Behaviour of AAC Infilled RC Frames under In Plane and Out of Plane Seismic Demands

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Abstract

Observations after several earthquakes revealed that infill walls may significantly alter the response of reinforced concrete frame buildings. They increase the lateral stiffness and strength of frames subjected to low to moderate in-plane seismic excitation, however they may experience sudden failure under the combined action of in- and out-of-plane seismic demands. Autoclaved aerated concrete (AAC) is a popular choice of infill wall material due to its advantages such as light weight, good insulation and high durability. In this study, the in-plane and out-of-plane behaviour of AAC infill walls were investigated by conducting combined in-plane and out-of-plane tests. Three specimens were tested under the action of in-plane (IP) deformation demands and out-of-plane (OOP) acceleration induced forces. Sudden OOP failure with limited ductility was observed under the combined IP-OOP loading at a drift ratio of about 1%, which was significantly smaller than the drift capacity of RC frame subjected to in-plane loading only. An interaction diagram in the form of sustainable interstory drift ratio to out-of-plane acceleration demands were obtained from the test results. The results demonstrated the importance of considering IP and OOP interaction for safe design of RC frame buildings.

Keywords: AAC infills, in-plane, out-of-plane, response

1. INTRODUCTION

The performance of RC framed buildings in earthquakes constructed by using the rules presented in the contemporary design standards was observed to be adequate (EERC 2011.a, Christchurch EQ 2011). However, the performance of the infill walls was not sufficient and they showed excessive damage during severe earthquake excitations, causing both economical and psychological damages (Kocaeli EQ 1999, EERC 2011.a, EERC 2012, Akkar *et al* 2011, EERC 2011.b). The interviews after devastating earthquakes showed that the inhabitants had a resistance to live in their apartments and tended to move to another safe place, despite the fact that damage was non-structural and limited to the cracking of the infill walls (Akkar *et al* 2011, EERC 2011.a, EERC 2012). Therefore, there is a need to understand and revise the design and construction practice regarding the performance of the infill walls in RC frames.

Numerous experimental studies were carried out to examine the performance and the interaction of brick infill walls with the RC frames (Mehrabi *et al* 1994, Marjani 1997, Mosalam *et al* 1998, Fardis *et al* 1999, Hashemi and Mosalam 2007, Asteris 2011, Kurt *et al* 2011 and Ezzatfar 2016). The tests on Autoclaved Aerated Concrete (AAC) infilled RC frames are lower in numbers compared to solid or hollow clay brick infilled frame tests. The previous tests on frames with AAC infill walls were mostly conducted within the plane of the frames by imposing cyclic displacement excursions (Costa *et al* 2011, Penna *et al* 2012, Bose and Rai 2014 and Penna *et al* 2015). These studies pointed that the infill walls may affect the frame stiffness, strength and deformability significantly. The effect of infill-frame interaction is beneficial for low lateral displacement demands by improving both the strength and lateral stiffness as long as the infills remains intact. However, this effect diminishes for moderate-to-high lateral displacement demands due to the low displacement capacity of infill wall material (Kurt *et al* 2011, Turgay *et al* 2015). In fact, the separation of the infill from the frame was found to be the key source of the formation of the compression strut mechanism, which increases the shear demands and damage on the boundary columns of the frame. Although majority of the past research focused on investigation of in-plane (IP) response, evidenced by the reconnaissance surveys after severe earthquakes (Akkar *et al* 2011, EERC 2011.a), infilled frames are usually excited under combined IP and out of plane (OOP) loading. Few experimental studies focusing on the IP and OOP interaction is available for brick masonry infill walls (Akhoundi *et al* 2015 and Furtado *et al* 2016.a). Brick infill material is stiffer than AAC whereas typical AAC block dimensions are larger than bricks providing easier construction with less bed and head joints. Hence, the experimental results from brick infill wall tests are not applicable to estimate the response of AAC infilled RC frames. The reduction in the capacity of infill walls due to interaction of IP and OOP demands for AAC infilled RC frames requires further research.

In this study, IP and OOP tests were conducted to reveal the interaction of IP and OOP effects and to observe the effect of OOP application on the IP performance of AAC infilled frames. To this end, three tests were conducted to simulate i- IP only, ii- OOP only and iii- IP + OOP demands. The in-plane effects were reflected to the RC framed AAC infilled specimens by two-way cyclic displacement excursions whereas the OOP effects were simulated by applying uniform pressure by using an airbag loading system. Results from the tests are presented in the following sections.

2. SPECIMENS AND LOADING PROTOCOL

Single-bay and single-story half-scaled portal frame specimens with planar dimensions of 2500x1500mm were constructed for the purposes of this study (Fig. 1). The column dimensions were 200x200mm with eight of 8-mm-diameter deformed bars as the longitudinal reinforcement and 6 mm-diameter plain bars as stirrups. Stirrup spacing in the columns was 50 mm at the ends of columns for a distance of 300 mm whereas it was 100 mm in the middle portion of columns. The presence of the slab was also considered by constructing a flanged beam with an effective slab width of 1000 mm and a slab thickness of 70 mm. The total beam height was 150mm and the web thickness was 200mm. At the ends of the beam, confined zones were also formed by reducing the transverse reinforcement spacing to 50mm for a distance of 400mm, whereas the spacing of the transverse reinforcement was 100mm for the remaining portion of the beam. All the reinforcement details complied with the Turkish Earthquake Code (2007). All the stirrups were anchored using 135^o hooks for all columns and beam to simulate a code-compliant detailing. Target concrete compressive strength was 30 MPa, whereas AAC blocks had a compressive strength of 2.5 MPa.

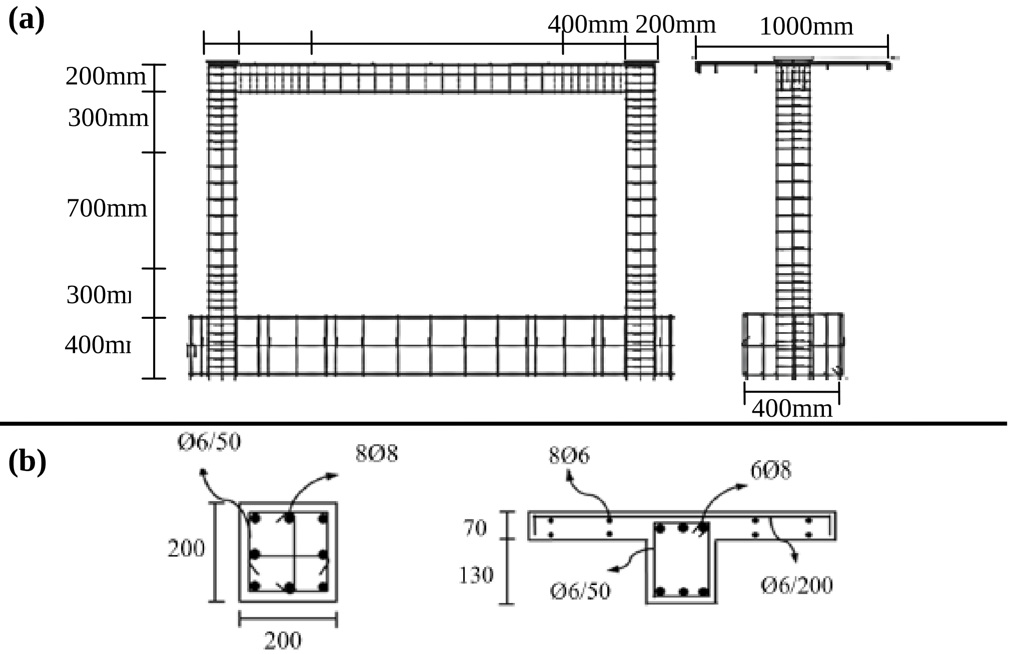


Fig. 1. (a) Specimen dimensions (in mm) and (b) reinforcement details

Similar physical properties were used for all the frames and the AAC blocks in the specimens. For each specimen, an AAC infill wall was constructed inside the RC frame. The key variable in each test was the loading scheme. While designing the test setup, a five story three bay prototype building was designed and gravity loads acting on the first story columns and beams were determined. Accordingly, concentrated axial forces with a magnitude of 200 kN were applied on the columns of each specimen to simulate axial forces from upper stories. A distributed load of 7kN/m were placed on the beams by using steel blocks to simulate gravity loads transferred from slabs based on the analysis of the prototype building. The loading protocol for the first specimen (E1) was constant vertical gravity loading in addition to the two-way cyclic in-plane displacement excursions with the protocol given in Fig. 2. The second specimen (E2) was subjected to vertical loads and increasing out-of-plane pressure. The last specimen (E3) was tested under the effect of constant OOP pressure (equal to 33% of the OOP capacity), the vertical loads simulating the gravity loads on beams and columns and the two-way cyclic in-plane displacement excursions. The details of test setup for IP loading and OOP loading are presented in Figs. 3 and 4.

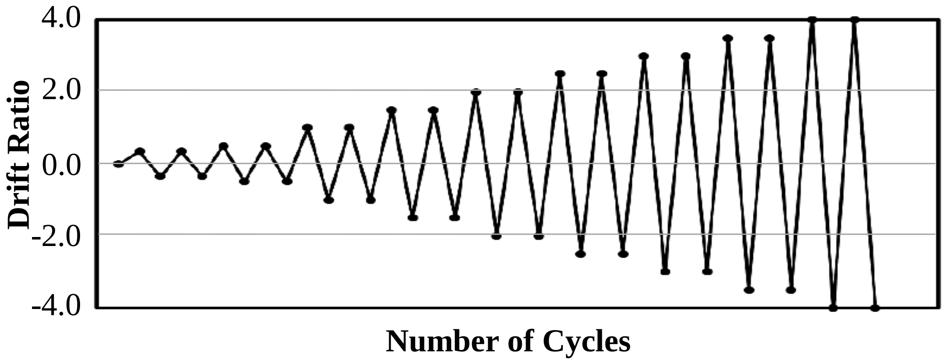


Fig. 2. IP loading protocol

The OOP loading was applied to the specimen by using an airbag. The OOP loading protocol was different for OOP only (E2) and IP+OOP (E3) tests. During OOP test (E2), the OOP pressure on the AAC walls was increased till the failure of AAC infill wall was observed. In contrast, the OOP pressure was constant throughout the IP+OOP experiment (E3) and the same IP loading protocol as IP only test was applied to the specimen till AAC infill wall failed.

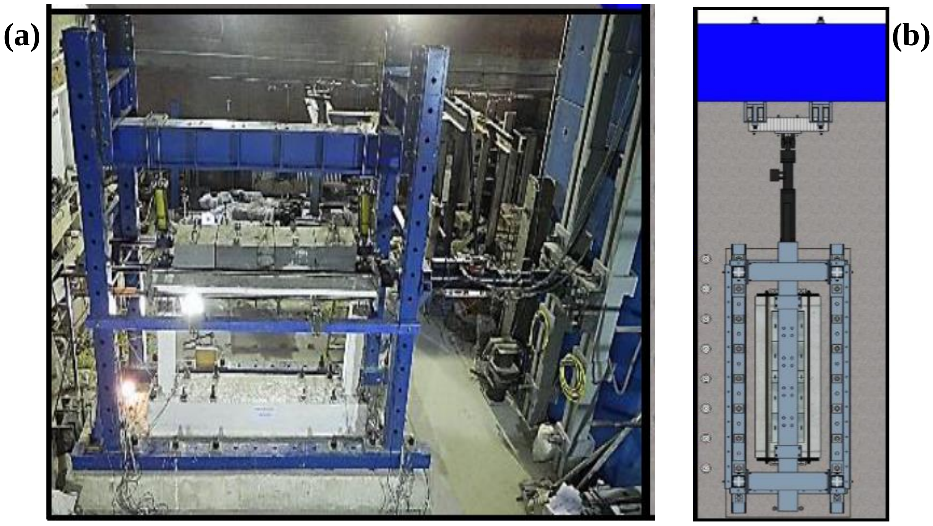
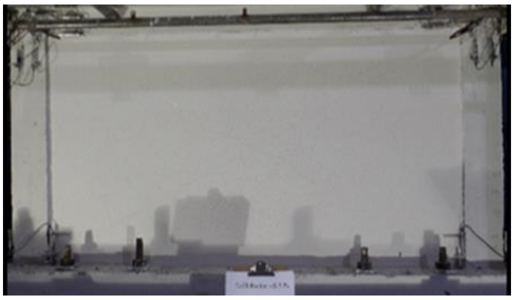


Fig. 3. IP test setup : (a) general view and (b) top view of the test setup

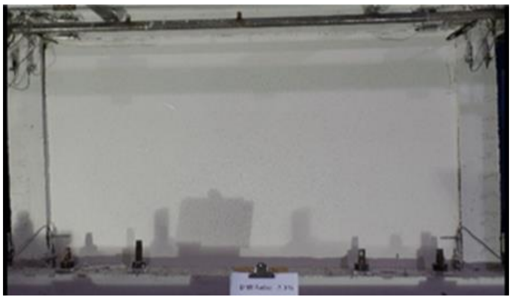
Fig. 4. Test setup and instrumentation for OOP loading: (a) loading setup for airbag and (b) displacement measurements

3. TEST RESULTS

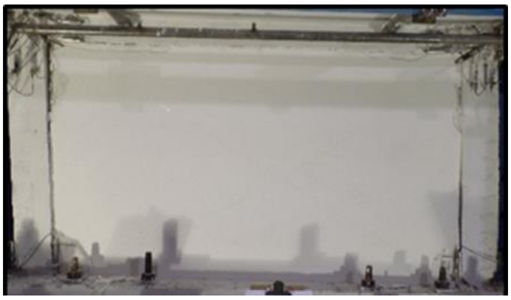
The IP, OOP and IP+OOP tests were conducted till either frame failure or AAC infill failure were observed. The detailed observations on the damage propagations and crack patterns are presented herein. The load-deflection curve and the observed damage pattern for Specimen E1 is shown in Fig. 5. Specimen E1 was pushed by applying reversed cyclic lateral displacements until a drift ratio of 4% was attained in the absence of out of plane pressure. At this drift ratio, the plastic hinges at both ends of the columns of the frame were observed. Therefore, the test was stopped due to the excessive damage on frame. This specimen was determined to lose 20% of its base shear capacity at a drift ratio of 1.5 %. It is important to note that the specimen could not maintain at least 80% of its ultimate capacity up to 2% drift ratio, which is the drift limit state for earthquake resistant design (Turkish Earthquake Code 2007). The lower deformation capacity is attributed to the presence of the infill wall. The AAC wall was determined to be intact till the end of the experiment. Although there was some crushing observed at the corners of the AAC infill wall, this damage did not cause total collapse of the AAC infill wall. This behavior was due to the energy dissipation provided by the composite mesh placed between two layers of plaster, improving the infill performance significantly. The evolution of the cracks in Specimen E1 is presented in Fig. 5.



(a) DR = 0.5 %



(b) DR = 2.0 %



(c) DR = 4.0 %

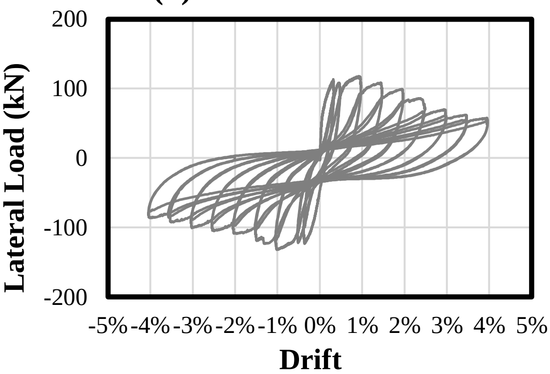


Fig. 5. Damage pattern and the load-deflection response (Specimen E1)

Specimen E2 was pushed in the OOP direction by applying uniform pressure until the complete failure of the AAC infill wall occurred in the absence of in plane loads. The observed cracks in Specimen E2 along with the measured out of plane total force to OOP displacement of the wall is presented in Fig. 6. A horizontal crack was observed at the center of the AAC infill wall. Then, this crack slightly inclined with the increase in the pressure along OOP direction. Finally, cracks from both directions converged to each other in a V-shaped crack. This crack caused the total collapse of the AAC infill wall.

The damage patterns obtained from the testing of Specimen E3 (i.e. IP+OOP experiment) demonstrated that the interaction of the IP and the OOP actions caused a decrease in the drift ratio capacity of the AAC infill wall. Specimen E3 showed that the drift ratio capacity of the AAC infill wall was nearly 1%, at which the total collapse of AAC infill wall was observed (Fig. 7). Therefore, the application of nearly 33% of the OOP pressure capacity resulted in nearly an equal amount of reduction in ultimate drift ratio. The lateral drift ratio capacity to OOP pressure is presented as an interaction diagram in Fig. 8. In Fig. 8, the drift ratio corresponding to the failure of the specimens tested under in plane loads (i.e. specimens E1 and E2) was determined as the drift ratio at 20% capacity drop from the ultimate lateral load. It can be observed that the interaction between drift capacity and OOP pressure appears to be linear. Turkish Earthquake Code (2007) limits the inter-story deformation to 2% in frame buildings. However, neither of the specimens tested in plane (i.e. E1 and E3) could maintain 80% of their ultimate load carrying capacity at a drift ratio of 2%. This finding suggests that presence of AAC infill walls are expected to reduce significantly the deformability of RC frame buildings. Hence AAC infill walls should either be considered in the seismic design or relevant measures should be taken to reduce their interaction with the boundary framing members.

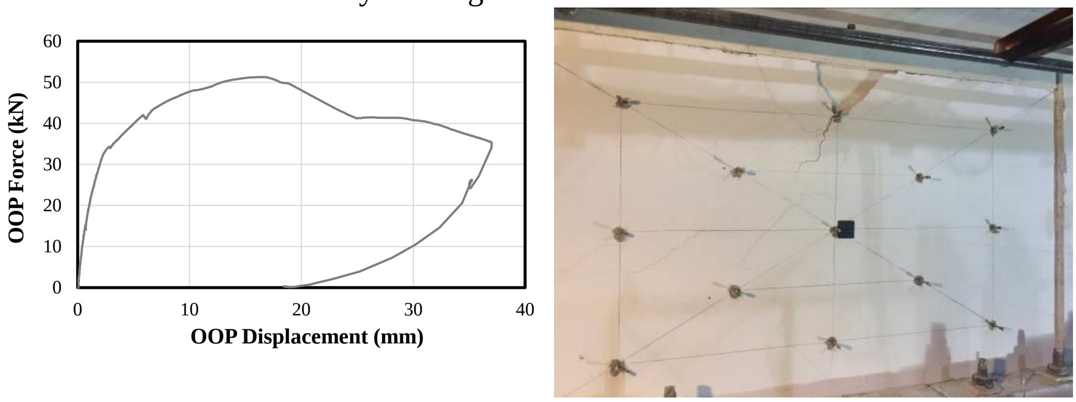


Fig. 6. Load-deflection response and the observed crack pattern for Specimen E2

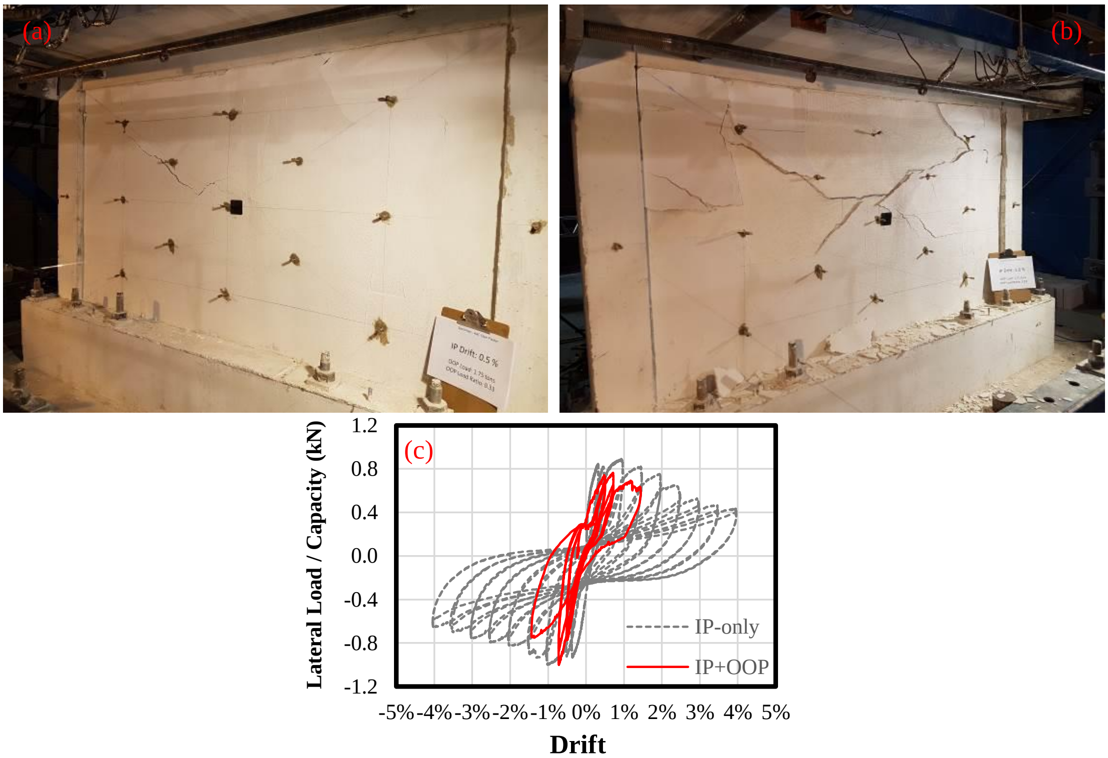


Fig. 7. Damages of AAC infill wall (Specimen E3) : (a) inclined cracks at a drift ratio of 0.5%, (b) cracks at the failure at a drift ratio of 1% and (c) comparison of normalized load-displacement curve

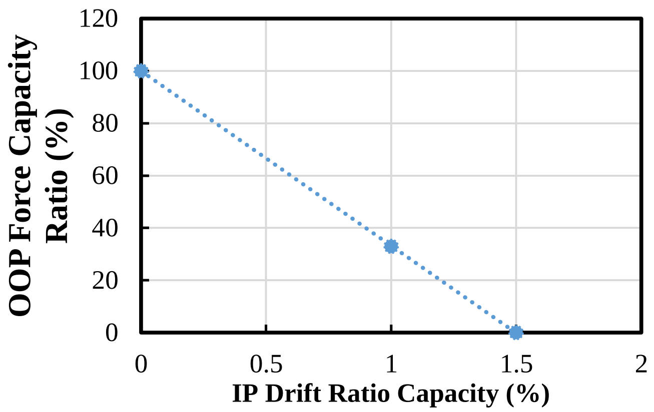


Fig. 8. IP and OOP interaction curve

4. CONCLUSIONS

In this study, the effect of combined IP and OOP demands on the performance of AAC infill walls was investigated experimentally. To this end, three tests were conducted to simulate IP only, OOP only and IP+OOP effects. The results of these tests revealed that the IP and OOP effects had a nearly linear interaction. Consequently, AAC infill walls having large OOP effects had lower in-plane capacities. Thus, this observation strongly suggests the consideration of IP and OOP interaction while estimating the performance of AAC infill walls under the effect of earthquake excitations.

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