Confined masonry construction for India: a techno economical solution for improved seismic behaviour

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Masonry constructions are the pervasive building stock in India. However, such constructions suffer widespread damage even at moderate ground shaking due to non-engineered construction. Alternatively, confined masonry shows better promise as a technology that has performed satisfactorily during past earthquakes worldwide. Present article outlines scenario of masonry construction in India, performance of confined masonry in past earthquakes and studies on confined masonry worldwide. The article also encompasses experimental seismic performance of full-scale models of unreinforced masonry (URM), reinforced masonry (RM) and confined masonry (CM) buildings in Indian context under quasi-static reversed cyclic lateral loading in terms of damage pattern, lateral strength, drift and stiffness. The cost analysis of URM, RM, CM and reinforced concrete (RC) residential buildings for a set of 20 samples in seismic Zone IV, keeping uniform input parameters, showed cost reduction in CM buildings when compared to RC buildings.

Keywords: Confined masonry, construction cost, reinforced masonry, seismic performance, unreinforced masonry.

MASONRY finds wide use even now in today's buildings, in low-to-medium rise constructions, than any other material. The success of brick masonry, in particular, is mainly due to its durability, sustainability, ease of construction, fire resistance, acoustic and thermal insulation characteristics. However, unreinforced masonry (URM) buildings, have proved to be vulnerable in seismic events, with significant building damage and numbers of fatalities all over the world. To improve the seismic resistance of masonry, different methods and techniques for reinforcing masonry have been attempted over the years, which led to the development of reinforced masonry (RM) and confined masonry (CM) systems. However, in India, adoption of these technologies remains restrained due to lack of standards and only few experimental efforts to understand the seismic response of such systems. The issue of seismic performance and safety of existing masonry buildings is characterized by numerous uncertainties. This paper presents an insight into the subject of CM, performance of CM buildings in major earthquakes, analysis and comparison of experimental data of masonry buildings in Indian scenario and probing the economical aspects. It is hoped that this paper will promote CM as a structural system in India.

Masonry construction scenario in India

Masonry construction is the commonly adopted method in India, both in rural and urban areas. Special characteristics of masonry construction are because of the bias towards locally available material, limitations of construction skills and constraints to construction activity. According to the Census of India in 2001 and 2011 (housing data), the distribution of houses based on predominant materials of wall showed that there were 249 and 304 million houses in 2001 and 2011 respectively, comprising around 85% masonry houses[1,2]. Also, there is a decline in the proportion of mud/unburnt bricks, wood, galvanized iron/metal sheet houses in 2011 as compared to 2001, with appreciable increased use of burnt clay units in masonry. Due to socio-economic constraints, some of the buildings are built with unburnt solid clay bricks or mud walls of 450–600 mm thickness up to two stories as load bearing walls. Such houses mostly do not have earthquake resistant features and become vulnerable even in small ground shaking. Past earthquakes have highlighted the inherent weaknesses of this type of construction and offer vivid demonstration of its vulnerability.

A wide range of variability in the mechanical and material properties of construction materials and workmanship exists in masonry construction across the country, which poses a challenge to characterize the seismic behaviour of such buildings in a quantifiable manner. The excessive use of cement based mortar (cement-sand, cement-stone dust-sand) have led to the gradual exclusion of lime mortar in recent constructions. The mortar composition for masonry varies, based on wall thickness, construction practice, etc. Generally, cement-sand mortar of 1 : 6 proportion by volume is adopted for 220 mm thick

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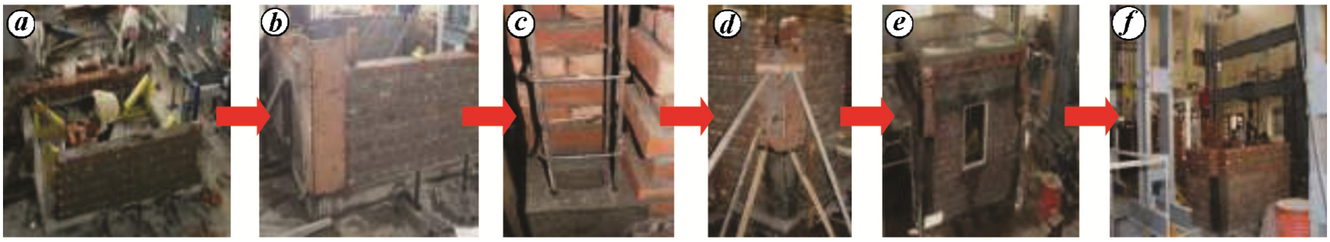


Figure 1. Sequence of construction of confined masonry (CM) building. ***a***, Construction of masonry wall with provision of reinforcement in tie-column. ***b***, Providing shuttering on two faces of tie-column. ***c***, Casting of tie-column followed by subsequent masonry. ***d***, Provision of keys in concrete and masonry for better bonding of concrete with masonry. ***e***, Subsequent shutting of tie-column; ***f***, Completed CM model.

Figure 2. CM construction in Kedarnath post 2013 disaster.

masonry walls while richer mix of 1 : 4 is used for 115 mm thick non-load bearing (partition) walls. The mortar thickness in masonry ranges between 10 and 15 mm. The masonry buildings are either founded on stone masonry, brick masonry stripped footing, plain concrete or in rare occasions of reinforced concrete (RC), for typically one to four storey buildings having 3.0–3.6 m storey height. The roofs of such constructions are either of wooden truss with GI sheets or clay tile or RC slab, simply resting over the walls, while floors are either of RC slab, or wooden logs (as beam) with mud/RC floors. The majority of masonry construction is based on thumb rules and traditions of construction technology that are handed down from one generation to the next. This has resulted in the increase of vulnerable building stock in the country as well as opening a large window for a promising masonry construction technology, confined masonry, which performs well in seismic events, if built properly.

Confined masonry

Confined masonry is a structural system consisting of URM wall panels embraced by lightly reinforced horizontal and vertical 'confining' RC members. In some cases, the masonry units are staggered or 'toothed' at tie column locations to create better interlock between the masonry and RC member. The sequence of construction of CM buildings consists of erecting reinforcement for tie-columns at corners, followed by construction of 1.2 m high masonry walls, leaving space for columns with a provision of toothing at wall edges for better bonding with concrete of tie-column that is to be poured later. This sequence of construction of CM building is shown in Figure 1. National Building Code[3] recommends to provide tie-columns at corners of rooms, wall intersections, free end of walls and jamb openings, having minimum size of 150 mm or equal to the wall thickness. Moreover, maximum spacing of tie-column is limited to 4.0 m. Similarly, bond beam is to be provided at roof level with nominal reinforcement.

Significant efforts have been done in India to promote CM as a structural system. Brzev's[4] research focused on the seismic behaviour of CM, factors affecting earthquake resistance, architectural and construction guidelines. Schacher[5] published a guidebook for technicians regarding CM of one to two storey buildings. Murty *et al.*[6] published construction tips and guidelines for non-engineered CM.

Figure 3. Good performance of CM construction in earthquakes. ***a***, Six-storey confined masonry building in Ica, 2007 Peru earthquake[4]. ***b***, No damage to confined masonry buildings, while collapse of other masonry buildings in El Salvador, 2001 San Salvador earthquake[5]; ***c***, Six-storey confined masonry building remained undamaged in 2007 Pisco (Peru) earthquake[6].

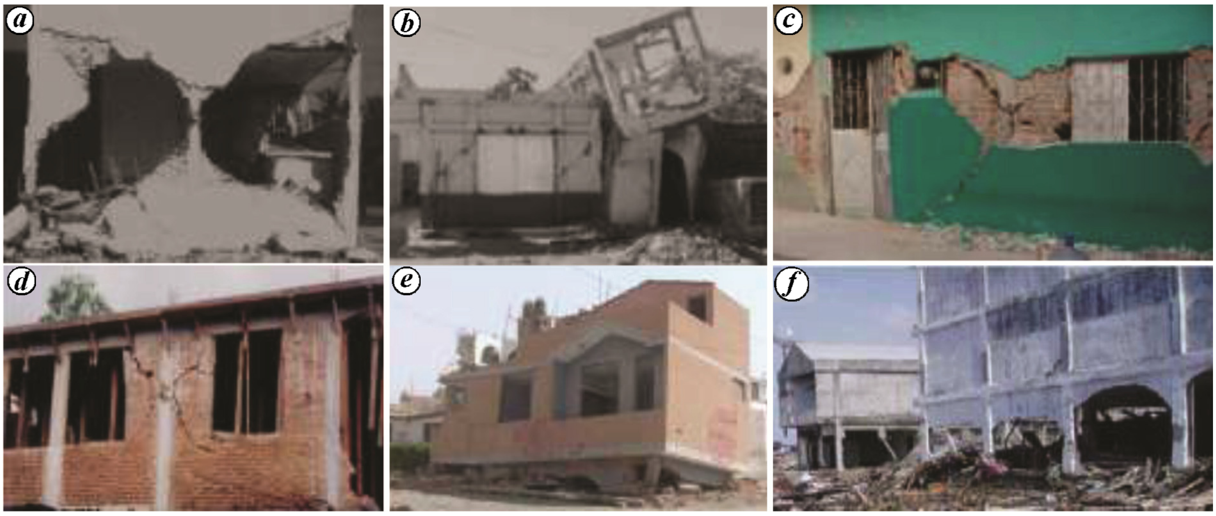


Figure 4. Damage to CM buildings: ***a***, In Llolleo, 1985 Chile Earthquake[7]; ***b***, In El Salvador, 2001 San Salvador earthquake[8]; ***c***, In Mexico, 2003 Colima earthquake[9]; ***d***, In Mexico, 1999 Tehuacan Earthquake[10]; ***e***, Collapse of CM with soft storeys, relevant irregularities and bad detailing in 2007 Pisco (Peru) earthquake[11]; ***f***, In Banda Aceh, Indonesia, Tsunami-induced out-of-plane failure of masonry walls at the ground floor level after 2004 Great Sumatra earthquake[12].

In recent years, CM has gained recognition in India due to its ease of construction, satisfactory seismic performance and economy. In 2013, Indian Institute of Technology Gandhinagar adopted CM for construction of 36 buildings, which included hostels and staff residents[7]. CSIR-Central Building Research Institute (CSIR-CBRI) Roorkee constructed 130 CM residential buildings for priests (Figure 2) during the reconstruction of Kedarnath, Uttarakhand, India and a two storey school building in Roorkee.

Reviews on the performance of CM buildings during past major earthquakes showed that they performed satisfactorily within the framework of seismic design philosophy (Figure 3). However, at a few earthquake events, poor performance of CM buildings was noticed due to substandard construction practices[8–13]. Damage data revealed that the typical damage patterns included: shear failure of walls; shear and bending failure at the ends of tie-column; separation of tie-column from walls; and development of first storey mechanism (Figure 4). In some of the cases, damage occurred at the upper storeys of the buildings with associated out-of-plane damage, mostly due to the absence of integral box behaviour of the storey. The predominant reasons of failure in CM buildings are attributed to: missing/largely spaced tie-columns; inadequate anchorage of reinforcement of bond beam with tie-column; largely spaced stirrups in tie-columns; high aspect ratio of masonry panel; asymmetric distribution of walls in plan; inadequate wall densities in two orthogonal directions; poor workmanship and poor quality of materials used; and gross construction errors. None of the cases of foundation failure of CM buildings has been reported. Nevertheless, CM construction, if constructed properly, has generally shown a good seismic performance and no significant damage has been observed during the past earthquakes.

The behaviour of CM walls under lateral cyclic loading has been widely evaluated by several researchers[14–31]. Tomazevic *et al.*[32] and Kazemi *et al.*[33] constructed full-scale tests on shake-table, while quasi-static test procedure was adopted by Agarwal *et al.*[34] for URM and RM models and Chourasia *et al.*[35,36] studied CM model. The review of experimental results and performance of CM buildings in past earthquakes shows a complex global

Table 1. Seismic design parameters for masonry buildings

Seismic parameter	Unreinforced masonry (URM)	Reinforced masonry (RM)	Confined masonry (CM)
Zone factor	0.24	0.24	0.24
Importance factor	1.0	1.0	1.0
Response reduction factor	1.5	3.0	3.0
Period (sec)	0.156	0.156	0.156
Base shear (kN)	30.35	15.35	16.00

Table 2. Material and structural features of tested masonry buildings

Building typology	Material specification	Structural features
URM (as per IS 1905 : 1987)	Burnt solid clay brick units, cement: sand (1:6) mortar, M20 grade RC slab.	220 mm thick brick masonry walls with openings for door and window. 100 mm thick slab. No seismic resistant features.
RM (as per IS 4326 : 2013)	Burnt solid clay brick units, cement: sand (1 : 6) mortar, HYSD (Fe415) reinforcement in corner vertical rebars and RC lintel band, M20 grade RC slab.	220 mm thick brick masonry walls with openings for door and window, 100 mm thick slab. One number 10 mm diameter corner vertical rebar at wall intersections and jambs of window and door openings; 220 mm wide and 75 mm thick lintel band having 2 numbers 8 mm diameter bars (Fe415) and 6 mm diameter hooks at 150 mm c/c.
CM	Burnt solid clay brick units, cement: sand (1 : 6) mortar, M20 grade tie columns at corners and beams at lintel level. M20 grade RC slab.	220 mm thick brick masonry walls with openings for door and window, 100 mm thick slab. 220 × 220 mm RC tie columns, 220 × 200 mm RC bond beams, 40 mm groove between masonry and tie column.

behaviour. The diverse behaviour of the reported results is mainly due to diagonal shear failure, however, in some cases flexure failure at initial stage within elastic limit has been noticed which may be attributed to low vertical loads. More interestingly, it is observed that, in CM buildings with higher number of storeys, deformation and damages are concentrated at first storey only showing shear failure[23]. It is also noted that failure mechanism is strongly dependent on horizontal reinforcement ratio, leading to uniform distribution of cracks in masonry. In general, brittle behaviour of hollow clay bricks/concrete block has been observed as compared to solid clay brick units. However, different CM buildings are constructed using varying material properties and geometrical configuration, local tradition, and are not fully representative of Indian architecture. In India, masonry residential building storey height usually ranges between 3.0 and 3.3 m and the door/window top (lintel) levels are at 1.9–2.1 m and RC slab as flooring/roofing system providing rigid diaphragm action. To confine masonry between lintel and roof level (spandrel masonry), it is preferred to provide RC band at lintel level. Whereas, National Building Code shows a CM building figure in which the door opening is for full storey height, i.e. up to slab level. Similar is the case for windows as well, which is not true in Indian practice. Hence, it was felt to investigate the CM aspect from Indian perspective. Thus, the suggested alternative was made by providing bond beam at lintel level, adequately connected to tie-column and confining masonry. Further, the rigid diaphragm action of RC slab and bond beam confine spandrel masonry adequately. For this reason, a comprehensive masonry test programme for Indian context was undertaken at CSIR-CBRI, with an aim to evaluate the seismic behaviour of indigenously built masonry buildings.

Experimental programme

URM, RM and CM were designed with reference to IS 1905 : 1987 (ref. 37), IS 4326 : 2013 (ref. 38) and EC-6 (ref. 39) respectively. The seismic design parameters were considered as per IS 1893 : 2002 as specified in Table 1. The full-scale building models with uniform geometry and material properties were constructed with locally prevailing construction practices. The masonry buildings were 3.01 × 3.01 m in plan and 3.0 m in height, having 220 mm thick walls and 100 mm thick RC slab. CM building was provided with 200 mm thick bond beam at lintel level and 220 × 220 tie-columns with 40 mm toothing with masonry. The structural details of CM building are shown in Figure 5. Table 2 shows material specifications and structural details of tested masonry buildings. Figure 6 shows full-scale URM, RM and CM building models subjected to quasi-static displacement controlled reversed cyclic lateral loading tests at roof level. A foundation beam was casted on the strong floor of the laboratory and fixed through steel buttress.

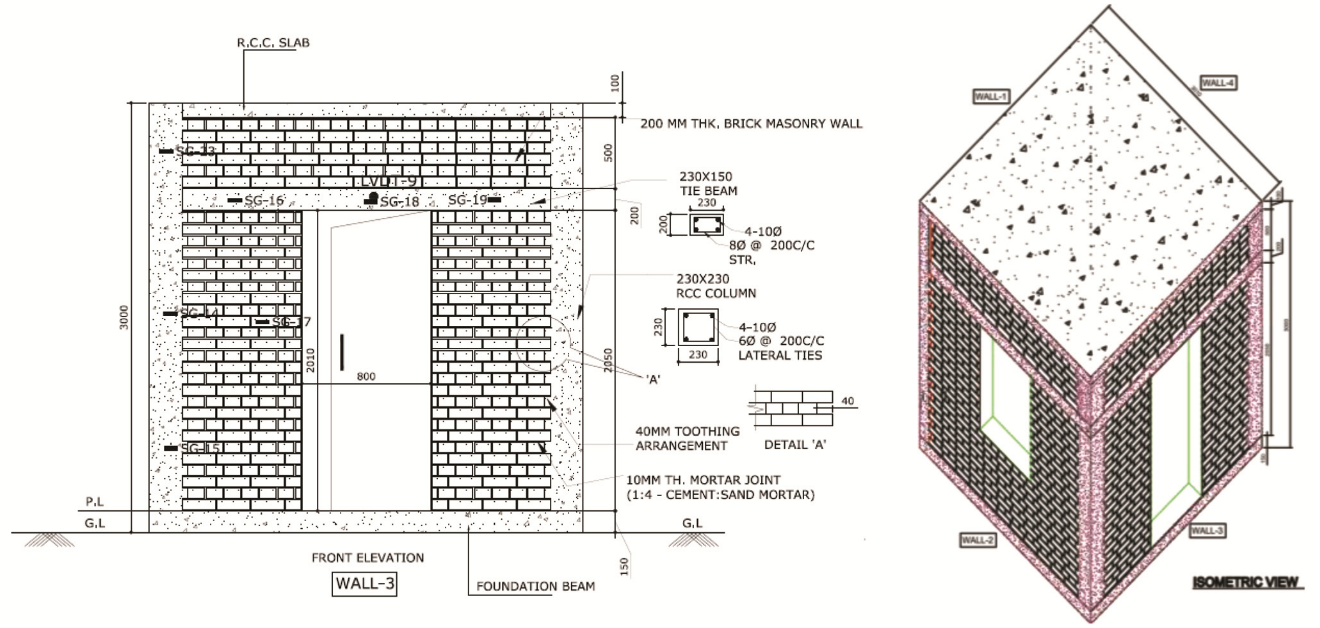


Figure 5. Structural details of tested CM building.

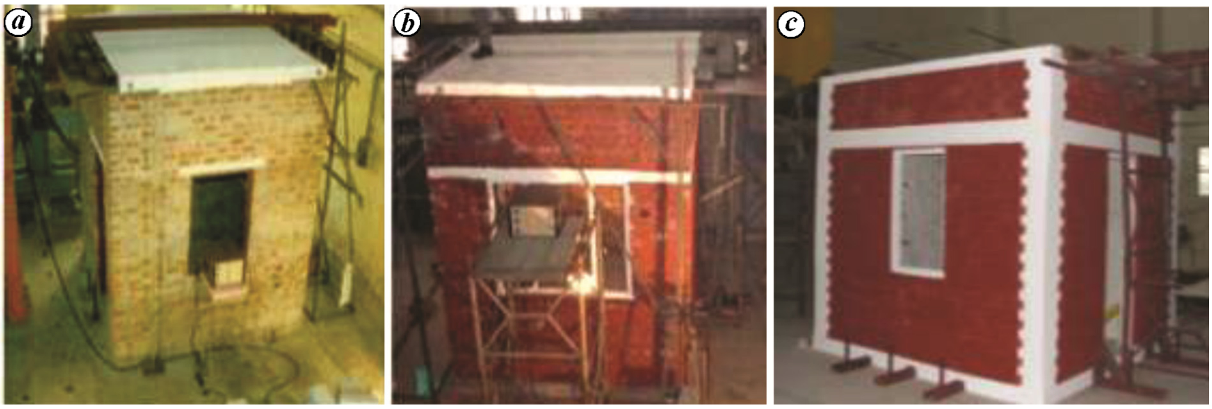


Figure 6. View of (***a***) URM; (***b***) RM; and (***c***) CM building.

The cyclic loading was applied through a servo-hydraulic actuator with 500 kN capacity and 75 mm stroke length. The deformation of the buildings at critical locations was measured using linear variable displacement transducer (LVDT) and acquired in data acquisition system. The tests were terminated before reaching the collapse state to prevent damage to test instruments and equipments.

The performance of masonry buildings was assessed with respect to damage pattern, lateral load capacity, stiffness and drift. URM demonstrated brittle failure with significant diagonal cracks and slab sliding. On the other hand, intensity of cracks was relatively low in RM, owing to the provision of RC lintel band and corner vertical reinforcement, which formed an integral box mechanism and allowed out-of-plane and in-plane walls to effectively contribute in resisting the lateral load. CM experienced horizontal cracks along the mortar joint in lower courses of the masonry wall during initial displacement cycles. Diagonal cracks initiated near the opening corners and propagated diagonally in the masonry. These cracks were arrested by bond beam and tie-columns to propagate further into spandrel masonry and corners of the wall. However, at higher loading, masonry crushing at compression toe was observed. Overall, CM exhibited confinement action due to bond beam and tie-column, leading to improved seismic performance. Figure 7 shows damage pattern of CM building after the test. The experimental load-deflection envelope of different masonry models, i.e. URM, RM and CM is shown in Figure 8. The overall observation shows major improvements in seismic performance of CM building over URM and RM, with features such as increase in lateral strength, stiffness, drift, ductility and response reduction factor as well as improvement in stability, integrity and containment of

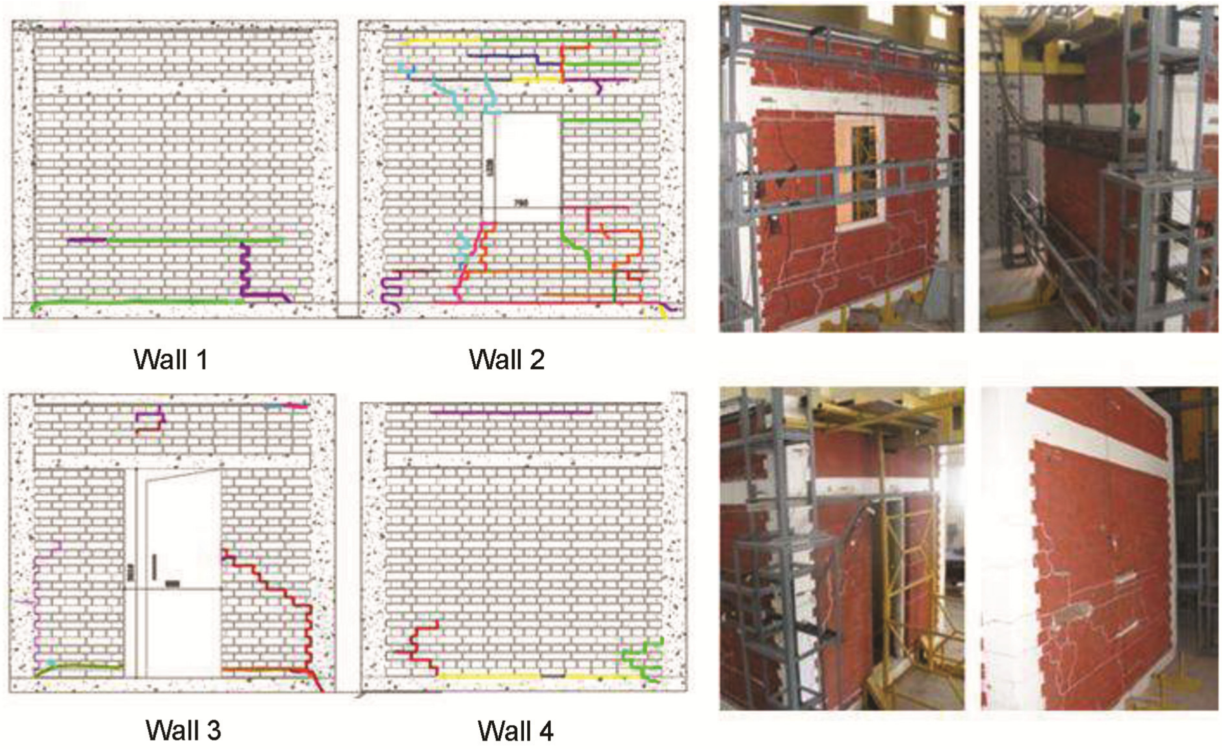


Figure 7. Damage pattern of tested CM building.

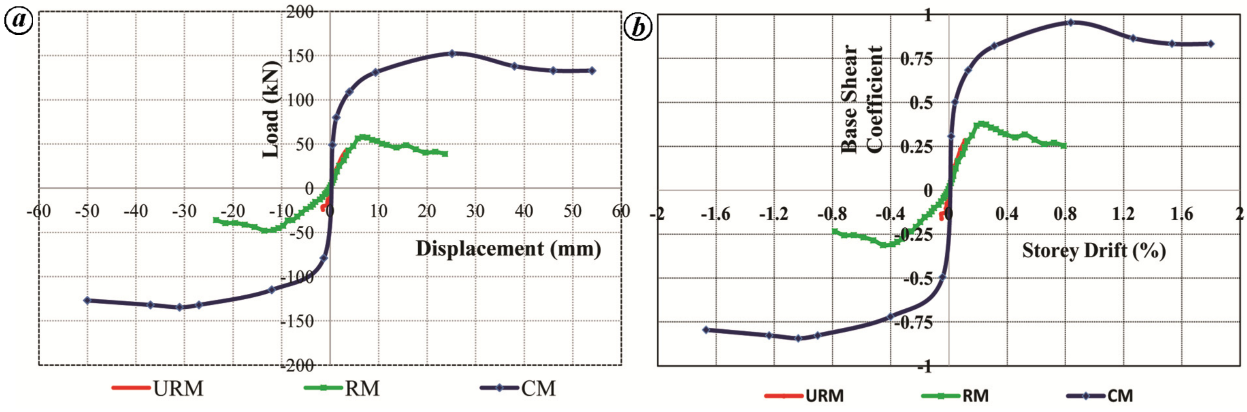


Figure 8. Average envelope curve for different masonry systems in terms of (***a***) lateral load-deformation; and (***b***) non-dimensional form.

Table 3. Peak lateral load, stiffness and drift

Building typology	Maximum lateral load (kN)	Initial stiffness (kN/m)	Drift (%)
URM	44.50	14.83	0.123
RM	57.85	15.30	0.790
CM	152.25	56.74	1.800

masonry walls. Table 3 demonstrates the obtained peak lateral load, stiffness and drift for URM, RM and CM, exhibiting excellent performance of CM. It is to be noted that the tests were terminated when crack width under lateral load exceeded more than 5 mm, so as to prevent damage to equipments.

As CM building construction uses the same materials and techniques to that of URM, but with higher level of safety, there is ample opportunity to adopt this technology in India as a feasible housing alternative. However, its economics need to be analysed in detail, as compared to other structural systems. Majority of the building stocks in India range up to four storeys, comprising different building typologies, i.e. RC framed structure with masonry infill, URM and RM. Adequate seismic resistance along with reduction in construction cost of buildings is one of the challenges to be addressed by the structural engineer. The experimental results demonstrated higher seismic resistance of CM buildings, as compared to URM and RM. Hence to balance strength, safety and economy,

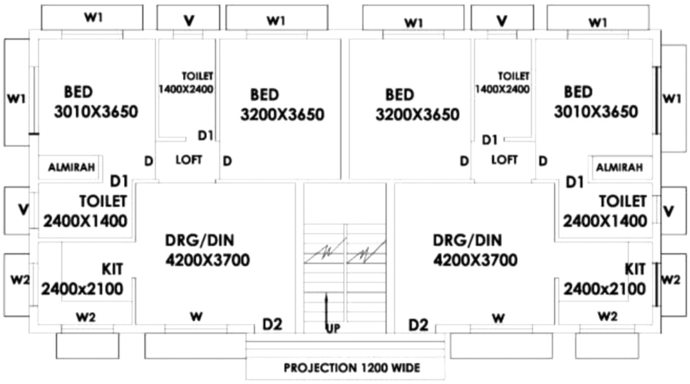
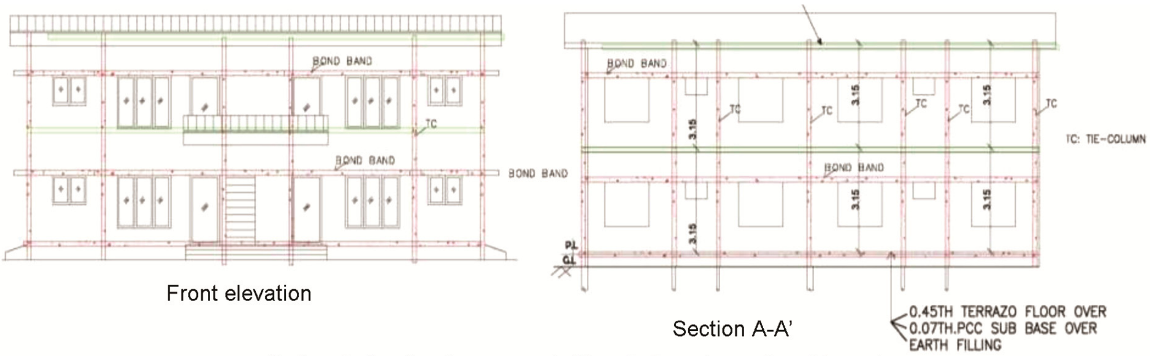


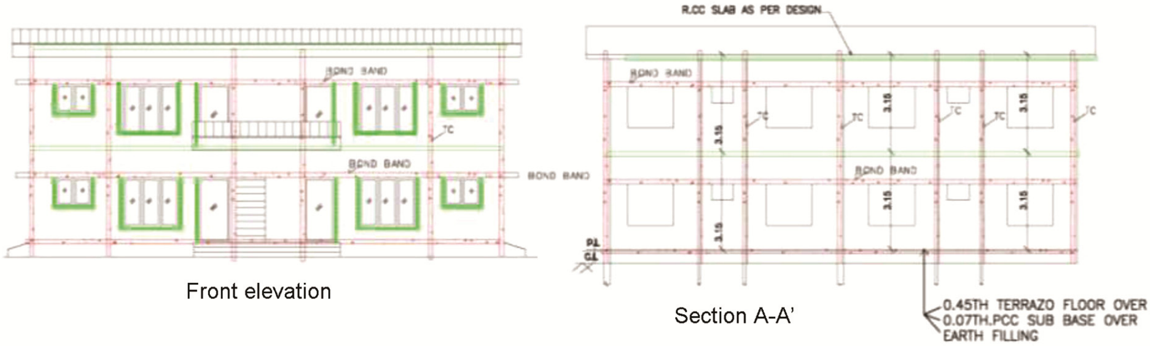
Figure 9. Typical plan of a building for cost analysis.



Front elevation

Section A-A’

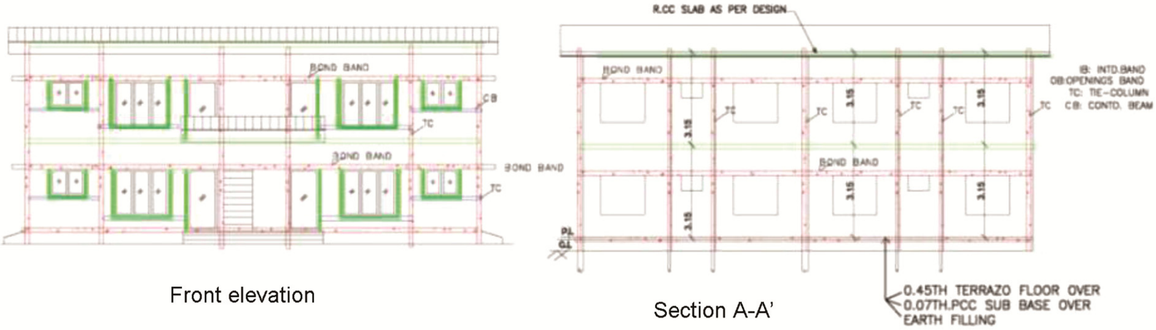
Option-1: Confined masonry (with only tie-column, bond beam)



Front elevation

Section A-A’

Option-2: Confined masonry (with tie-column, bond beam intermediate bond beam, band around openings and horizontal reinforcement at every 4th course)



Front elevation

Section A-A’

Option-3: Confined masonry (with tie-column, bond beam intermediate bond beam (continuous TC–TC), band around openings and horizontal reinforcement at every 4th course)

Figure 10. Option I: Typical details of various options incorporated in CM. Option II: Typical details of various options incorporated in CM. Typical details of various options incorporated in CM.

CM may be adopted as an appropriate solution. However, to justify the economy in construction, rigorous cost analysis is warranted.

Economic aspect

To carry out economic study of different building typologies in Indian buildings, 20 complex residential building plans ranging up to four storeys were considered. Figure 9 shows a typical plan of a building consisting of living room, kitchen, stair-case, balcony, etc., which is the commonly adopted building layout in India, with a storey height ranging between 3 and 3.4 m. These buildings were designed as RC, URM, RM and CM for uniform design parameters, i.e. seismic zone – IV (PGA = 0.24 g), live load (2 kN/m^2) and founded on soil having safe bearing capacity of 100 kN/m^2 at 1.50 m from natural ground level. Similarly, uniform material properties, viz. grade of concrete (M20), grade of reinforcement (Fe415), masonry (compressive strength – 7.5 MPa, in 1 : 6 cement : sand mortar with 19.2 kN/m^3 as masonry density) were considered in the design. CM buildings were designed with three different features: (i) CM building comprising only tie-columns and bond-beams (CM1); (ii) CM building with additional feature of RC element around openings (CM2), and (iii) CM building consisting of RC elements around opening for full height/width of the panel and one 8 mm diameter horizontal reinforcement in mortar joint at every fourth course of masonry (CM3). The typical details illustrating the various options of CM considered for deriving economic aspects are provided in Figure 10.

The RC buildings were designed in accordance with the relevant Indian standards, viz. IS-456 : 2000, IS-1893 : 2002 and IS-13920 : 1993 (refs 40–42). Similarly, URM, RM and CM buildings were designed as per IS-1905 : 1987 and IS-4326:2013 (refs 37, 38). In addition, Eurocode-EC6 was also referred in the design of CM buildings[39]. A detailed quantity estimation of each building was carried out for different items and their costs were calculated based on prevailing market rates in India and CPWD-Delhi Schedule of Rates (DSR) (2014).

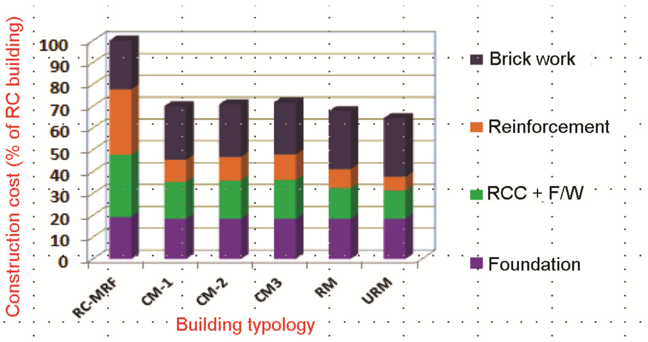


Figure 11. Average construction cost of masonry buildings with reference to RC framed building.

To have more clarity in cost comparison, the values are expressed in terms of percentage of total cost of RC building as a reference. Figure 11 shows the average overall construction cost along with the cost of major items for different building typologies. It can be seen from Figure 11 that URM construction costs 64.4% to that of RC building. Similarly, RM, CM1, CM2 and CM3 cost an average of 67.6%, 69.33%, 70.76% and 71.68% respectively to that of RC. The figure indicates that average cost of construction of foundation is almost similar in case of URM, RM and CM while it is slightly higher for RC buildings. Higher cost component of RC building is due to the cost of reinforcement and concrete.

Based on the above analysis, it can be summarized that CM, RM and URM buildings allow an average cost reduction of structure by 30%, 33% and 36% respectively with reference to RC framed buildings. Thus, CM offers significant amount of saving as compared to construction cost of RC building along with assurance of higher level of safety when compared with URM/RM buildings.

Conclusion

The goal of the present paper is to develop a framework that provides the essential information to construct CM buildings with good seismic resistance, considering the scenario of masonry buildings in India. To understand the seismic behaviour of CM, extensive reported experimental data and damages of CM buildings in major earthquakes are analyzed. Also, the test results of quasi-static lateral cyclic loading on full-scale single storey masonry buildings, viz. URM, RM and CM in Indian context have been taken into account. To demonstrate economic aspects of CM building, an ensemble of 20 building samples representing typical housing in India are designed as RC, URM, RM and CM with uniform design parameters and site condition. The conclusions drawn are:

(1) Considering the present masonry building scenario and its vulnerability in India, CM emerged as a promising construction technology showing better seismic performance compared to unreinforced and reinforced masonry.

(2) The failure mechanism of CM building under seismic actions is mainly due to diagonal shear failure. Flexural failure at initial stage within elastic limit occurs due to low vertical loads. In three to five storey CM buildings, deformation and damages concentrate at first storey showing shear failure, and hence calls for adequate checks for shear.

(3) Keeping in view of Indian construction practices for residential buildings, bond beam is provided at lintel level. The provision of bond beam at lintel level contributed in damage control due to the confinement of spandrel masonry within bond beam, RC slab and tie-column.

(4) The tested masonry buildings (URM, RM and CM) demonstrated distinguished seismic behaviour from the standpoint of damage pattern, lateral strength and drift. URM exhibited brittle failure with diagonal cracks in masonry, sliding of RC slab along with low lateral strength. Contrary, RM demonstrated 30% increase in lateral load carrying capacity attributed to corner vertical reinforcement and RC band. CM exhibited flexural and diagonal cracks in in-plane walls. While confining RC elements, toothing between tie-column and masonry provided encasement and integral action to the masonry. Consequently, CM showed improved seismic performance with lateral strength of 3.42 and 2.63 times to that of URM and RM respectively.

(5) CM buildings exhibited higher initial stiffness and drift compared to URM and RM buildings. Enhancement in seismic characteristics of CM building typology over URM and RM forms the basis of its potential to withstand ground motions.

(6) CM, RM and URM buildings allow average cost reduction of structure by 30%, 33% and 36% respectively, than that of RC frame buildings. Thus, CM can be adopted for low-to-medium rise buildings ensuring good seismic performance and economy.

It is hoped that this article will help sensitize and inform building professionals in India and elsewhere about the excellent features of confined masonry, and will propagate a better construction technology in the country and worldwide.

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