Evaluation of Shear Demand on Columns of of Masonry Infilled Reinforced Concrete Frames

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SUMMARY:
Masonry infilled reinforced concrete (RC) frames under the action of in-plane lateral loads often fail due to shear failure in columns. This is attributed to additional shear force generated on RC columns of such frames because of development of compressive diagonal strut in masonry infill walls. In the current experimental cum analytical study, an attempt has been made to evaluate the actual shear demand on columns by testing half scaled specimens of masonry infilled RC frames under displacement controlled slow cyclic lateral loads. The shear demand thus estimated was found to be significantly higher than the provided shear capacity of columns. Therefore, shear capacity of the columns was enhanced by upgrading the design of shear reinforcement appropriately and by increasing the compressive strength of concrete, and two specimens with the mentioned improvements were tested. It was observed that these infilled frames with enhanced shear capacity exhibited significantly better shear behaviour.

Keywords: reinforced concrete, masonry infill, shear failure, seismic design, cyclic loading.

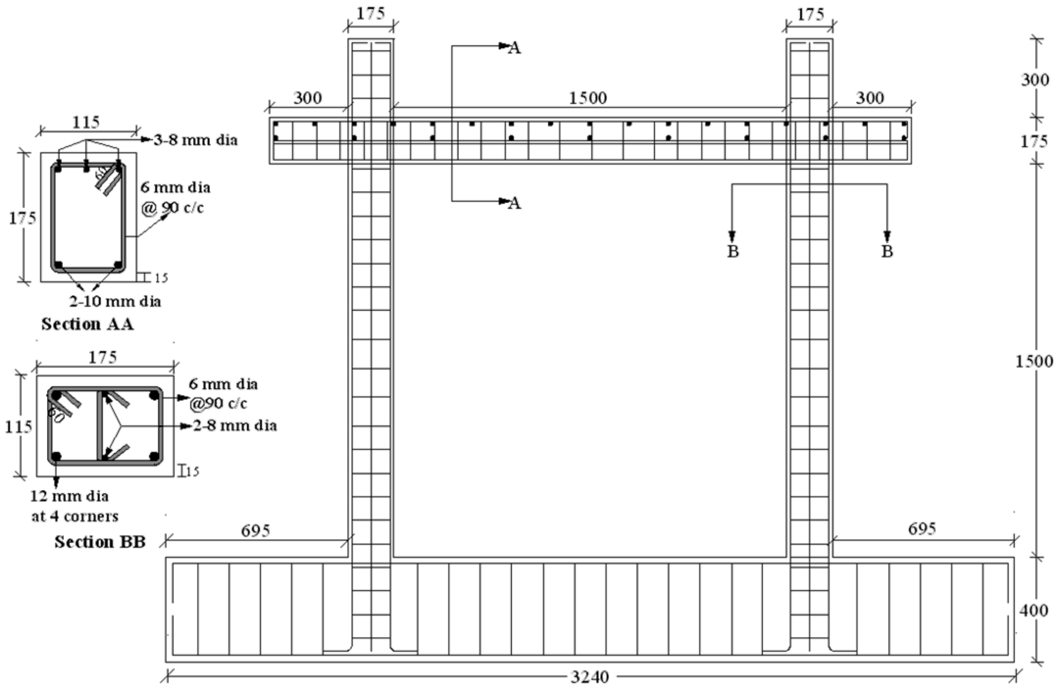
1. INTRODUCTION

Masonry infilled reinforced concrete (RC) frame buildings are the most common structures in several countries including India which are prone to earthquakes. The presence of masonry infills in framed structures significantly modifies the structural response to strong ground motion in terms of stiffness, strength and failure modes. Even though infills impart highest resistance during earthquakes, infills are considered as non-structural elements in analysis and design due to variety of reasons that vary from region to region.

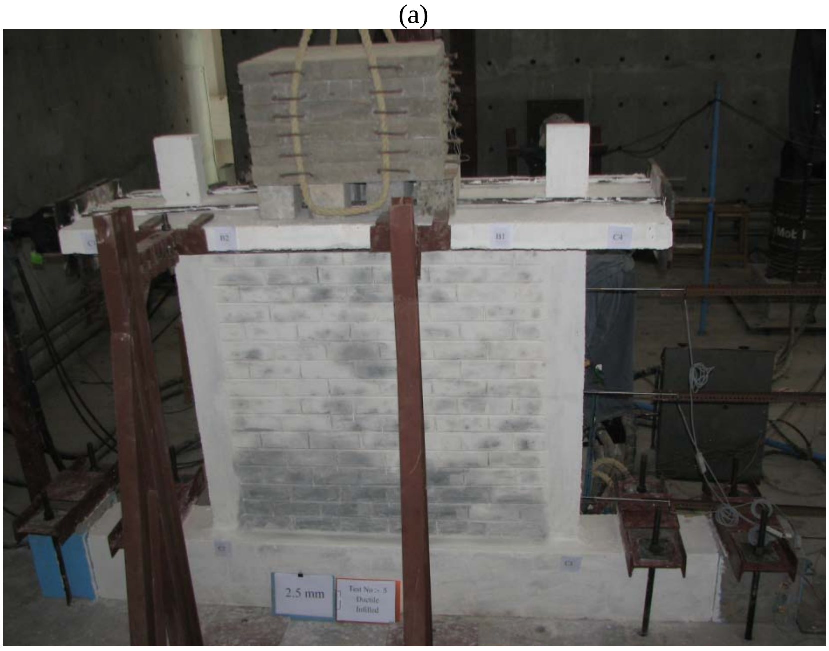
In the last five decades a lot of research has been carried out on masonry infilled RC frames and the understanding level on the behavior of infilled frames has been outstanding. Irrespective of the much research till date it has been a difficult task to quantify the interaction of infill with the surrounding frame. Several relevant past research were presented in state of art reports by Moghaddam & Dowling (1987) and CEB (1996). In the recent years most of research is mainly concentrated on improving the design provisions and proposals to avoid unwanted failure mechanisms of masonry infilled RC frames (Crisafulli et al. 2000, Fardis 2000, El-Dakhakhni et al. 2004, D'Ayala et al. 2009, Kaushik et al. 2009 and Mohammadi et al. 2011). The objective of the current study is to evaluate a design strategy in order to delay the shear failure of RC columns in masonry infilled frames. For this purpose eight half scaled specimens were tested and their behavior in terms of influencing parameters like strength, stiffness, energy dissipation, ductility and failure modes were compared. From the experimental study it was observed that all the infilled specimens were failing due of shear failure of columns. Analytical study was carried out to evaluate the conditions leading to the failure of the infilled frames. Based on the results obtained in the analytical and experimental study, a method for estimation of realistic shear demand on RC columns of infilled frame was developed. Shear capacity of RC columns of the frame was increased using the proposed method and two infilled frames with improved shear capacity were tested and the results were compared with the earlier tested frames.

2. EXPERIMENTAL PROGRAM

A RC frame from existing RC building was chosen and designed in accordance with relevant Indian standards and reduced to half-scale by dimensional analysis keeping in-view the constraints of laboratory. The size of beams and columns were 115×175 mm. A 90 mm thick slab was constructed over a width of 800 mm to assimilate the realistic gravity load on the building. The columns were constructed on a RC beam of size 400×350 mm, and to avoid out-of-plane movement of the frame under the action of lateral cyclic loads, the frame was supported by two roller bearing steel frames on either side. Reinforcement detailing of the frame is shown in Fig. 1a and it is in accordance with Indian standards (BIS 2000, BIS 1993). Test setup used in all the tests is shown in Fig. 1b.



(a)



(b)

Figure 1. (a) Reinforcement detailing of ductile frame considered in the present study; (b) details of instrumentation and test set up.

Details of the RC frame specimens tested in the current study are given below. All the specimens were tested after 28 days of casting, and results of the tests will be discussed in the next section.

- Ductile Bare Frame (without infill wall)
  The term ductile in the current study is referred to define that the frames were designed for both gravity and earthquake loads (BIS 2000, BIS 2002) and to follow the ductility provisions of IS 13920 (BIS 1993). In ductile bare frame, transverse reinforcement of columns was provided in the form of 3-legged stirrups at a spacing of 90 mm upto a distance of 500 mm from the face of top and bottom beams, respectively, and rest at a spacing of 110 mm (Fig. 1a). Shear reinforcement in beams was provided in the form of 2 legged stirrups at a spacing of 90 mm upto a distance of 500 mm from the face of both columns, and at a spacing of 120 mm rest. The other reinforcement details are shown in Fig. 1a.
- Non Ductile Bare Frame (without infill wall)
  Non ductile bare frame was designed to resist both gravity and earthquake loads (BIS 2000, BIS 2002) but was not detailed to exhibit ductility (BIS 1993). The shear reinforcement in columns and beams was provided at a spacing of 110 mm and 120 mm throughout the length, respectively. The remaining reinforcement details and strength of concrete were same as that of the ductile bare frame (Fig. 1a). Both ductile and non ductile frames serve as the reference frames in the current study.
- Ductile Frame Infilled with Full Scale Bricks
  In ductile frame infilled with full scale bricks, infill wall was constructed with full scale bricks of size 230 mm×110 mm×75 mm. A 1:4 (cement: sand) mix mortar was used with a water cement ratio of 0.6. The reinforcement details and strength of concrete were as same as that of the ductile bare frame.
- Non Ductile Frame Infilled with Full Scale Bricks
  Reinforcement detailing was same as that of non ductile bare frame and the construction of wall was carried out using full scale bricks.
- Ductile Repaired Frame Infilled with Full Scale Bricks
  One of the most common retrofitting strategies used for damaged RC frames is simply replacing the concrete in damaged RC members by welding additional steel in the region where reinforcing steel has yielded. In addition, shear reinforcement is also provided wherever required. This strategy has been studied in the current study by testing two retrofitted frames. The tested and damaged ductile frame infilled with full scale bricks was repaired by replacing the damaged concrete after welding additional reinforcing bars in the region where reinforcing bars have yielded during the test. The other reinforcement details (transverse reinforcement) were same as that of the ductile bare frame. Casting of frame was carried out without increasing the column and beam size, and the same type of mix design of concrete was used. Wall was constructed using full scale bricks and same mortar mix was used with a water cement ratio of 0.6.
- Non Ductile Repaired Frame Infilled with Full Scale Bricks
  Using the same methodology of retrofitting as discussed above for the ductile frame specimen with full scale bricks, the Non ductile frame infilled with full scale bricks was also repaired. The new shear reinforcement details were provided same as that of non ductile bare frame.
- Ductile Frame Infilled with Half Scale Bricks
  In this specimen half scaled bricks (115 mm×55 mm×37.5 mm) were used to construct the infill wall instead of the full scale bricks. The reason behind using half scale bricks was to resemble the model as per dimensional analysis. The reinforcement details and strength of concrete were same as that of the ductile bare frame.
- Non Ductile Frame Infilled with Half Scale Bricks
  In this specimen, half scaled bricks were used to construct the infill wall and the other details of the frame were same as that of the non ductile bare frame.

Some of the experimental results used in the current study have been taken from a previous study (Manchanda 2010). Material properties of concrete, steel and masonry were determined by conducting tests in according with Indian standards. The average compressive strength of concrete cubes at 28 days was 23 MPa. The compressive strength of brick units were around 5 MPa and that of masonry prisms was found to be about 2-3 MPa. A 1:4 mix (cement:sand) mortar with water cement ratio of 0.6 was used in the construction of the masonry infill wall; compressive strength of mortar cubes was found to be about 6-8 MPa. Lateral cyclic loading was applied using a 250 kN load capacity and ± 125 mm displacement capacity servo controlled hydraulic actuator. The lateral deflection along the length of the column was measured with external LVDTs and strain gauges were used to record the strain in reinforcement bars of beams and columns of the frame. Three cycles of same displacement level (Fig. 2) was applied and the response of the system was recorded using a data acquisition system. All specimens were tested till their failure.

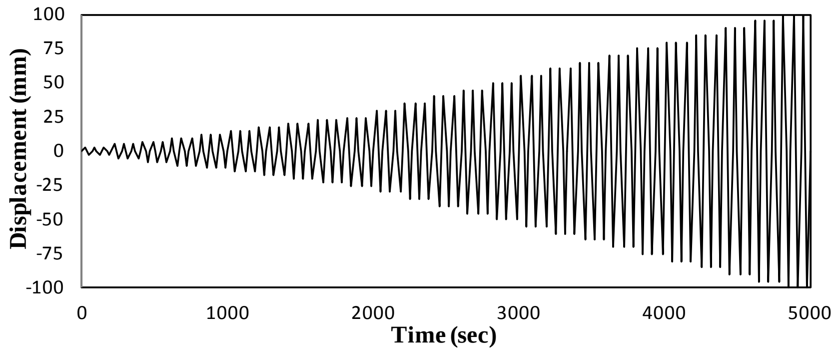


Figure 2. Displacement history applied on specimens.

3. RESULTS

Lateral load response of all the specimens tested is presented in the form of hysteresis loops as shown in Fig. 3. From the figure it can be noted that loops are more or less symmetrical in both push and pull directions. It was observed that the lateral load resistance of all masonry infilled frames degraded drastically, compared to the bare frames, after cracking of masonry walls. This behaviour of masonry infilled RC frame shows that one should not rely only upon masonry infill walls for lateral load resistance. Primary objective of the current study is to improve the shear design of RC columns of masonry infilled RC frames based on the test results such that shear failure can be delayed significantly. It is expected that this may further result in improving the lateral load resistance and failure modes of the frames.

Lateral strength, stiffness and energy dissipation that influence the lateral load behavior of masonry infilled RC frames are calculated and shown in Table 1. The initial stiffness of infilled frames is about 7.5 to 10 times of the corresponding bare frames. Ductile and non ductile frames infilled with half scale bricks exhibited higher initial stiffness when compared with frames infilled with full scale bricks. It was primarily due to the fact that the lateral load resistance of frame infilled with half scaled bricks was significantly higher than that of the ductile frame infilled with full scale bricks in the first displacement cycle (77 kN and 44 kN, respectively). Table 1 also shows the lateral load carrying capacity of all the frames after normalizing with the yield stress of the reinforcing bars. This is to take care of the difference in the yield stress of reinforcing bars used in the study.

It is well known that masonry infills act as the chief energy dissipating mechanisms during earthquake excitations and the same can be interpreted from Table 1. The energy dissipation of ductile frame infilled with half scale bricks was very low, as the frame failed at a displacement level of 55 mm where as the other frames failed at a much higher displacement level of 75 mm. It may be due to the fact that the frame resisted higher lateral load in the initial stage itself that lead to early damage (Fig. 3). As the amplitude of the displacement level increased, failure in infill commenced and lead to the degradation of stiffness and lateral load carrying capacity. Ductile repaired frame infilled with full scale bricks observed the highest lateral load carrying capacity in the current study.

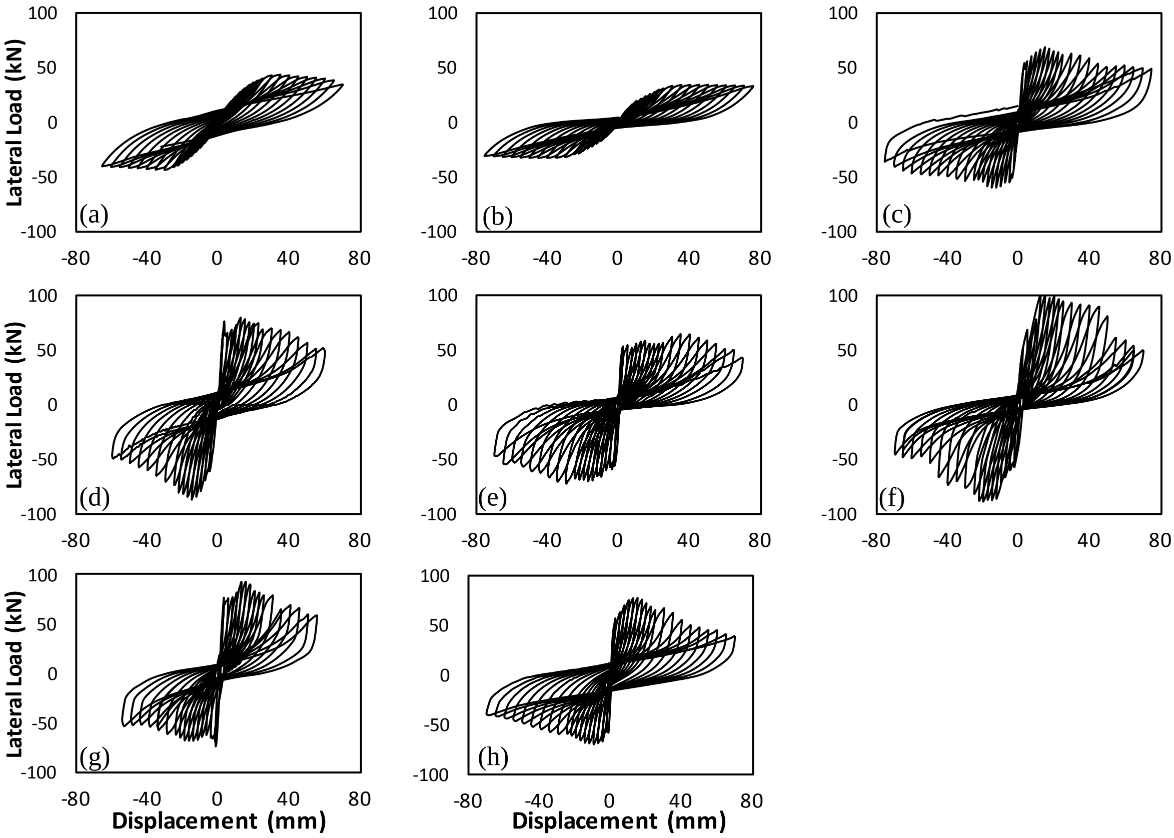


Figure 3. Hysteretic behavior of infilled frames; (a) ductile bare frame, (b) non ductile bare frame, (c) ductile frame infilled with full scale bricks; (d) non ductile frame infilled with full scale bricks; (e) ductile repaired frame infilled with full scale bricks; (f) non ductile repaired frame infilled with full scale bricks; (g) ductile frame infilled with half scale bricks; (h) non ductile frame infilled with half scale bricks.

Table 1. Parameters influencing the behavior of tested specimens

S. No	Type of frame	Initial Stiffness	Energy Dissipation	Maximum Lateral Load
		(kN/mm)	(kNmm)	(kN)
1	Ductile bare frame	4.0	15500	44 (0.09)*
2	Non ductile bare frame	3.2	11400	33 (0.07)*
3	Ductile frame infilled with full scale bricks	28.6	22800	73 (0.16)*
4	Non ductile frame infilled with full scale bricks	29.2	18900	87 (0.19)*
5	Ductile repaired frame infilled with full scale bricks	30.5	17600	63 (0.14)*
6	Non ductile repaired frame infilled with full scale bricks	31.2	22000	101 (0.21)*
7	Ductile frame infilled with half scale bricks	31.0	15300	93 (0.20)*
8	Non ductile frame infilled with half scale bricks	30.1	27000	76 (0.16)*

* Numbers in the brackets are maximum lateral load normalized with yield strength of steel.

5. Failure modes

The cracks developed in the RC members of the frame as well as in masonry infill wall were marked during the testing and the failure modes were identified based on the crack pattern observed (Fig. 4). During the initial stages of the test most of the cracks were concentrated in the masonry infill walls, later they propagated to the RC frame elements. Similar crack pattern was witnessed in masonry infill walls in almost all the test specimens. The order of formation of cracks in infill can be characterised as the interface cracks between RC frame and infill wall itself along the periphery, sliding of brick layers due to the weakening of mortar joints, diagonal cracking in the wall, and crushing of infill in the corners. In some cases sliding of bricks layers was observed even before diagonal cracking in walls. In case of ductile and non ductile repaired frames, damage in infill was very less when compared to RC members (Fig. 4e and 4f). In case of frames infilled with half scale bricks similar crack pattern was observed as in the case of frames infilled with full scale bricks, but in case of the specimens with half scale bricks, out-of-plane movement of the wall was observed after a displacement level of 50 mm.

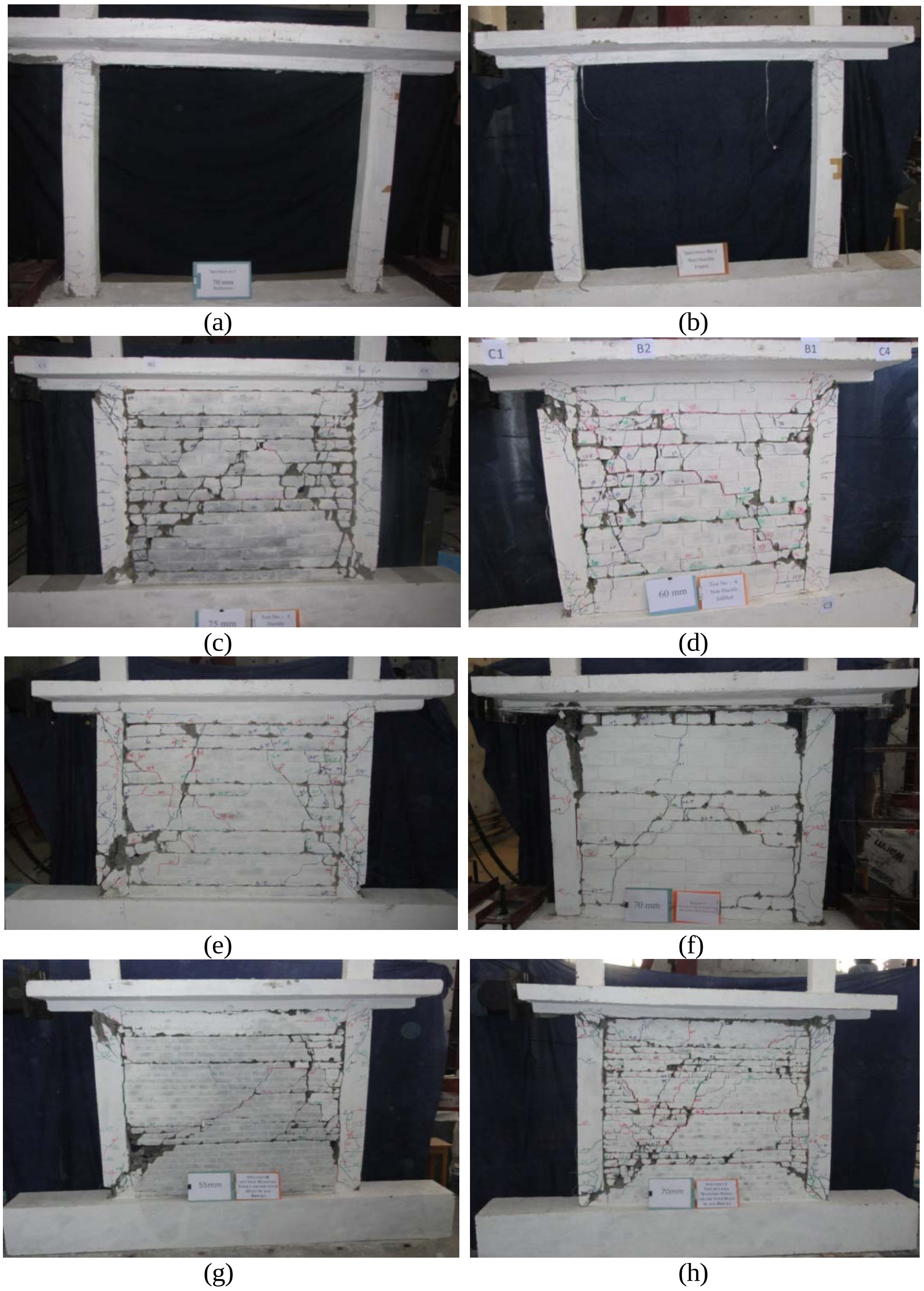


Figure 4. Failure mechanisms of infilled frames; (a) ductile bare frame, (b) non ductile bare frame, (c) ductile frame infilled with full scale bricks; (d) non ductile frame infilled with full scale bricks; (e) ductile repaired frame infilled with full scale bricks; (f) non ductile repaired frame infilled with full scale bricks; (g) ductile frame infilled with half scale bricks; (h) non ductile frame infilled with half scale bricks.

In case of bare frames flexural cracks developed in the beginning of the test along the column length, and shear cracks were observed at a much later displacement level (~ 22.5 mm) in columns near the beam column connections. On the other hand, shear cracks in columns (near the beam-column connections) of the infilled frames were observed at a low displacement level of 12.5 mm, and flexural cracks were observed along the length of the column at later stage. Plastic hinges were not observed in RC beams of any of the frames, though minor damage was observed in beams of some specimens. This highlights the rigid RC slab-beam connection (T-beam action) of the frame. The final failure can be characterised as the crushing of bricks in the corners, out-of-plane movement of infill wall in half scale brick frames, crushing of concrete and shear failure of columns near the beam column connections. It is important to mention here that RC columns in all the specimens with masonry infill walls failed prematurely in shear mode. This is primarily due to transfer of the high shear forces from masonry infill wall to finite portions of RC columns of the frame (contact length of wall and RC columns). Therefore, it is important to evaluate the actual and realistic shear demand on RC columns of masonry infilled frames, and then design these columns for improved shear capacity such that the shear failure in RC columns is delayed, if not completely prevented.

4. ANALYTICAL STUDY

Actual shear demand on the columns of masonry infilled RC frames under the action of lateral loads was evaluated in the current study by modelling the effect of masonry infill walls as a uniformly distributed load along the contact length of the column (Fig. 5). In the present study contact length was estimated using three methods: from experimental observations, from width of equivalent diagonal strut, and from empirical formulae available in literature. The empirical relation suggested by Stafford-Smith (1967) has been used in the current study to estimate the contact length between RC column of the frame and masonry infill walls. The contact length was estimated by modelling the masonry infill walls as equivalent compressive diagonal strut in case of geometric calculations. In case of photographic studies, the length of contact was calculated from the crack pattern marked during the test. The effect of infill is calculated using the axial compressive strength of masonry as $F=f'_m \times w_s \times t$, where f'_m is the masonry prism strength, w_s is the width of the equivalent diagonal strut, and t is the thickness of the infill wall. The width of the strut w_s is calculated from the initial stiffness of the masonry $k_i=(A_s \times E_m)/l_m=(w_s \times t \times E_m)/l_m$, where A_s is the equivalent area of the diagonal strut, E_m is the modulus of elasticity of masonry calculated as 550 times f'_m, and l_m is the diagonal length of the masonry wall. The horizontal component of the axial strength of infill is applied along the contact length and analysis was carried out.

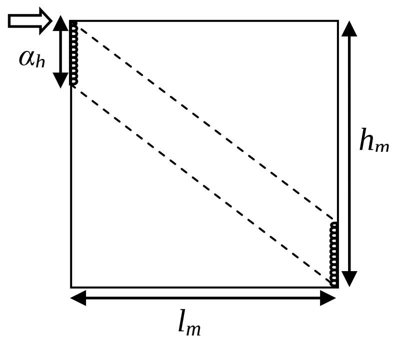


Figure 5. Estimation of actual shear demand on RC columns of masonry infilled RC frames

The analyses results showed that shear capacity of the RC columns was lower than the demand estimated using the above mentioned method. The shear demand on RC columns of various frames tested in the current study was found to be about 40-60 % more than the shear capacity of these columns. Therefore, in order to delay the shear failure in columns, shear capacity was enhanced by upgrading the design of shear reinforcement appropriately and by increasing the compressive strength of concrete. Two ductile masonry infilled RC frame specimens (with full scale bricks) with improved column shear capacity were then tested to validate the method developed in the current study for estimation of actual shear demand on RC columns. In one of these frames transverse reinforcement in the form of 8 mm diameter bars with 3 legs were provided at a spacing of 90 mm throughout the length of the column (6 mm bars were used in the original frame). In the second frame, 8 mm diameter bars with 3 legs at a spacing of 90 mm in critical regions (500 mm from the face of the top and bottom beam) and at a spacing of 110 mm along the remaining length of the columns were provided as shear reinforcement. In addition, the compressive strength of concrete cubes was also increased from 20 MPa to 25 MPa in both the specimens.

The proposed method for estimation of actual shear demand on RC columns of masonry infilled RC frames is an improvement over current requirements of Eurocode 8 (CEN 2004) and IS 13920 (BIS 1993). According to Eurocode 8, where infills extend to the entire length of the adjacent columns and there are masonry walls on only one side of the column, the entire length of the column is treated as a critical region and is reinforced with the amount and pattern of stirrups required for critical sections. Similarly according to IS 13920 columns supporting reactions from discontinued stiff members, such as walls, shall be provided with special confining reinforcement over their full height. Though these codes anticipate increased shear demand on RC columns due to interaction between RC frame and masonry infill wall under the action of lateral earthquake loads, a method for estimation of the increased shear demand is not described in any of the codes.

The specimens with improved shear capacity were tested and the results of the same are presented in Table 2. From the hysteresis loops (Fig. 6) it can be observed that the loops are closely spaced in the initial stages before reaching maximum lateral load carrying capacity, later they are unevenly spaced which may be due to the failure of infill and frame entering into non linear region. The initial stiffness, lateral load resistance, and energy dissipation of ductile infilled frames with improved shear capacity are comparable to the previously tested specimens. The tensile strength of steel reinforcing bars used in shear capacity improved frames was less than that of steel in the earlier specimens and this may be the reason for the frames to exhibit lesser load carrying capacity. The crack pattern observed in masonry infill wall of the shear capacity improved frames was similar to that observed in infill wall of the other frames. The shear cracks in RC columns of shear capacity improved frames were observed to be initiated at a lateral displacement level of 15 mm near the loading corner. Later most of generated cracks in RC columns were flexural cracks. Interestingly, volume of shear cracks developed in RC columns of previously tested masonry infilled RC frames was significantly more than that in case of the frames with improved shear capacity (Fig. 7a and 7b). Finally the test was stopped when the lateral load carrying capacity of the frame deceased to 75 % of its maximum. Final failure of the frame specimen took place due to crushing of RC columns near the beam-column joints and out-of-plane failure of masonry infill walls. This validates that the developed method for improvement of shear design of RC columns of masonry infilled RC frames is indeed helpful in reducing the shear cracks in columns under lateral loads, and thus, in delaying the shear failure of columns.

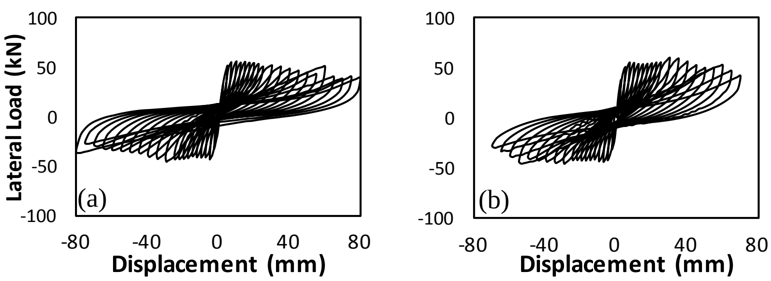


Figure 6. Hysteretic behavior of infilled frames: (a) ductile frame infilled with full scale bricks with improved shear capacity throughout the column length; (b) ductile frame infilled with full scale bricks with improved shear capacity in critical regions.

Table 2. Parameters influencing the behavior of tested specimens

S. No	Type of frame	Initial Stiffness	Energy Dissipation	Maximum Lateral Load
		(kN/mm)	(kNmm)	(kN)
1	Ductile frame infilled with full scale bricks with improved shear capacity throughout the column length	30.3	19900	55 (0.15)*
2	Ductile frame infilled with full scale bricks with improved shear capacity in critical regions	30.5	22800	60 (0.16)*

* Numbers in the brackets are maximum lateral load normalized with yield strength of steel.

(a) (b)

Figure 7. Failure modes: (a) ductile infilled frame with full scale bricks with improved shear capacity throughout the length of the column; (b) ductile infilled frame with full scale bricks with improved shear capacity in critical regions.

6. CONCLUSIONS

A fairly detailed experimental study involving testing of eight half-scale specimens of masonry infilled RC frames designed in accordance with the current code specifications exhibit significant higher lateral stiffness and lateral load resistance when compared to the bare RC frames. It was also observed that even though the behavior of the masonry infilled RC frames was excellent in terms of strength and stiffness under earthquake excitations, the frames failed prematurely mostly due to shear failure of columns which is an undesirable phenomenon at an early stage. Analytical study to evaluate the actual shear demand on the RC columns of such frames due to the effect of masonry infill was carried out by modelling the effect of infill along the contact of the column. Two frames with upgraded shear capacity were tested and the results compared with the previously tested specimens. The main difference between the original frames and the shear capacity improved frames was in the failure modes; the amount of shear cracks observed in shear capacity improved frames was very less when compared to the original infilled frames. In case of shear capacity improved frames, limited shear cracks were observed in RC columns mostly during the initial stages of testing, after which most of the developed cracks were flexural in nature. In comparison, most of the cracks developed in the original masonry infilled frames at different stages of loading were shear cracks. The approach proposed in the present study has given promising results. But a more in-depth study is needed in order to propose a model so as to delay the shear failure of columns under earthquake excitations.

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