

# SEISMIC BEHAVIOUR OF RC FRAMES INFILLED WITH DIFFERENT TECHNIQUES

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#### Abstract

Besides their primary implementation as heat isolation and partitioning off the living space, infill walls have great potential to influence building response during seismic excitation. Affecting the infilled RC building stock of Turkey, Mw 7.4 Kocaeli (1999) and Mw=7.1 Van (2011) earthquakes have shown that "non-structural" infill walls might be very critical for vertical stability of buildings under severe earthquakes and their performance is important in determination of global building performance especially under moderate earthquakes. In order to better understand infilled frame response, to determine performance levels for the infill walls and to enhance seismic resistance via new materials and various infill wall construction techniques; cyclic tests on 8 half scale, single RC frames were conducted in METU Structural Mechanics Laboratories. Namely, bare frame (B), infilled frame (I), infilled frame with plaster (P), infilled frame with steel mesh reinforced plaster (MRP) locking brick infilled frame with horizontal slip layer (LB), infilled frame separated with horizontal steel plates (HSP), auto aerated concrete infilled frame (AAC), AAC infilled frame with fiberglass mesh reinforced plaster (AACP) were tested. Investigation and comparison of damage patterns, performances and contributions of infill walls to global response are presented.

Keywords: infill wall; reinforced concrete frame; cyclic test; performance limit states



## 1. Introduction

The seismic response of reinforced concrete (RC) frames with infill walls have been a major topic of investigation since 1950's. Much research has been conducted for a better understanding of the interaction between the frames and infill walls but practical design procedures still do not exist. Whereas codes or guidelines such as Eurocode, ACI 530 or ASCE 7 recommend that infill walls should be taken into account, the anticipated improvement in performance is not easily quantified, nor are they confirmed by field experience [1]. Under service loads infill walls are non-structural passive members. Under lateral loads they interact with the bounding frame through formation of compressive diagonals and participate in the global response. Because of their high initial lateral stiffness compared to the bounding frame, presence of infill walls changes predominant frame response to predominant truss response [2]. However, they have a brittle nature and tendency to crack at very low drift values so their contribution decays quickly.

Controversial arguments have been set forth on the role of infill walls modifying the seismic response of RC frames. Some researchers [3, 4, 5, 6] claim that infill walls are unaccounted in the design, so they serve as a reserve capacity increasing the stiffness and the strength of the RC frames and provide better deformation control for the structure. Other researchers, on the other hand, claim that presence of infill walls may jeopardize the seismic design philosophy for frame action [7, 8] due to the damage imposed on the boundary elements. Both arguments are perhaps correct in the context of the level of lateral deformation demands under consideration [9]. For small deformation demands they provide additional stiffness, whereas they may fail in a brittle manner at larger deformation levels. Their role can be positive, provided that their arrangement in-plan and in-elevation is adequate and that their effect on the building response is taken into account in the design phase [10, 11]. But, improper arrangement of infill walls may lead to unfavourable seismic behavior that has not been considered in the design stage. Irregular arrangement of infill walls along the height of the building causes an abrupt change of the building stiffness, resulting in weak-story and soft-story mechanisms or unsupported walls on the overhang may collapse in out of plane and pose threat to human life (Fig. 1).



a) Weak story mechanism

b) Soft story mechanism

c) Out of plane failure

Fig. 1 – Failures due to improper arrangement of infill walls from Van, Turkey Earthquake (2011)

Recent earthquakes in Turkey have once again shown the vulnerability of infill walls to seismic damage. Fig. 2 exhibits three buildings that experienced various degrees of damage from Van, Turkey Earthquake (2011). All buildings were 6 story reinforced concrete frame buildings with brick infilled walls. All of the buildings had minor structural damage on the RC elements. However, the infill behavior was quite different resulting in different damage levels showing that infill damage may actually determine the final damage state of a structure depending on the deformation demands.





a) Light damage

b) Moderate Damage

c) Heavy damage

Fig. 2 – Decisive role of infills for building damage from Van, Turkey Earthquake (2011)

In the current performance based engineering practice, building performance is generally determined based solely on the performance of RC elements. The performance limit states of the infill panels are still being investigated. In this regard, it should be emphasized that modern seismic design and assessment philosophy based solely on ductility concepts of members may be inadequate to estimate the actual expected damage unless they account for the contribution of infill walls. Neglecting the presence of infill walls and trying to estimate building vulnerability based on relatively well established performance states of RC members alone may mislead the earthquake hazard mitigation studies. Noting this urgent need in the earthquake engineering community, we conduct experiments on half scaled RC frames infilled with traditional and new techniques to better understand infill wall behavior, estimate performance limit states for the infilled frames and improve the infill wall performance for earthquake resilience.

## 2. Proposed Infill Wall Systems

Infill panels are vulnerable to seismic damage. In order to increase seismic resistance of infill panels, several techniques have been proposed. Recent studies to enhance infilled frame response focus on: (1) horizontal slip joints to prevent brittle failures and force infill panel fail in a slip mode which is more ductile [12], (2) vertical slip joints to provide slenderness to infill panel resulting in a rocking mode which is more stable and ductile [13], (3) use of weak mesh reinforcement or geotextiles to increase ductility and stability [14], (4) isolate infill panel with the frame by means of gaps or devices [15], (5) bed joint reinforcement [16].

The principal objective of this research is to develop masonry enclosure solutions for enhanced earthquake resistance by respecting local materials and construction practice so that the proposed systems can be used economically and effectively. Traditional brick units (perforated clay brick, locking brick, aac blocks) and materials (light steel mesh, fiberglass mesh, dowels, etc.) that are easily found on the market are preferred to be utilized for the proposed systems.

Mesh reinforcement of the plaster is an effective way of dealing with in and out of plane damage of infill walls. Our suggestion for brick infilled frames is bilateral attachment of light steel mesh with 25 mm nominal pitch and 2 mm wire diameter on both side of the infill panel before plaster application. Unlike familiar strengthening methods, steel meshes are not anchored to the RC frame rather they are attached to each other by tie wires passing through holes drilled at mortar joints as illustrated in Fig. 3.



Fig. 3 – Bilateral steel mesh application on a brick infilled frame

For aac infilled frames, fiberglass mesh with 4 mm nominal pitch and 160gr/m2 density is utilized. After aac blocks were laid, first level of light plaster is applied. Then fiberglass mesh is attached to the plaster and second layer of plaster is applied over the mesh (Fig. 4).



Fig. 4 – Fiberglass mesh application on acc block infilled frame

Another system proposed for damage mitigation of infilled frames is a combination of bed joint reinforcement and horizontal slip joint techniques. Flat slotted steel plates laid along bed joints are locked to closed U shaped steel profiles which are anchored to columns. The connection between closed U profile and the plate is simply satisfied by inserting and rotating which enables free movement of the plate in vertical direction whereas horizontal movement is restricted so steel plates act like horizontal reinforcement (Fig. 5). System aims to ensure composite action of RC frame and the infill panel under in and out of plane loading. The name given to this innovative system is INFILTIE [1].



Fig. 5 – Flat slotted plates acting as horizontal reinforcement and slip plane (INFILTIE)



Final proposed system is use of locking bricks without mortar at bed joints. These brick units are known as isolation bricks on the market. They are normally laid with their holes perpendicular to the ground leaving head joints free of mortar. Our suggestion is rotating locking bricks 90 degrees so that they are locked in bed joints (Fig. 6). By this way slip layers are formed at each bed joint resulting in sliding type of failure which is more ductile.



Fig. 6 – Use of locking brick to create horizontal slip layer for infilled frames

## 3. Experimental Program

Eight half scaled single RC frame specimens were tested under increasing reversed cyclic horizontal loading. Due to the limitations of the lab environment, half scaling is applied to the reference frame based on preserving the level of stresses constant. Scaling process resulted in dimensions of columns, beam and infill panel reduced to half. Whereas material properties of concrete, steel, brick and reinforcement ratios remain the same. Conducted frame tests are listed below:

- Bare frame (B)
- Infilled frame (I)
- Infilled frame with plaster (P)
- Infilled frame with steel mesh reinforced plaster (MRP)
- Locking brick infilled frame with horizontal slip layer (LB)
- Infilled frame separated with horizontal steel plates (HSP)
- AAC infilled frame (AAC)
- AAC infilled frame with fiberglass mesh reinforced plaster (AACP)

### 3.1 RC Test Frame

Test specimen is one bay, one story RC frame cut out from ground story of a typical five story reference building designed according to high ductility level of Turkish Earthquake Code 2007 [17]. Due to the limitation of the lab environment, reference frame is scaled to half keeping stresses and reinforcement ratios the same. Due to scaling 185x100x95 mm size perforated clay masonry units, 225x115x155 mm size clay bricks with locking ends and 125x100x300 mm size aac blocks were produced to be used as infill material. Extensive testing of brick units, masonry prisms and mortar was conducted [18]. Column and beam dimensions are 200mm x 200mm and 150mm x 200mm respectively. Story height to the beam centreline is 1.435m and the span length between column centrelines is 2.5m. A part of 70mm thick slab is also included in the specimen. Dimensions of the scaled test specimen is illustrated in Fig. 7.



Fig. 7 – Dimensions of half scaled single RC test frame

Concrete strength varied from 26.5MPa (infilled frame) to 33.5 MPa (mesh reinforced frame) with an average of 29.0 MPa. 8mm diameter deformed bars ( $f_y$ =420 MPa) were used as longitudinal reinforcement whereas 6mm plain bars ( $f_y$ =450 MPa) were utilized as stirrups. Stirrup spacing at confined and unconfined regions are 50mm and 100mm respectively. Column gross reinforcement ratio is 1%. All the longitudinal reinforcements are hooked at ends except column reinforcement at the top of the columns. Due to space limitation at beam-column joint, longitudinal reinforcements were welded to a 10mm thick steel plate at the top of the column to prevent slip. Reinforcement details are illustrated in Fig 8.



Fig. 8 - Reinforcement arrangement of the test frame

#### 3.2 Experimental Setup

An experimental setup capable of simultaneous application of vertical and horizontal loads is constructed in Structural Mechanics Laboratory of METU (Fig. 9). One 250kN capacity servo controlled hydraulic jack in horizontal direction and two 300kN capacity manually controlled hydraulic jacks in vertical direction were used for loading. Additionally weight blocks were placed on the top of the beam to idealize distributed slab loading.





Fig. 9 - Test setup at METU Structural Engineering Laboratories

After test frame was preloaded in vertical direction such that axial load ratio of columns are 0.175, a sequence of increasing lateral displacement reversals was applied up to 4.0% inter-story drift level. Drift angles of 0.35, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5 and 4.0% were applied twice in both the positive and negative directions. RC frame response was monitored through 47 channels of transducer output (Fig. 10). 3 load cells attached to hydraulic jacks, 12 strain gages attached to longitudinal reinforcement at the ends of members and 32 LVDT's placed to monitor column and beam end rotations, joint distortions, wall deformations and lateral drift were employed.



Fig. 10 - Instrumentation: LVDT's (orange), strain gages (green), load cells (blue)

### 4. Experimental Results

Bare frame experienced a ductile response. As a result of strong column-weak beam principle followed in design, flexural hinging at beam ends and bottom of columns are observed. Although infilled frame initially experienced diagonal cracking at 1.0% drift ratio, ultimate state is reached by crushing and spalling brick units at corner of the infill panel. Presence of plaster in traditionally infilled frame altered failure mechanism such that diagonal cracking is followed by corner crushing. Distinct slip planes formed in LB and HSP systems at early drift levels. Damage accumulation took place at those planes until failure. Both systems achieved to alter failure mode to sliding satisfactorily. MRF experienced corner crushing. At crushing regions tie wires bilaterally connecting steel meshes ruptured and mesh deformed in out of plane direction locally. However even under 4.0% lateral drift level, masonry panel still remained intact indicating possible out of plane stability in addition



to in plane stability. AACP also showed similar performance with MRP. Although extensive monitoring of the tested frames was made, only lateral load-drift curves (Fig. 11) and damage photos at certain drift levels (Table 2) are given below. Results related to initial stiffness (K<sub>i</sub>), maximum base shear ( $V_{max}$ ) and drift at maximum base shear ( $d_{max}$ ) are illustrated in Table 1.

Frame ID	K <sub>i</sub> (kN/mm)	V <sub>max</sub> (kN)	$\frac{K_i}{K_{i,BF}}$	$\frac{V_{max}}{V_{max,BF}}$	d <sub>max</sub>
В	12	83	1.0	1.0	1.5%
Ι	38	119	3.2	1.4	1.0%
AAC	19	133	1.6	1.6	3.0%
Р	41	139	3.5	1.7	0.5%
MRP	103	190	8.7	2.3	0.35%
AACP	47	132	4.0	1.6	1.0%
HSP	55	141	4.7	1.7	1.0%
LB	40	121	3.4	1.5	0.5%

Tablo	1.	Experimental	results



Fig. 11-Hysteresis loops for tested frames



Frame	Lateral Drift					
Label	0.5 %	2.0 %	4.0 %			
I						
Р						
MRP						
HSP						
LB						
AAC						
AACP						

Table 2. Damage on infilled frames with respect to lateral drift



# 5. Performance Assessment of Infilled Frames

In order to achieve an accurate performance estimation of infilled frames, performance limits depending on infill damage should be defined. Four performance limit states, namely, operational limit state (OLS), damage limitation limit state (DLS), ultimate limit state (ULS) and near collapse limit state (NCLS) are suggested for to describe the infill damage. Initiation of infill damage by means of detachment of panel with bounding frame and very light cracking in the masonry panel in the bed and/or in the head joints is defined as operational limit state. Damage limitation state is considered as repairable damage. Formation of diagonal cracking, sliding in the bed joints and very limited crushing and spalling of plaster can take place. Ultimate limit state indicates severe damage. Reparability is not economical. Crushing and spalling of mortar and brick units are more widespread however size of falling units do not pose risk to human life. At the ultimate damage state, the maximum base shear capacity is generally reached. Near collapse limit state is reached when infill damage is extensive to the extent that panel is close to collapse. Contribution of panel to lateral strength and stiffness is very limited for this limit state. Falling parts might risk the human life and possibility of out of plane failure of panel under out of plane actions is high.

Damage stages of tested frames were carefully investigated and performance limit states associated with corresponding drift levels are illustrated in Table 2. OLS is associated with first major change in initial stiffness of the infilled frame. For all tested infill systems, OLS is around 40% to 50% of maximum base shear capacity.

Frame ID	Damage Limit States				
	OLS	DLS	ULS	NCLS	
Ι	0.06%	1.0%	1.5%	2.5%	
AAC	0.1%	0.5%	1.0%	2.5%	
Р	0.08%	1.0%	1.5%	3.0%	
MRP	0.04%	2.5%	4.0%	N.A.	
AACP	0.04%	1.5%	4.0%	N.A.	
HSP	0.04%	1.0%	2.0%	3.0%	
LB	0.02%	0.5%	1.5%	2.5%	

Table 2. Damage limit states for tested infilled RC frames

## 6. Conclusions

Eight identical half-scale, single RC frames infilled with traditional and new techniques were tested under increasing cyclic displacements. Load deformation responses as well as observed damages were noted. Comparative evaluation and performance of each system is discussed. Performance based inter-story drift limits for all infilled system were proposed.

Test specimen is a code designed, ductile frame having an aspect ratio of 0.57. Column axial load ratio is 0.175 and light clay brick masonry is utilized as infill material. Lateral loading is applied only at in-plane direction. Under these circumstances lateral load response of the tested infill systems are summarized in Fig. 12 and following conclusions might be drawn:

- On the average, infilled frames increased base shear capacity and initial stiffness of the bare frame by 60 percent and 400 percent, respectively.
- After reaching maximum base shear capacity, infilled frames decay with increasing damage and finally converge to bare frame response around 2.5 3.0 percent drift ratios. Systems enforcing slip type of infill failure (LB and HSP) performed better in sustaining the lateral load after the peak.
- Fiber/Steel mesh reinforced plasters (AACP, MRP) and horizontal tie systems (HSP) kept the infill panel intact at increasing in-plane drift levels. They are also believed to increase out-of-plane capacity of infill panels with in-plane damage.



- MRF and AACP performed well in terms of damage limitation at low drift levels (i.e. service level earthquake) and keeping wall integrity at high drift levels (i.e. design level earthquake). LB and HSP on the other hand lacks early cracking problem.
- Proposed systems are feasible, effective and affordable ways of improving infilled frame performance which do not require special equipment or sophisticated materials.





One significant limitation of this research is the determination of infilled frame performances considering in-plane actions only. Mutual interaction of in-plane and out-of-plane infill damage should be investigated for a better assessment of proposed techniques. We believe that effectiveness of especially mesh reinforcement systems and HSP would be more noticeable under biaxial lateral loading.

As proven by recent earthquakes and experimental researches, if infill walls are adequately detailed in plan and over the height of the building, they provide additional lateral stiffness and strength to the building. Hence, reliable analysis and design procedures as well as performance limit states for infilled frames should be developed and current structural codes should be updated accordingly.

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