1790

BENEFICIAL INFLUENCE OF MASONRY INFILL WALLS ON SEISMIC PERFORMANCE OF RC FRAME BUILDINGS

C V R MURTY[1] And Sudhir K JAIN[2]

SUMMARY

Masonry infills in reinforced concrete buildings cause several undesirable effects under seismic loading: short-column effect, soft-storey effect, torsion, and out-of-plane collapse. Hence, seismic codes tend to discourage such constructions in high seismic regions. However, in several moderate earthquakes, such buildings have shown excellent performance even though many such buildings were not designed and detailed for earthquake forces. This paper presents some experimental results on cyclic tests of RC frames with masonry infills. It is seen that the masonry infills contribute significant lateral stiffness, strength, overall ductility and energy dissipation capacity. With suitable arrangements to provide reinforcement in the masonry that is well anchored into the frame columns, it should be possible to also improve the out-of-plane response of such infills. Considering that such masonry infill RC frames are the most common type of structures used for multistorey constructions in the developing countries, there is need to develop robust seismic design procedures for such buildings.

INTRODUCTION

Most reinforced concrete (RC) frame buildings in developing countries are infilled with masonry walls. Experience during the past earthquakes has demonstrated the beneficial effects as well as the ill-effects of the presence of infill masonry walls. In at least two moderate earthquakes (magnitude 6.0 to 6.5 and maximum intensity VIII on MM scale) in India, RC frame buildings with brick masonry infills have shown excellent performance even though most such buildings were not designed and detailed for seismic response [Jain *et al*, 1991; 1997]; these buildings are characterised by fairly uniform configuration and small panel size (typically about $2.7m \times 3.5m$ with *0.23m* masonry thickness). The design codes have, however, been mainly focusing on the malefic effects. The seismic design of masonry infilled RC frame buildings is handled in different ways across the world. Some of the prevalent design practices are:

- Infills are adequately separated from the RC frame such that they do not interfere with the frame under lateral deformations. The entire lateral force on the building is carried by the bare RC frame alone.

- Infills are built integral with the RC frame, but considered as *non-structural* elements. The entire lateral force on the building is carried by the bare RC frame alone. This is the most common design practice in the developing countries.

- Infills are built integral with the RC frame, and considered as *structural* elements. The in-plane stiffness offered by the infill walls is considered in the analysis of the building. The forces from this analysis are used in the design of RC frame members and joints [e.g., CEN, 1994; NBC 201, 1994].

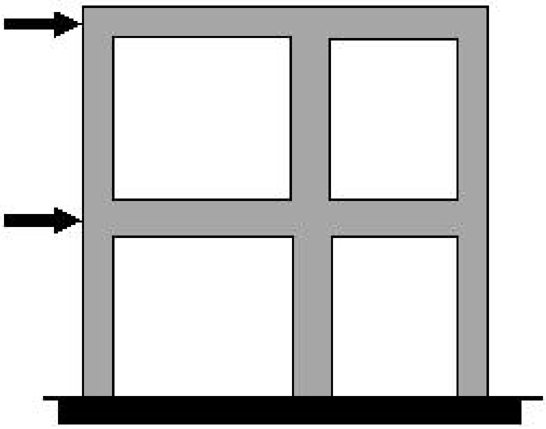
This paper presents experimental results of masonry infilled RC frames subjected to lateral loading. The performance of infilled masonry frames is compared with that of the bare frames. Masonry infills consist of unreinforced or reinforced burnt-clay bricks in cement mortar. Two cases of reinforced infills are considered -

[1] *Assistant Professor, Dept. of Civil Engg., Indian Institute of Technology, Kanpur 208016, India, Email:cvrm@iitk.ac.in*
[2] *Professor, Dept. of Civil Engg., Indian Institute of Technology, Kanpur 208016, India, Email:skjain@iitk.ac.in*

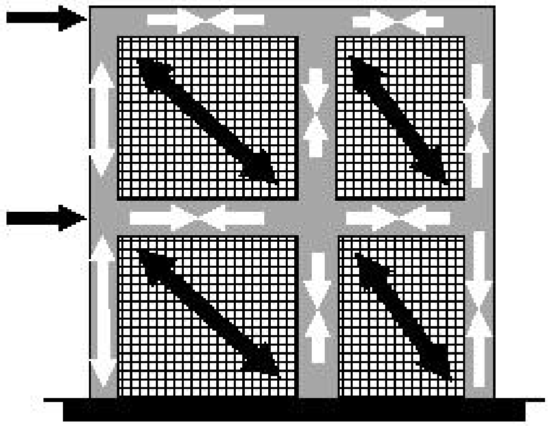
masonry with and without reinforcement anchored into the frame columns. The effect of brick size on the hysteretic response is discussed. Based on these experimental results and past analytical studies, this paper explores the beneficial effects of masonry infill walls on seismic behaviour of RC frame buildings.

INFLUENCE OF MASONRY INFILL WALLS

Significant experimental and analytical research effort has been expended till date in understanding the behaviour of masonry infilled frames [CEB, 1996]. Infills interfere with the lateral deformations of the RC frame; separation of frame and infill takes place along one diagonal and a compression strut forms along the other. Thus, infills add lateral stiffness to the building. The structural load transfer mechanism is changed from frame action to predominant truss action (Figure 1); the frame columns now experience increased axial forces but with reduced bending moments and shear forces.



(a) Frame action in bare frame



(b) Predominant truss action in infilled frame

Figure 1: Change in the lateral load transfer mechanism owing to inclusion of masonry infill walls.

When infills are non-uniformly placed in plan or in elevation of the building, a hybrid structural load transfer mechanism with both frame action and truss action, may develop. In such structures, there is a large concentration of ductility demand in a few members of the structure. For instance, the *soft-storey effect* (when a storey has no or relatively lesser infills than the adjacent storeys), the *short-column effect* (when infills are raised only up to a partial height of the columns), and *plan-torsion effect* (when infills are unsymmetrically located in plan), cause excessive ductility demands on frame columns and significantly alter the collapse mechanism. Another serious concern with such buildings is the out-of-plane collapse of the infills which can be life threatening. Even when the infills are structurally separated from the RC frame, the separation may not be adequate to prevent the frame from coming in contact with the infills after some lateral displacement; the compression struts may be formed and the stiffness of the building may increase.

Infills possess large lateral stiffness and hence draw a significant share of the lateral force. When infills are strong, strength contributed by the infills may be comparable to the strength of the bare frame itself. The mode of failure of an infilled building depends on the relative strengths of frame and infill (Table 1). And, its ductility depends on the (a) infill properties, (b) relative strengths of frame and infill, (c) ductile detailing of the frame when plastic hinging in the frame controls the failure, (d) reinforcement in the infill when cracking in infills controls the failure, and (e) distribution of infills in plan and elevation of the building.

Table 1: Modes of failure of masonry infilled RC frames

	Weak Infill	*Strong Infill*
Weak Frame	-	•Diagonal cracks in infill •Plastic hinges in columns
Frame with Weak Joints and Strong Members	•Corner crushing of infills •Cracks in beam-column joints	•Diagonal cracks in infill •Cracks in beam-column joints
Strong Frame	•Horizontal sliding in infills	-

In a bare frame, inelastic effects in RC frame members and joints cause energy dissipation, while in an infilled frame, inelastic effects in infills also contribute to it. Thus, energy dissipation in an infilled frame is higher than that in the bare frame. If both frame and infill are detailed to be ductile, then stiffness degradation and strength deterioration under cyclic loading are nominal. However, if inelastic effects are brittle in nature (*e.g.*, cracking of infill, bond slip failure in frame, or shear failure in frame members), the drop in strength and stiffness under repeated loading may be large. When physical gaps exist between the frame and the infills, or when sliding takes place in infills along mortar beds, the hysteresis loops demonstrate increased pinching.

EXPERIMENTAL STUDY

Twelve single-bay single-storey RC frames of *1:2.7* reduced-scale (Figure 2) are experimentally studied under reverse cyclic displacement-controlled loading at the Structural Engineering Laboratory of the Indian Institute of Technology Kanpur; ten of these are infilled with burnt clay brick masonry in cement mortar. Frame columns are detailed to yield in flexure before shear failure. The infill masonry is made with full-scale (*223×112×68mm*) and *1:2* reduced-scale (*116×54×36mm*) burnt-clay bricks. The specimens tested include (a) bare frame, (b) frame with unreinforced masonry (URM) in full- and reduced-scale bricks, and (c) frame with unanchored and anchored reinforced masonry (RM) in full- and reduced-scale bricks. The reinforcement in infills consists of two bars of *6mm* mild steel (MS) when full-size bricks are used, and two wires of *3.5mm* MS when reduced-size bricks are used; these are placed in every third layer of masonry. In specimen with anchored RM, the *6mm* bars are welded to steel plates anchored on the inside face of the column, while the *3.5mm* wires are anchored into the columns by drilling holes in the inside face of the column and epoxy grouting the wires. One of the URM infills consisted of inclined brick courses laid symmetrically from the two columns at an inclination of 45° to the horizontal. Three cycles of displacement loading are applied at each of the following excursions (in *mm*): *±1*, *±2*, *±3*, *±5*, *±7.5*, *±10*, *±15*, *±25* and *±40*.

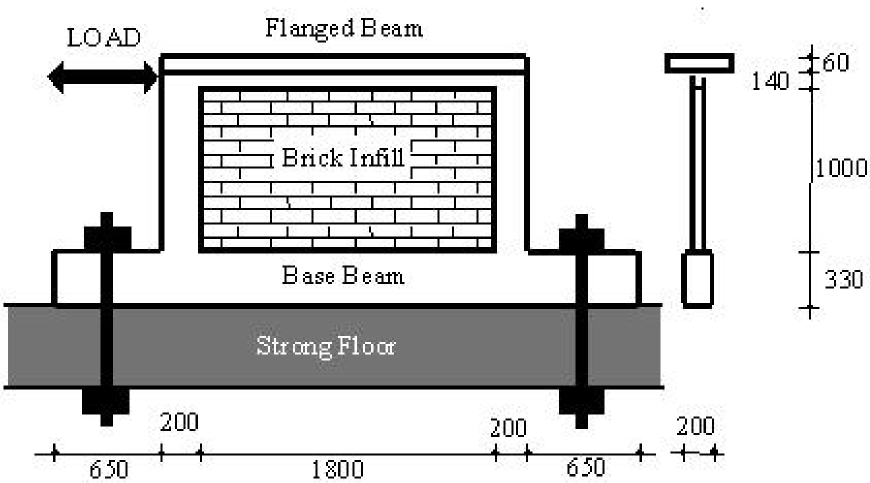


Figure 2: Geometry of frames tested. All dimensions are in mm.

On the envelope backbone curve obtained from the experimental lateral load-displacement data, the point at which a clear departure from linear behaviour occurs is taken as the yield point. The maximum force reached during a cycle is taken as the cycle strength, and the slope of the line joining the extreme displacement points of the cycle, as the cycle stiffness. The following quantities are derived (Table 2):

Yield displacement Δ_y :: Average of displacements corresponding to yield points on positive and negative backbone curves

Initial stiffness k_i :: Slope of line joining the yield points on positive and negative backbone curves

Ultimate load H_u :: Average of maximum load on positive and negative backbone curves

Ultimate displacement Δ_u :: Maximum displacement excursion or average displacement at which strength drops to *80%* of ultimate load on the softening positive and negative backbone curves

Ductility μ :: Ratio of Δ_u and Δ_y

Cumulative Hysteretic Energy $E_{cum,25}$ :: Area enclosed by all load-displacement hysteresis loops up to and including those at the displacement excursion of *25mm*

Stiffness Degradation Δk :: Drop in cycle stiffness in the second and third *25mm* displacement cycles, expressed as a percentage of that in the first *25mm* cycle

Strength Deterioration ΔH :: Drop in cycle strength in the second and third *25mm* displacement cycles, expressed as a percentage of that in the first *25mm* cycle

Table 2: Comparison of responses of the various frames tested

Specimen	Description	k_i (kN/mm)	Δ_y (mm)	H_u (kN)	μ	Δk (%) Repeat Cycle		ΔH (%) Repeat Cycle		$E_{cum,25}$ (kNm)
						1	2	1	2	
MRF11	BF (Monotonic)	6.9	3.6	53.7	12.5	M	M	M	M	M
MRF2	BF (Cyclic)	6.9	3.7	42.2	6.2	Fail	Fail	Fail	Fail	1.3
MRF1	IF :: URM :: FB	44.2	1.7	89.4	16.7	20	27	21	29	6.4
MRF13	IF :: URM :: FB	41.6	0.9	63.2	37.9	19	25	19	24	5.8
MRF22	IF :: URM :: SB	25.8	1.6	62.8	23.9	32	40	28	38	5.1
MRF24	IF :: URM :: SB	24.6	1.2	58.9	34.4	19	26	20	26	4.2
MRF23	IF :: URM :: IFB	11.4	3.9	82.5	10.1	21	27	11	30	7.7
MRF12	IF :: RM-U :: FB	34.0	0.9	60.7	38.5	19	23	19	24	5.2
MRF14	IF :: RM-U :: FB	35.3	0.9	61.3	41.0	24	28	20	25	5.6
MRF21	IF :: RM-A :: FB	13.0	3.9	62.5	11.5	26	31	21	27	4.7
MRF26	IF :: RM-A :: FB	38.1	1.2	76.8	34.8	21	25	17	22	4.5
MRF25	IF :: RM-A :: SB	18.6	1.3	55.3	32.8	21	27	19	28	3.9

Note:
BF : Bare frame | URM : Unreinforced masonry | FB : Full-scale bricks
IF : Infilled frame | RM : Reinforced masonry | SB : Reduced-scale bricks
U : Infill reinforcement not anchored to frame | IFB : Masonry with inclined courses of full-scale bricks
A : Infill reinforcement anchored to frame
Fail : Specimen failed in first 25mm displ. cycle | M : No data since load is monotonic

The main conclusions drawn from these tests are:

Stiffness:
Average initial stiffness of infilled RC frame is about *4.3* times that of bare frame when masonry is unreinforced, and about *4.0* times that of bare frame when masonry is reinforced. This difference is explained by the inadvertent increase in mortar thickness in every third brick course in reinforced masonry where the reinforcement is provided. URM infill with inclined brick courses (MRF23) caused the smallest increase in stiffness relative to the frames with horizontal brick courses; the unduly large thickness of mortar and smaller cut-pieces of bricks used in this specimen explain the smaller increase.

Strength:
On an average, URM infilled frames have about *70%* higher strength than the bare frames; the value is about *50%* higher in case of RM infilled frames. The increase is the largest when the brick courses are inclined to the horizontal, since these inclined brick courses prevent the formation of weak horizontal planes of sliding observed with horizontal brick courses.

Ductility:
Under cyclic loading, the bare frame failed in the first *25mm* displacement cycle; this may have been an exceptional case. On the other hand, the bare frame under monotonic loading sustained up to *47.8mm* displacement while the infilled frames under cyclic loading sustained three cycles of *40mm* displacement excursion and failed in the first excursion to *50mm*. Thus, the deformability of bare and infilled frames is quite comparable. The yield displacement of infilled frames is much smaller than that of the bare frame, and hence, the infilled frames have a considerable larger ductility. Further, as expected, addition of reinforcement in infills increases the ductility of infilled frames. The average ductility of URM infilled frames is about *4.0* times that of the bare frames; ductility of RM infilled frame is about *5.1* times that of the bare frames.

Energy Dissipation:
Since the bare frame MRF2 failed in the first 25*mm* cycle, comparison of the energy dissipation in bare frame versus that in the infilled frames is not possible. The average energy dissipation in unreinforced infill frames is about 22% higher than that in the reinforced infill frames. This is because of the localisation of sliding along the few mortar bed joints along which reinforcements are placed.

Influence of Reinforcement in Masonry:
While placing the reinforcement in the masonry, a larger thickness of mortar than normal is inadvertently provided. The weak horizontal planes thus introduced adversely affect the stiffness, strength and energy dissipation in RM frames as compared to the URM frames. In general, frames with RM infills showed lesser separation at failure between the frame and the infills, than that in the frames with URM infills; this implies a better out-of-plane response of the RM infilled frames. Infilled frames with unanchored reinforcement (RM-U) show higher stiffness, ductility and energy dissipation than those with anchored reinforcement (RM-A). In the latter case, the mechanism of anchoring the reinforcement leads to larger mortar thickness in that vicinity; this may have been responsible for the above. However, the strength of RM-U infill is lower than that of RM-A infill, owing to the contribution of the anchored reinforcement.

Influence of Brick Size:
In the RC frames considered in this study, crushing of bricks is observed at the frame corner when reduced-scale bricks (SB) are used, implying the formation of the compression strut in the masonry infill. This mode of damage was absent in the frames where full-size bricks (FB) are used; instead, the predominant mode of damage in this case is by sliding along the bed joints of the mortar. Also, in case of small bricks, the ratio of mortar thickness to brick thickness is larger which makes the infill weak. The test results reflect this in the form of reduced lateral stiffness of SB infilled frames when compared to that of frames with FB infills.

Strength Deterioration and Stiffness Degradation:
The average drop in cycle stiffness is about *22%* in the first repeat cycle and about an additional *6%* in the second repeat cycle. Similar drop is also observed in the cycle strength - about *20%* in first repeat cycle and about an additional *8%* in the next. Frames with URM infills show similar drop in strength and stiffness in the first repeat cycle as frames with RM infills. However, the drop in the second repeat cycle in the latter is much smaller than that in the former, because the reinforcement helps in reducing the damage in the infilled frame.

DESIGN IMPLICATIONS AND COMMENTS

Masonry infill wall panels increase strength, stiffness, overall ductility and energy dissipation of the building. More importantly, they help in drastically reducing the deformation and ductility demand on RC frame members [Murty and Nagar, 1996]. This explains the excellent performance of many such buildings in moderate earthquakes even when the buildings were not designed or detailed for earthquake forces. The reinforcement in the infills does not contribute significantly towards stiffness and strength; in fact, it may lead to reduction in stiffness and strength due to increased mortar thickness in the layers containing the reinforcement. However, the reinforcement helps in improving the post-cracking behaviour of the masonry and in preventing out-of-plane collapse.

Most multistorey building constructions in the developing countries consist of RC frames with URM infills. Often the RC frame is not even formally designed for seismic loading even in severe seismic zones. This situation is not likely to change significantly in the near future. Such buildings are commonly used as residential or office buildings which typically have a fairly large number of infills placed more or less uniformly and have small to moderate panel size. It should be possible to develop suitable detailing schemes for anchoring masonry reinforcement into the frames and thereby improve the out-of-plane behaviour of the infills. In such situations, the infills could be relied upon to ensure good seismic performance.

The detrimental effects of infills, *e.g.*, short column effect, soft-storey effect and torsion, however, remain and could be a serious concern. For instance, in the Jabalpur earthquake of 1997 in India [Jain et al., 1997], the only RC frame buildings that sustained damage were those with soft-first storey created by the absence of infills in the ground storey to facilitate parking. It is not reasonable to expect that the developing countries will be able to adopt a significantly different structural system in the short run. Extensive research is needed with a view to develop robust seismic design methodologies for such buildings. The seismic design provisions addressing such buildings in the European and the Nepalese codes are an excellent beginning.

ACKNOWLEDGEMENTS

Experimental results reported here are based on the Masters' theses of Neeraj K. Vasandani, Rakesh K. Saxena and Kiran J. Akella, conducted under the supervision of the authors. The authors gratefully acknowledge the financial support from the All India Council for Technical Education, New Delhi, to conduct this study.

REFERENCES

CEB (1996), *RC Frames Under Earthquake Loading - State of the Art Report*, Comite Euro-International Du Beton, Thomas Telford, UK.

CEN (1994), *Eurocode 8 - Design Provisions for Earthquake Resistance of Structures*, European Committee for Standardisation, Brussels.

Jain, S.K., Singh, R.P., Gupta, V.K., and Nagar, A. (1991) "Garhwal Earthquake of October 20, 1991," EERI Special Earthquake Report, *EERI Newsletter*, Vol.26, No.2, February 1992, 4p.

Jain, S.K., Murty, C.V.R., Arlekar, J.N., Sinha, R., Goyal, A., and Jain, C.K. (1997), "Some Observations on Engineering Aspects of the Jabalpur Earthquake of 22 May 1997," EERI Special Earthquake Report, *EERI Newsletter*, Vol.32, No.2, August 1997, 8p.

NBC 201 (1994), *Nepal National Building Code: Mandatory Rules of Thumb - Reinforced Concrete Buildings with Masonry Infill*, Ministry of Housing and Physical Planning, Kathmandu, Nepal.

Murty, C.V.R., and Nagar, A. (1996), "Effect of Brittle Masonry Infills on Displacement and Ductility Demand of Moment Resisting Frames," *Proceedings of Eleventh World Conference on Earthquake Engineering*, Acapulco, Mexico.