the country, that is, concrete, masonry and steel. It only requires nominal care in design and construction and yet performs very well in earthquakes. Therefore, confined masonry is a better alternative for sustainable housing in seismic-prone regions of India.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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