FULL-SCALE SEISMIC TESTING OF A BUILDING CONSTRUCTED WITH AAC PANELS

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Abstract

Thanks to its cellular internal structure, Autoclaved Aerated Concrete (AAC) is well known for superior characteristics such as low self-weight, good thermal insulation and high fire resistance. In addition to them, the AAC materials high workability boosts its usage, particularly for construction of non-structural elements such as infill walls or façade claddings. With regard to building physics, AAC has two important aspects, which are its low thermal insulation value and low water vapor diffusion resistance factor which helps to build healthy and energy efficient homes, besides its structural advantages. The construction of houses with reinforced AAC panels is easy, quick and economic. This type of houses, which are generally single or two story, had been built in various regions of Turkey and performed well against destructive earthquakes. In this type of buildings, wall panels of the structure are load-bearing elements and the reinforcements between the joints of load bearing panels are covered with grout. The joint reinforcements are anchored to foundation and bond beams. This connection provides integrity and increases the load bearing capacity. Floor and roof panels are also built with AAC panels; these are approximately three times lighter than conventional concrete slabs. Thus, light weight provides lower axial stress on load bearing panels, and also decreases the earthquake forces acting on the structure. AAC panels are prefabricated elements and produced according to certain production standards. After production, in order to secure quality, AAC and reinforcements in AAC are tested. Factory produced elements are always more controlled than structural elements produced on site. Although, the porous nature of the AAC leads to relatively lower mechanical characteristics with respect to ordinary concrete, thanks to its light weight, the seismic demand in the form of inertial forces is also low. This low seismic demand enables the use of reinforced AAC panels for construction of low-rise buildings even in regions with high seismicity. However, the experimental studies available in the literature that aim to investigate the seismic behavior of such AAC Panel structures are scarce and limited to certain application practice that generally varies depending on the region and manufacturer. Moreover, only limited design documents address to seismic design of this type of buildings. In order to shed some light on the issue, in this study, a full-scale three-dimensional building has been tested under simulated earthquake loads. The quasi-static test has been performed as part of an extensive experimental campaign, which includes several material and member tests. The building is two stories high and has approximately 6 m x 6 m plan dimensions. In this paper, in addition to the introduction of the investigated building typology, the followed testing procedure is also briefly described. Then the main experimental results and observations are summarized.

Keywords: autoclaved aerated concrete; AAC; earthquake; full-scale test; panel

1. Introduction

Turkey and many other countries in seismic regions suffer from severe earthquakes quite frequently. These earthquakes cause remarkable losses in terms of human lives as well as tremendous social and economic negative impacts on the affected area. The major cause of huge losses are the damages and collapses of existing buildings mostly due to poor construction materials and techniques, which cannot be avoided because of improper quality control and inspection. While a lot of efforts are spent in recent years to improve the construction and inspection system, simple and robust construction systems, for which quality control and inspection can be executed easily, are still demanded. On the other hand, the Autoclaved Aerated Concrete (AAC) industry in Turkey is highly developed and the volume of production of AAC construction materials/components in terms of blocks and reinforced panels in Turkey has been one of highest in the world in recent years. Since AAC blocks and panels are constructed in a factory environment, a proper quality control can be achieved easily. Practical construction techniques that allow an efficient quality control and inspection on-site while using these quality-controlled construction materials/components may lead to safer constructions [1]. In this aspect, use of reinforced AAC panels as load bearing structural members for construction of low-rise buildings becomes a strong alternative.

However, the existing research for seismic behavior of AAC panel buildings is scarce and limited mainly to the research program carried out at University of Texas Austin. In scope of this research activity, the behavior of walls with reinforced AAC panels under the combined action of vertical and reversed cyclic lateral loads was examined extensively [2, 3, 4]. In the experimental part of the project, Tanner [2] tested both shear and flexure dominated walls and observed that the walls can exhibit a satisfactory performance. Additionally, the seismic performance of a two-story model building with AAC walls and AAC floor panels was also investigated under quasi-static reversed cyclic lateral loads. The performances of predictive models for flexural and shear behavior are compared with the test results and assessed [2]. Another study that investigated the seismic behavior of reinforced AAC panel structural system was carried out by Ugurlu et al. [5]. In that study, the seismic performance of a real school building that experienced the 1999 Marmara earthquakes was assessed by using finite element method and behavior under seismic loading was explained.

Aiming to investigate the seismic behavior of AAC panel buildings and draft proposals for seismic design rules of such structures, recently, a joint research group has been formed by the Turkish AAC Association (TGUB), Istanbul Technical University (ITU) and Middle East Technical University (METU) and a research project has been initiated. The completed and ongoing activities of the research group includes an extensive experimental campaign that includes several material and member level tests, in addition to full-scale building tests. In this study, firstly, the investigated building typology is briefly described and the quasi-static testing process of a full-scale AAC panel building described. Then, the main observations and result obtained from this test are briefly summarized.

1.1 AAC material and reinforced AAC panels

Autoclaved aerated concrete (AAC) is a lightweight cementitious building material with closed internal voids. AAC is made from cement, fine silica sand, mixing water, aluminium powder and unhydrated lime. The low density is achieved by the formation of non-connecting, macroscopic cells uniformly distributed within the mass. Chemical reactions between the aluminium powder and the alkaline slurry produce hydrogen gas bubbles that are kept in the matrix and subsequently increase its volume. After initial setting and cutting to shape with stainless-steel wires, the AAC elements are then autoclaved at a temperature of 190℃ and a pressure of 12 atmospheres for 10 hours. AAC has many advantages with respect to its alternatives. Some of these advantages are its lightweight, significant thermal insulation and non-flammable characteristics [6].

AAC elements can mainly be classified in two groups as reinforced and unreinforced members. Unreinforced members are known as blocks used for infill or structural walls, insulation boards used for thermal insulation purposes and filler blocks used in hollow tile floor slabs. Reinforced AAC members are mainly used for vertical and horizontal wall panels, and floor and roof panels [6].

As also mentioned above, AAC can be used to produce factory-reinforced panels (lintels, beams, floor panels, roof panels, and wall panels). Welded-wire reinforcement consisting of longitudinal and transverse wires is used for reinforcing the reinforced AAC panels. A typical detail of welded-wire reinforcement in an AAC reinforced panel is shown in Fig. 1. It should be noted that, in Europe, reinforced AAC panels are designed and produced according to engineering rules defined in EN 12602 [7]. In addition, ACI 523.4R-09 [6] describes the design of reinforced panels and also provides information regarding the construction of buildings with AAC panels. Vertical and horizontal walls (which behave as cladding materials, when used at the facade of the building), floor panels and roof panels are typically produced with a maximum length of 600 cm and width of 60 cm. The thicknesses of these panels vary between 10 and 30 cm. On the other hand, load bearing vertical walls generally have a maximum length of 300 cm and a width of 60 cm. The thicknesses of these panels vary between 20 and 30 cm [6].

In Turkey, reinforced AAC panels are produced in two main classes: AAC 3.5 and AAC 5.0. In Table 1, the specified material properties of these material classes are presented [7]. Generally, AAC 3.5 class of AAC panels are used as roof panels, whereas AAC 5.0 class of AAC panels are used as load bearing wall panels and floor panels.

Fig. 1 – Welded-wire reinforcement in an AAC reinforced panel [8].

Table 1 – Specified material characteristics of AAC [7]

Characteristic	AAC 3.5	AAC 5.0
Dry Density	500 kg/m^3	600 kg/m^3
Compressive Strength	3.5 MPa	5 MPa
Modulus of Elasticity	1750 MPa	2250 MPa
Coefficient of Thermal Expansion	8x10-6 /◦K	
Poisson's Ratio	0.2	

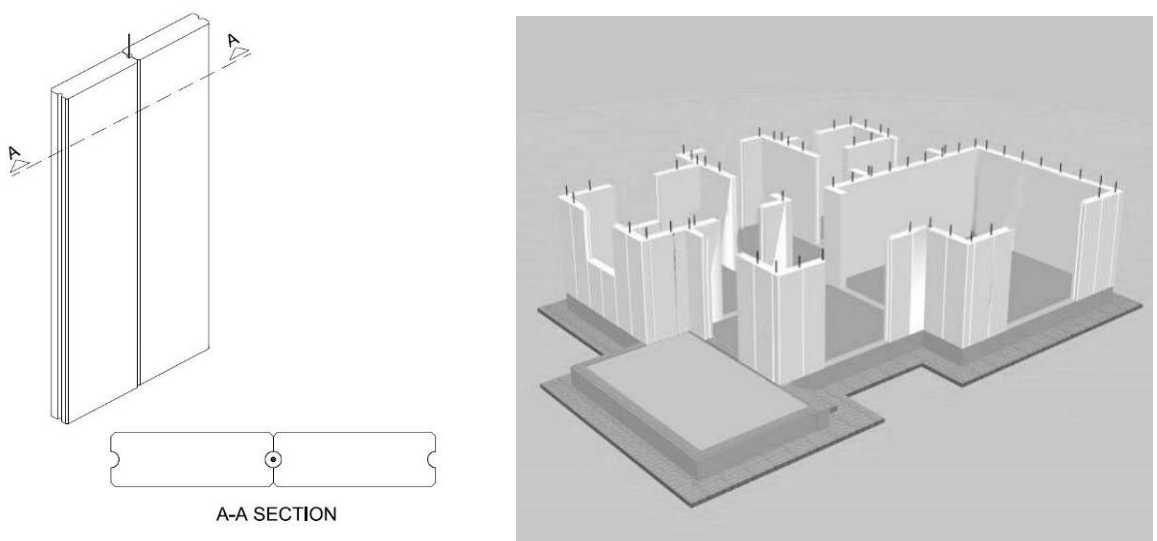
1.2 AAC structures constructed with reinforced AAC panels

In this type of structures, which are generally up to 2 or 3 stories high, internal and external walls are constructed by using load bearing AAC vertical wall panels and slabs and roofs are constructed by using AAC floor and roof panels. Connection between vertical walls and floor panels are formed via reinforced concrete bond beams [5].

In Turkey, since 1970 approximately 5000 structures (mainly housing units) were constructed by using this construction technique. About 250 out of 5000 buildings experienced destructive earthquakes like 1999 Kocaeli (7.4 M_w), 1999 Duzce (7.2 M_w) and 2011 Van (7.1 M_w) earthquakes. It should be noted that, after these earthquakes some of these 250 buildings were inspected and no significant damage was reported [9]. These buildings are still being used by their residents. Moreover, structures constructed with AAC reinforced panels were used as shelter houses for earthquake victims, as shown in Fig. 2 [5].

Fig. 2 – Post-earthquake housing units constructed with AAC reinforced panels [5]

In case of a typical AAC panel building, the production starts with the construction of the reinforced concrete (RC) foundation over the levelled ground. During the construction of the foundation, starter bars for vertical reinforcement between the panels are embedded into foundation with a spacing of 60 cm. Then wall panels are placed between these bars. The intersection point of wall panels forms a hole where reinforcement can pass through (Fig. 3a). These holes are filled with grout after a reinforcing bar is placed and overlapped with the starter bar. The length of the reinforcing bar is 50 cm longer than the wall panel so that this part of the bar is anchored to the bond beam above the wall panels (Fig. 3b).



(a) (b)

Fig. 3 – (a) Vertical reinforcement between two panels, (b) typical view after erection of the first story [8]

In the next step, RC bond beams are cast on top of the wall panels. Starter bars for upper story wall joint reinforcements are also anchored into the bond beams again with a spacing of 60 cm to commence the construction of second story wall panels. Then floor panels are placed on bond beams, which behave as simply supported beams. The connection between each floor panel is filled with a reinforcement of 10 mm diameter and covered with grout. In Fig. 4, details of the connections of floor panels can be seen.

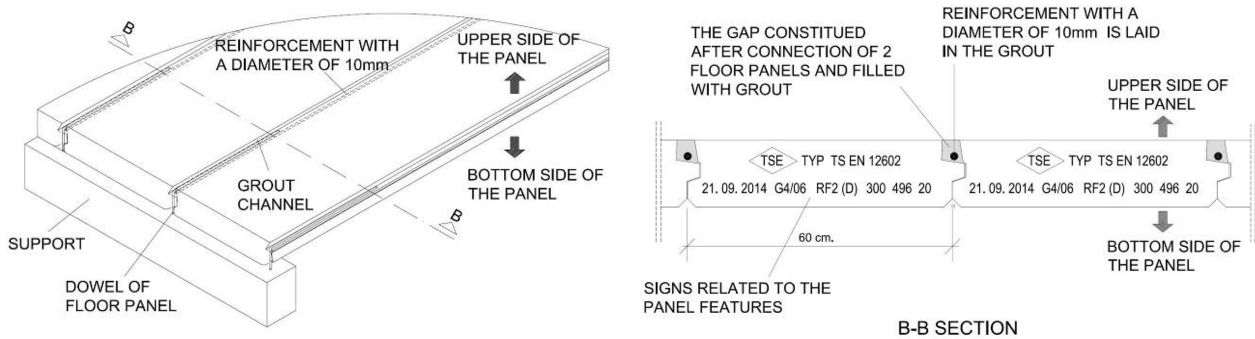


Fig. 4 – Connection details for floor panels [8]

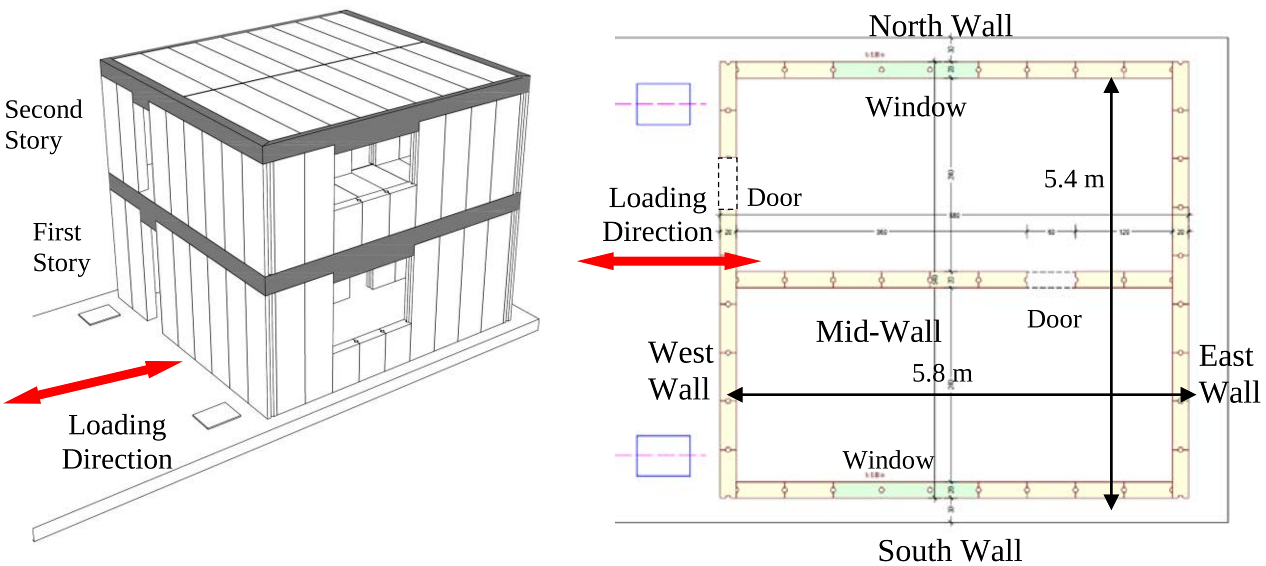
2. Experimental Study

In scope of the experimental campaign carried out by the TGUB-ITU-METU research group, a two-story, full-scale building (Fig. 5a) was constructed and tested at the campus of Istanbul Technical University. A similar test was also performed by METU with a different building specimen.

2.1 Main features of the test building and construction

The test building had plan dimensions of 5.8 m × 5.4 m and a total height of 5.0 m (first story 2.75 m, second story 2.25 m). As also seen in Fig. 5, three wall axes were available in the loading direction (named as north wall, mid-wall and south wall) and two wall axes were available along the direction vertical to loading (named as west wall and east wall). Each of the northern and southern walls consisted of two sub-walls that were formed either with two or four panels. Additionally, a three panel wide window was available at these walls. Mid-wall and west wall consisted of one six panel wide and one two panel wide sub-wall, separated by a door. Finally, the east wall consisted of nine panels without any openings. The plan layouts of both first and second stories were identical.

Wall, floor and roof panels of the tested building were produced in Turk Ytong Inc. Pendik factory and transported to the test site available at the Istanbul Technical University Campus. The open air testing area was used before for other large-scale experiments, therefore, the 40 cm thick RC foundation was ready. Since the foundation was already available, the starter bars of the 10 mm diameter vertical panel joint reinforcements were anchored to the foundation by using epoxy bonding with an embedment length of 20 cm. The vertical wall panels were erected over a 2 cm thick cement mortar with the help of a mobile crane. Following the placement of vertical wall panels, the vertical panel reinforcements were placed (using an overlap length of 100 cm with the starter bars) and a cement grout with an approximate compressive strength of 10 MPa was poured into the joints. Then, the reinforced concrete bond beams (with cross-section dimensions of 20 cm ×35 cm at first floor level and 20 cm ×30 cm at roof level) over the vertical panels were cast by using a concrete mix with a mean compressive strength of 30 MPa. Both the panel joint and bond beam reinforcements were deformed bars with a specified yield strength of 420 MPa. The floor panels were placed over the bond beams and the 10 mm diameter joint reinforcements placed between the floor panels were anchored to the bond beams by using a cement based mortar. Lintels above the door and windows openings were integrated to the bond beams and total cross section height of the bond beams above doors and windows was 55 cm. Then, the similar procedures were followed for the second story and construction was completed in a total time period of two weeks. Various stages of the test building construction can be seen in Fig. 6.



(a) General view of the test building (b) Plan layout of the first and second stories

Fig. 5 – Three-dimensional and plan views of the tested building

Fig. 6– Construction of the test building

In order to characterize the utilized AAC material, compression and modulus of rupture tests were performed and the mean values given in Table 2 were obtained. It should be noted that, during the construction of the load bearing vertical walls and the first story slab; panels made of AAC 5.0 were used and the roof panels were made of AAC 3.5.

Table 2 – AAC Material test results

	AAC 3.5	AAC 5.0
Moisture Content (%)	6	6
Compressive Strength (N/mm²)	4.6	6.5
Flexural Strength (N/mm²)	0.9	1.3
Modulus of Elasticity (N/mm²)	2080	2260

2.2 Test setup

The open-air large-scale testing area available at ITU is equipped with the electrical supply, lightening fixtures and hydraulic actuator pump. The five-meter-high steel-construction reaction frame, rising above the 40 cm thick reinforced concrete foundation was modified, so that the hydraulic actuators could be attached to the building at both first and top story floor levels. Each of the three servo controlled hydraulic actuators had a force capacity of 300 kN (push and pull) 800 mm stroke length. Two of the actuators were attached at the top floor level, while one was attached at the first floor level as seen in Fig. 7. The actuators at the top level were displacement controlled and the lower level actuator was force controlled, so that the load distribution along the building height could be kept as 2P for top floor level and P for first floor level. The reversed cyclic loading, which targeted first story drift ratios of ±0.125, ±0.25, ±0.5, ±0.75, ±1.0, ±1.5 and +2.0%, was performed in a quasi-static manner.

Fig. 7 – Test setup

The measurement system consisted of a 64-channel data logger, potentiometers and the internal load and displacement transducers actuators. The displacements used for controlling the loading pattern and out-of-plane rotations were measured at the floor levels by using wire gauges, mounted on rigid steel-construction towers independent from the test building (Fig 8). Displacement measurement plan for walls was made as to observe potential rocking and sliding response. Due to symmetry in loading direction (west to east), displacement measurements were basically carried out on the north wall and mid-wall panels of the both stories. As seen in Fig. 9, depending on the previous experience from the shear tests on AAC panel walls performed in the laboratory, linear potentiometers with 100 mm gage length were mounted on the two distant bottom corners of the panels. These potentiometers measured relative displacements between floors and panels. All wall panels were labelled in a systematic manner and in addition to the electronic measurements, crack widths and other damage indicators such as crushing, spalling or sliding were also manually registered and photographed.

Fig. 8 – Reference frames for measuring the floor level displacements

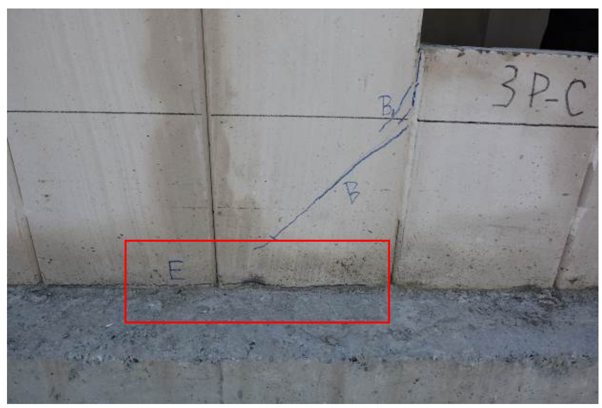
Fig. 9 – Measurement of the wall panel rocking

3. Test Results and Observations

The structure was tested on 08.02.2016, approximately two months after the completion of the building construction. The drift reversals of the loading pattern were imposed to the building up to %2 drift ratio. Since the strength loss at this drift ratio was in the order of 30% and the damage was significant, the test was terminated for the sake of safety. It should be noted that the drift ratios indicated in the following paragraphs correspond to first story drift ratio, where the damage was concentrated.

The damage was first seen as shear cracks at the corners of window openings of first story north and south walls (at 0.125% drift ratio, Fig. 10a). At about 0.25% drift ratio level, separation cracks initiated at the bottom of the first story wall panels (Fig. 10b) indicated that each of the panels were rocking. At 0.5% drift ratio, first shear cracks became visible on the first story four and six panel walls (Fig. 10c), widths of the panel bottom separation cracks increased and uplifting of the foundation in the pulling direction was observed (Fig. 10d). At about 0.75% drift ratio, number and width of shear cracks increased (Fig. 10e). Additionally, panel bottom separation cracks were observed at the east and west walls, which were subjected to out of plane loading (Fig. 10f). Although, shear cracks similar to northern and southern walls also occurred on the mid-wall, at about 1.0% drift ratio, the beginning of sliding over the foundation behavior could be observed. In the following cycles, the sliding of the wall panels above the foundation became apparently visible (Fig. 10h and Fig. 10i) and this sliding dominated the behavior. After drift ratio of 1.5%, six panel walls of mid-wall significantly separated from west and east walls due to sliding on the foundation. At drift ratio of 2%, the test was terminated due to extensive damage and significant strength loss. Although high levels of displacement cycles were achieved and extensive damages occurred on the load bearing walls of the building, no damage was observed in the AAC floor diaphragms.

(a) 0.125% drift ratio

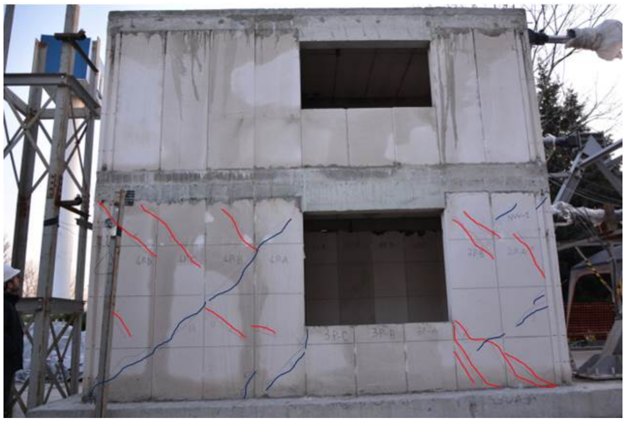


(b) 0.25% drift ratio

(c) 0.5% drift ratio

(d) 0.5% drift ratio

Fig. 10 – Evolution of damage



(e) 0.75% drift ratio

(f) 0.75% drift ratio

(g) 1.0% drift ratio

(h) 1.5% drift ratio

(i) 1.5% drift ratio

Fig. 10 – Evolution of damage (continued)

The obtained lateral load versus first story drift ratio hysteresis (Fig. 11) was indicative of the highly nonlinear behavior. In general, the strength and stiffness degradation was gradual. The peak load capacities were achieved at 0.5% drift ratio levels as 290 kN in the pushing direction and -315 kN in the pulling direction. After completing 1.0% drift ratio, with the influence of sliding behavior, the loops started to get narrower (pinching behavior) and strength degradation took place particularly in the pushing direction. At 1.5% drift ratio, which was the last cycle achieved for both pushing and pulling directions, the amount of strength loss was about 20% in the pushing and 10% in the pulling directions. The cyclic loading resulted with stable loops (particularly until 1.0% drift ratio). This is a clear indication of a well-balanced energy dissipation characteristic and damping capability, given that the building consists of individual panels with numerous discontinuities.

Although the test building was loaded to a high level of lateral displacement, even after the 2.0% drift ratio the overall integrity of the structure was still maintained as seen in Fig. 12. After the test, most of the cracks were closed and only the slight dislocations of the panels were left. This indicates that, even after a major earthquake, the self-centering characteristic of the structural system can reduce the experienced damage.

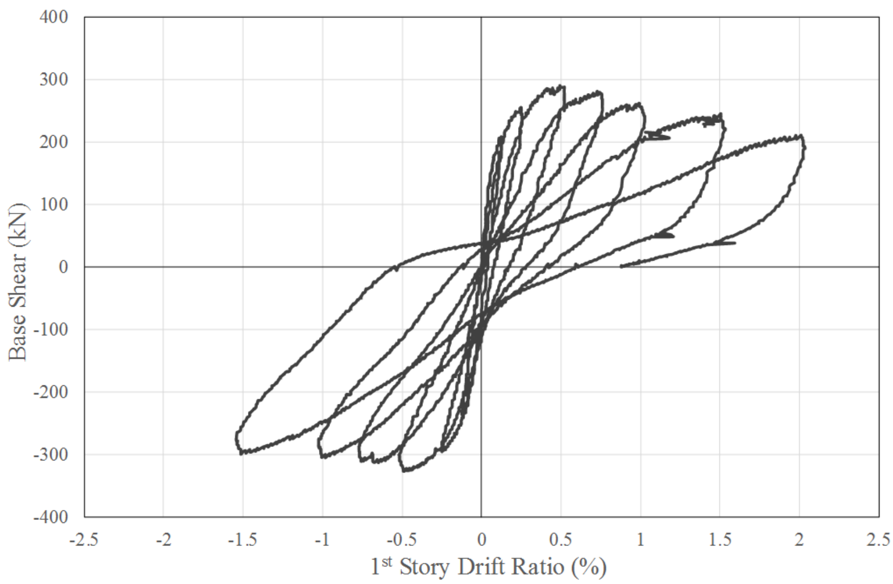


Fig. 11 – Base shear vs. first story drift ratio hysteresis of the tested building

Fig. 12 – General view of the building after being tested to 2.0% drift ratio

4. Conclusions

In this study, field test of a two story full-scale reinforced AAC panel building subjected to gravitational loads and lateral displacement reversals was completed successfully. The following results are determined from the test observations:

- At early stages of the test, flexural behavior of panels dominated the structural response of the test building. When the drift ratio reached to 0.50% (at this drift ratio the building reaches to lateral load capacity, Fig. 11), shear damages became clearly visible (Fig. 10c). Between 0.5% drift ratio and 1.0% drift ratio, shear damages progressed (Fig. 10e). After 1.0% drift ratio, sliding failure of panels at bottom dominated the overall response of the test building (Fig. 10g-I and Fig. 11).

- Although the test building experienced a considerable lateral drift ratio of 2.0% and damage indicators such as rocking, shear cracking, sliding and local crushing were observed, the building still accomplished to maintain its structural integrity.
- The obtained lateral load versus displacement hysteresis was indicative of the highly nonlinear and relatively ductile behavior. The strength degradation that began after 0.5% drift ratio was gradual and at 1.5% drift ratio, the amount of strength loss was about 20% in the pushing and 10% in the pulling directions.
- The hysteretic loops of base shear-first story drift ratio of the test building were stable and energy dissipative that point to a considerable damping capability.

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