BEHAVIOR OF AAC INFILLED RC FRAME UNDER LATERAL LOADING

Supratik Bose¹ and Durgesh C. Rai²

ABSTRACT

Conventional infill materials significantly influence the overall response of framed structures due to their higher strength and stiffness. Recently, autoclaved aerated concrete (AAC) blocks have been widely used all over the world as a potential infill material and its application in upper stories of open-ground-story (OGS) frames can be beneficial. However, limited experimental work has been performed on AAC infilled RC frame and hence, a reduced scale model of a RC prototype frame was constructed in the laboratory to evaluate its performance under lateral loading. The average values of unit compressive strength and elastic modulus of AAC masonry was observed to be approximately one-third and one-half of that of conventional masonry, respectively. The AAC infilled RC frame was subjected to displacement controlled slow-cyclic test to study its hysteretic response. The low strength and stiffness of AAC infill results in improved load sharing between infill and frame, which help to develop yield mechanism in the frame earlier for better energy dissipation. The performance of AAC infilled RC frames is evaluated by non-linear static and dynamic analysis based on the FEMA P695 methodology. Incremental dynamic analysis (IDA) of OGS prototype frame infilled with AAC blocks and conventional masonry was performed to calculate their probability of collapse at maximum credible earthquake (MCE). It was observed that AAC infilled RC frame designed with response reduction factor of 5 has lower probability of collapse at MCE compared to conventional infills. Thus, the AAC infill improves the seismic behaviour of OGS-RC frame due to its lower strength and stiffness.

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Conventional infill materials significantly influence the overall response of framed structures due to their higher strength and stiffness. Recently, autoclaved aerated concrete (AAC) blocks have been widely used all over the world as a potential infill material and its application in upper stories of open-ground-story (OGS) frames can be beneficial. However, limited experimental work has been performed on AAC infilled RC frame and hence, a reduced scale model of a RC prototype frame was constructed in the laboratory to evaluate its performance under lateral loading. The average values of unit compressive strength and elastic modulus of AAC masonry was observed to be approximately one-third and one-half of that of conventional masonry, respectively. The AAC infilled RC frame was subjected to displacement controlled slow-cyclic test to study its hysteretic response. The low strength and stiffness of AAC infill results in improved load sharing between infill and frame, which help to develop yield mechanism in the frame earlier for better energy dissipation. The performance of AAC infilled RC frames is evaluated by non-linear static and dynamic analysis based on the FEMA P695 methodology. Incremental dynamic analysis (IDA) of OGS prototype frame infilled with AAC blocks and conventional masonry was performed to calculate their probability of collapse at maximum credible earthquake (MCE). It was observed that AAC infilled RC frame designed with response reduction factor of 5 has lower probability of collapse at MCE compared to conventional infills. Thus, the AAC infill improves the seismic behaviour of OGS-RC frame due to its lower strength and stiffness.

Introduction

Masonry buildings are most common throughout the world due to its low cost, durability, aesthetics and good acoustic and thermal properties. However, infills are not considered for analysis and design purposes. But still, they influence the overall behavior of the structure particularly in case of lateral loading. Presence of infill reduces the natural period of vibration, thereby attracting greater seismic forces. Irregular placement of infills along the plan and elevation can cause serious damage to the structures at the time of earthquake. One of the most common type of irregularities observed in buildings are absence of masonry walls in the ground story commonly referred to as open-ground-story buildings (OGS). The stiffness of the ground story in such buildings is much less than the upper infilled stories, thereby creating a weak/soft story. As a result, during seismic events, the lateral deformation demand is not evenly distributed along its height, mostly concentrated in the weak ground story. The net effect is the failure of the ground story columns finally resulting in collapse of the entire building.

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Autoclaved aerated concrete (AAC) blocks is mainly used for infill purposes in framed structures. The primary advantages of using AAC as infill material are its lightweight, low strength and stiffness. Previous research on AAC masonry, led to the development of response modification coefficient for design of AAC structural systems [1]. Varella et al. [1] proposed maximum drift ratio of 1% to avoid collapse. Imran and Aryanto [2] studied the behavior of RC frames infilled with lightweight materials (AAC blocks) and conventional masonry under cyclic loading and observed that AAC blocks exhibited better seismic performance. Ravichandran [3] investigated the seismic behavior of steel moment frames with masonry infills using the systematic ATC 63 methodology and observed that “infill strength ratio” has significant influence on seismic behavior of an infilled frame. Liu and Li [4] carried out static and cyclic testing on full-scaled AAC-infilled steel frames to study its hysteretic behaviour and found that AAC infill enhances the strength and stiffness of steel frames to a large extent.

The previous studies also showed that the AAC infill can be beneficial in improving the seismic performance of infilled frames if the shear strength of infill is lower than story shear strength of the frame [2-4]. However, limited experimental work has been performed on AAC infilled RC frame and hence, an experimental investigation is carried out to study its hysteretic behavior. The primary objective of the present study is to evaluate the effectiveness of AAC infills in improving the performance of OGS RC frames based on FEMA P695 [5] methodology.

**Experimental Program**

**Details of Test Specimen**

A typical four-bay five-story RC building with OGS is considered as the prototype structure (Figure 1) in the present study. The building is assumed to be located on firm rock site in the highest seismic Zone V of Indian seismic code IS 1893 [6]. The response reduction factor ($R$) is taken as 5 for the special moment resisting frames (SMRF) as per IS 1893. Stiffness of the masonry infills is typically not considered in the design of the frame in India and other countries. Ductile detailing of frame members were according to IS 13920 [7] and the special confining reinforcement were provided near the frame ends.

A reduced scale (1:2.5) single-story single-bay RC frame representing an interior bay of the prototype frame was constructed as test specimen in this study. The dimensions and reinforcement detailing of various members are summarized in Table 1. As the initial properties of bare RC frame were obtained, AAC infill was constructed with half-scaled AAC blocks of average dimensions 312 mm×124 mm×99 mm. The thickness of the infill was kept 125 mm and the wall was constructed in the same plane as RC frame.

| Table 1. Dimensions and Reinforcement Detailing of RC members |
|-----------------|----------------|----------------|-------------------|
| **Member**      | **Overall size (L×B×H)** | **Clear cover (mm)** | **Longitudinal reinforcement** | **Transverse reinforcement** |
| Footing         | 3240×200×350   | 20              | 12φ (6 nos.)       | 8φ @300 mm c/c       |
| Column          | 1330×200×200   | 12              | 10φ (8 nos.)       | 6φ @60 mm c/c        |
| Beam            | 3210×200×200   | 10              | 10φ (9 nos.)       | 6φ @40 mm c/c        |
| Slab            | 3210×800×60    | 10              | 10φ (8 nos.)       | 8φ @300 mm c/c        |
Test Setup and Load History

Servo-hydraulic controlled actuator (capacity 250 kN and stroke length 125 mm) with in-built load cell and LVDT was used to apply cyclic lateral load. Four hot-rolled steel channel sections were used to distribute the lateral load uniformly along the roof slab. The RC footing of the specimen was connected to the laboratory strong floor by means of 45 mm anchorage bolts to prevent its possible movements. The specimen was laterally supported by steel triangular frames to prevent its out-of-plane movement. In addition to self-weight, the frame was subjected to additional gravity loads using sand bags which develop a uniform pressure of 6.5 kPa on roof slab. Wire potentiometers (WPs) were used to measure the lateral displacements of the columns and strain gauges were attached to the longitudinal reinforcements of RC members at critical sections. In addition, diagonal LVDTs were provided in masonry panels to calculate the shear deformation (Figure 2). The test specimen was subjected to reversed cyclic lateral displacements as per ATC 63 [9] loading protocol. Figure 3 shows the loading history used in this study for displacement-controlled slow cyclic test.

<table>
<thead>
<tr>
<th>DL</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<td>0.15</td>
<td>0.30</td>
<td>0.45</td>
<td>0.60</td>
<td>0.75</td>
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<td>1.35</td>
<td>1.50</td>
<td>2.00</td>
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<td>DL</td>
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<td>14</td>
<td>15</td>
<td>16</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>Drift (%)</td>
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<td>3.00</td>
<td>3.50</td>
<td>4.00</td>
<td>4.50</td>
<td></td>
</tr>
</tbody>
</table>

![Figure 2. Position of sensors](image2.png)

![Figure 3. Loading protocol](image3.png)
Material Properties

Tests for compressive and splitting tensile strength were conducted on AAC blocks and axial compression, tension bond and diagonal tension tests were performed on AAC masonry assemblages. Concrete mix of characteristic compressive strength 25 MPa was suitably proportioned according to IS 10262 [8] provisions. TMT bars of specified yield strength 415 MPa were used for reinforcements. Figure 4 and 5 shows the stress-strain plots of the compressive strength test on 5-block stack bond AAC prism and tensile test on rebars, respectively. Polymer modified thin bed mortar (“Fixoblock”, Make: UltraTech) was used in this study for construction of AAC infill. The average material properties are summarized in Table 2.

![Stress-strain plots](image)

**Figure 4.** AAC masonry prism test  
**Figure 5.** Tension test on rebar

| Table 2. Material Properties of Concrete and AAC masonry *(all units are in MPa)* |
|---------------------------------|-----------------|-----------------|-----------------|
| Concrete and Rebars             | AAC Unit        | AAC masonry     |
| Strength                        | Value           | Strength        | Value           | Strength        | Value           |
| Compressive                     | 37.6            | Compressive     | 2.39            | Compressive     | 2.38            |
| Flexural                        | 5.5             | Tensile         | 0.36            | Tension Bond    | 0.12            |
| Yield (Rebar)                   | 418.4           | Elastic Modulus | 2327.7          | Diagonal (Shear)| 0.30            |

Test Results and Evaluation

Forced vibration test was conducted on the test specimen and natural frequency was observed to be 14.1 Hz and 27.3 Hz for bare frame and AAC infilled frame, respectively. The elastic stiffness of RC frames was obtained by conducting load-controlled slow-cyclic test of low magnitudes (2 kN and 5 kN). Lateral stiffness of 35.6 kN/mm for bare RC frame increased to 130.9 kN/mm in the presence of AAC infill, which is an increase of 268%.

Observed Failure Pattern in AAC Infilled RC Frame

The first crack in the infill panel was observed at story drift (SD) of 0.15%. Boundary separation cracking between the infill and top beam was also observed at 0.15% SD indicating weak joint at the frame-infill interface. The major cracks were developed till 1.05% SD, beyond which no new significant cracks were formed in the infill panel. Major cracks in RC columns were observed to initiate at 2.0% SD. Crushing of concrete and bending of reinforcement bars were observed at much higher drift levels (SD=3.0%). The final failure of the frame was characterized by
formation of plastic hinges in the RC columns, corner crushing of the infill, loosening and fall out of portion of AAC blocks (Figure 6). The masonry panel separated from the surrounding RC frame divides into two blocks at mid-height and slide along the bed joint during the subsequent loading with considerable load sharing between the infill and the bounding frame.

Figure 6. Crack pattern observed in DL17 (SD=4.5%)

**Load Displacement Response**

The average roof displacement was plotted against the lateral force to obtain the overall hysteretic behavior of the AAC infilled RC frame as shown in Figure 7. The hysteretic response is symmetric in nature with maximum lateral forces of 145.5 kN and 137.1 kN in the pull and push directions, respectively. At each drift levels, the first hysteretic loop exhibited higher strength compared to the subsequent repeat cycles (see Figure 8). Post-yield strain hardening behavior observed during the test was followed by strength degradation. This degradation in strength initiates at SD of 2.00% primarily due to development of major cracks in RC columns.

Figure 7. Hysteretic response  
Figure 8. Strength Deterioration
Overall Behaviour of AAC Infilled Specimen

Bending moments in RC columns were obtained from the strain values recorded by rebar strain gauges. As the columns were under double curvature bending, shear can be calculated from the end moments. Shear force calculated from the strain gauge can be assumed to be a good estimate of the actual frame force and is compared with the backbone curve of AAC infill alone and AAC infilled frame in Figure 9. The contribution of AAC infill as percentage of total shear taken by the AAC infilled RC frame is presented in Figure 10. It can be seen that the majority of the shear stress is taken by the AAC infill at lower drift levels and its contribution decreases with increase in the story drift. The contributions of both frame and infill are fairly constant at higher drift levels indicating improved load sharing between them.

![Lateral Force vs Story-Drift](image9.png)  
**Figure 9.** Envelope plots

![Shear Stress vs Drift level](image10.png)  
**Figure 10.** Contribution of infill

Stiffness Degradation and Energy Dissipation

Figure 11 shows the variation in lateral stiffness of the AAC infilled RC frame with increase in story-drift. The AAC infilled RC frame showed a gradual decline in lateral stiffness from 215 kN/mm to 1.5 kN/mm. Cumulative energy dissipation is a measure of the seismic efficiency of a structural system and is defined as the total area bounded by the hysteresis loops produced at each drift level. Its variation with increase in story-drift is plotted in Figure 12.

![Stiffness vs Drift ratio](image11.png)  
**Figure 11.** Cyclic stiffness degradation

![Cumulative Energy vs Story Drift](image12.png)  
**Figure 12.** Cumulative energy dissipation
FEMA P695 Evaluation of Infilled RC Frames

Pushover and fragility analysis of OGS RC frame infilled with AAC blocks and conventional masonry (clay and fly-ash bricks) was carried out according to FEMA P695 [5] methodology.

Analytical Modeling of RC members and infill

Beams and columns in the study frame were modeled as two-noded frame elements with six-degrees of freedom at each node. Plastic hinge properties in RC members are shown in Figure 13. Masonry infill walls were modeled as compression only equivalent diagonal strut element. The thickness of the diagonal strut was taken equal to actual thickness of the masonry infill and the width was taken as one-fourth of the diagonal length of the wall. The simplified tri-linear stress strain model for masonry infill proposed by Kaushik [10] is used in this study (Figure 13). The stress-strain curves of conventional masonry were obtained from compressive strength tests conducted on masonry prisms of clay and fly-ash bricks. The stress strain response of AAC infill is obtained from the load displacement plot using strut action. The control points on stress-strain curves for infill model used in SAP 2000 [11] program is summarized in Table 3.

![Figure 13. Typical plastic hinge properties of RC members and masonry infill](image)

<table>
<thead>
<tr>
<th>Stress Level</th>
<th>Clay-Brick</th>
<th>Fly-Ash Brick</th>
<th>AAC Block</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Stress(MPa)</td>
<td>Strain</td>
<td>Stress(MPa)</td>
</tr>
<tr>
<td>0.75( f_m' )</td>
<td>2.918</td>
<td>0.00177</td>
<td>5.498</td>
</tr>
<tr>
<td>1.00( f_m' )</td>
<td>3.890</td>
<td>0.00546</td>
<td>7.330</td>
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<tr>
<td>0.20( f_m' )</td>
<td>0.778</td>
<td>0.01503</td>
<td>1.466</td>
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<tr>
<td>0.20( f_m' )</td>
<td>0.778</td>
<td>0.01776</td>
<td>1.466</td>
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</table>

Table 3. Control points on stress-strain curves for infill used in SAP 2000
Pushover Analysis

The backbone curve of the reduced frame obtained experimentally is well reproduced by pushover (PO) analysis (Figure 14) which verifies the analytical model in SAP 2000 [11] program. Pushover (PO) analysis was performed on the prototype frame and the results are compared in Table 4 and Figure 15. The ratio of initial elastic stiffness of infilled frames ($K_I$) to that of bare frame ($K_{BF}$) was close to unity for AAC infill, much less compared to conventional infills. The increment in base shear ($V_B$) was also the least in case of AAC infill (19%) compared to conventional infills (40% and 69% for clay brick and fly-ash brick, respectively), as also evident from the overstrength factors ($\Omega$) shown in Table 4.

Table 4. Summary of results from pushover analysis

<table>
<thead>
<tr>
<th>Frame Type</th>
<th>$K_I / K_{BF}$</th>
<th>$V_B$ (kN)</th>
<th>$\Omega$</th>
<th>Ductility</th>
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</thead>
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<tr>
<td>Bare Frame (BF)</td>
<td>1</td>
<td>1178.61</td>
<td>2.9</td>
<td>8.6</td>
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<tr>
<td>Clay Brick (CB)</td>
<td>2.62</td>
<td>1653.48</td>
<td>4.1</td>
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<tr>
<td>Fly-Ash Brick (FA)</td>
<td>4.24</td>
<td>1988.16</td>
<td>4.9</td>
<td>6.9</td>
</tr>
<tr>
<td>AAC blocks (AAC)</td>
<td>1.53</td>
<td>1405.33</td>
<td>3.5</td>
<td>7.6</td>
</tr>
</tbody>
</table>

Incremental Dynamic Analysis (IDA)

IDA is widely used to evaluate the seismic performance of structures against various levels of ground motion shaking and helps to generate the collapse fragility curves. The 20 ground motions used by Parool [12] representing magnitudes of range 6.5-7.6 recorded on firm soil are normalized and scaled according to FEMA P695 [5] and selected in the present study for carrying out IDA. Roof drift ratio of 1% is considered as the collapse criteria based on the experimental works done by Varela et al [1]. The median collapse intensity and collapse margin ratio (ratio of collapse spectral intensity and MCE level spectral intensity) of the AAC infilled OGS RC frame was the highest among the infilled frames indicating better performance at MCE compared to conventional masonry infills. It was seen that conventional infills cause local shear failures, thus decreasing the collapse spectral intensity. AAC infill also reduces the damage at both MCE and DBE level ground motions compared to conventional infills.
Mean Displaced Profile at collapse during IDA

The mean displacement profiles of bare frame and masonry infilled OGS frames, when maximum story drift exceeded 1% for each of the 20 ground motions is plotted in Figure 16. For, clay brick infilled OGS frame, the failure is concentrated at the lower story, thereby forming a weak ground story mechanism. This behavior, however, was not seen in AAC infilled OGS frame, in which, the failure is distributed throughout the entire height of the frame.

Collapse Fragility Curve

The probability of collapse at MCE and the collapse fragility curves for the bare frame, conventional masonry and AAC block infilled OGS RC frames are evaluated according to FEMA P695 [5] methodology and are presented in Figure 17. The probability of collapse at MCE for the AAC infilled frame was 9.2%, while 5.6% was obtained for the bare frame. However, the probability of collapse at MCE for the clay-brick and fly-ash brick infilled frames was obtained as 26.1% and 33.6%, respectively, which is much higher than those obtained for the bare frame and AAC infill. Thus, among all the infilled frames, AAC infilled OGS frame had shown better performance at MCE.

The probability of collapse of AAC infilled OGS RC frame was within the acceptability criteria specified in FEMA P695 [5] and hence the response reduction factor (R) of 5 used for SMRF can be used for design of AAC infilled frames as well. However, the conventional masonry infilled RC frame had probability of collapse higher than the acceptable limit and R needs to be reduced for their design. Thus, the original design procedure of bare RC frame need not to be altered for AAC infilled frames unlike conventional infills.

Figure 16. Mean displaced profile at collapse

Figure 17. Collapse fragility curves

Summary and Conclusions

An experimental investigation is carried out on reduced scale AAC infilled RC frame to study its hysteretic behavior and the performance of masonry infilled OGS RC frames are compared based on FEMA P695 methodology. The average values of compressive strength and elastic modulus of AAC masonry was observed to be approximately one-third and one-half of
conventional masonry, respectively. The low strength and stiffness of AAC masonry results in improved load sharing between infill and frame which leads to early development of yield mechanism in the frame leading to an enhanced energy dissipation capacity. Post-yield strain hardening behavior was observed during the displacement controlled slow-cyclic test.

Non-linear static and dynamic analyses performed according to FEMA P695 methodology demonstrate superior behavior of AAC infilled OGS RC frame compared to conventional infills. AAC infilled OGS RC frame designed using response reduction factor ($R$) of 5, results in lower probability of collapse at MCE (9.2%) and also reduce the damage both at MCE and DBE level ground motions. On the contrary, probability of collapse of conventional masonry infilled OGS RC frame was much higher; 26.1% and 33.6% for clay and fly-ash bricks, respectively, which is almost three times of that of AAC infill. Therefore, the value of $R$ used for SMRF needs to be reduced accordingly for the design of conventional infilled RC frames.

**Acknowledgements**

The authors would like to acknowledge UltraTech Cements Limited for providing mortar material for construction of the test specimens. The authors sincerely appreciate the assistance received from the staff of the Structural Engineering Laboratory of the IIT Kanpur. Additional support from the Poonam & Prabhu Goel Foundation at IIT Kanpur for research and outreach activities in earthquake engineering is greatly appreciated.

**References**


