**F. Taddei*, L. Reindl*, J. Park*, C. Butenweg*, F. Karadogan***

RWTH Aachen, Chair of Structural Statics and Dynamics**, Istanbul Technical University*

# Numerical investigation of AAC wall panels based on the damage plasticity constitutive law

**ABSTRACT:** This paper gives a short overview on the Ytong Building System and discusses possible seismic verification concepts. Moreover it proposes three-dimensional finite element models for unreinforced and reinforced walls panels in aerated autoclaved concrete on the basis of the concrete damage plasticity constitutive law implemented into the FEM toolkit ABAQUS. The paper focuses on an unreinforced ten panel shear wall and on a reinforced four panel shear wall. For the latter, two different solutions are developed: in the first the reinforcement is directly embedded into the AAC mesh, while in the second grouted cores around the reinforcement bars are taken into account. The quasi-static loading condition was simulated using both static and dynamic implicit analysis, switching from the former to the latter at the occurrence of nonlinearities. The simulation results show that the AAC shear wall models can correctly represent the load-displacement responses as well as the cracking patterns and crack propagations. The concrete damage plasticity constitutive law allows for a proper representation of the cyclic behavior and the damage accumulation of AAC shear walls, which is very important for the performance-based design of structures under seismic loading. Further researches are recommended in order to improve the results and to investigate different combinations of applied axial load, aspect ratios and reinforcement details. The long term goal is the development of a feasible and powerful deformation based seismic verification procedure for the Ytong Building System.

**KEY WORDS:** autoclaved aerated concrete, seismic design, wall panels

## 1. Introduction

Autoclaved aerated concrete (AAC) is a lightweight, precast building material frequently used for masonry construction both internally and externally. In addition to its structural resistance and high thermal insulation capacity, one of AAC's advantages in construction is its quick and easy installation due to its versatile workability. AAC products include a wide range of different construction elements, such as blocks, factory-side reinforced wall panels, roof panels, floor panels, lintels, beams and other special shapes

Over the past years new construction methods using prefabricated AAC panels have been developed. These methods consist of factory-side reinforced floor, roof and wall panels as well as lintels and beams. They allow for a quick and cost-effective construction of residential, commercial and industrial buildings.

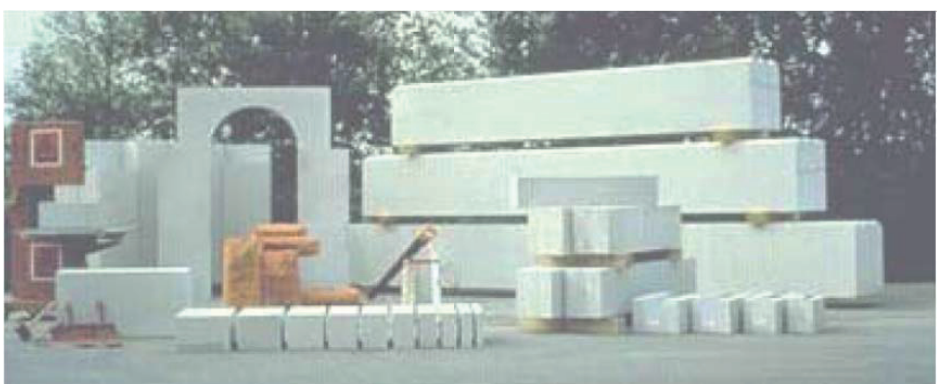

Fig. 1. AAC products [1].

The YTONG Building System [2], for example, makes it possible to build a two-story residential house in eight weeks as turnkey. They are assembled of reinforced vertical wall panels as load-bearing walls in conjunction with reinforced floor and roof panels. RC ring beams are placed on top of all walls connecting the horizontal and vertical panels. Vertical and horizontal panels are reinforced in each joint (Fig. 2). At this time the YTONG Building System is gaining popularity internationally, especially on the Turkish market.

It is well known that north Turkey is among the regions with the highest seismic hazard worldwide and has experienced strong earthquakes several times over the past decades (Fig. 3). Since a certain East-West-progression of the earthquake epicenters over time can be recognized, experts assume a major earthquake is due to strike Istanbul in the foreseeable future.

The Turkish government aims to reduce the corresponding seismic risk through the introduction of design codes for all building types. The fatal consequences of the earthquake in L'Aquila have shown once again the high importance of practical seismic design rules. Although buildings constructed with the YTONG Building System have proven their stability in past earthquakes, seismic design rules are still missing for this construction type. The reason is simple: The system was successfully developed relying simply on engineering knowledge and experience. Therefore theoretically well founded and at the same time simple and safe seismic design rules for the YTONG Building System are strongly needed.

Extensive research into the material properties of ACC and also into the behavior of the above mentioned structure types under horizontal loads has already been carried out at different universities in the USA [1, 4, 6]. However, the amassed experimental data on reinforced ACC panels do not cover the entire scope of products available nowadays, including the YTONG Building System. Building systems can differ considerably in the geometries of the panels and the amount of internal and external vertical reinforcement designated. Hence, further research into reinforced ACC panels under seismic loads is indispensable.

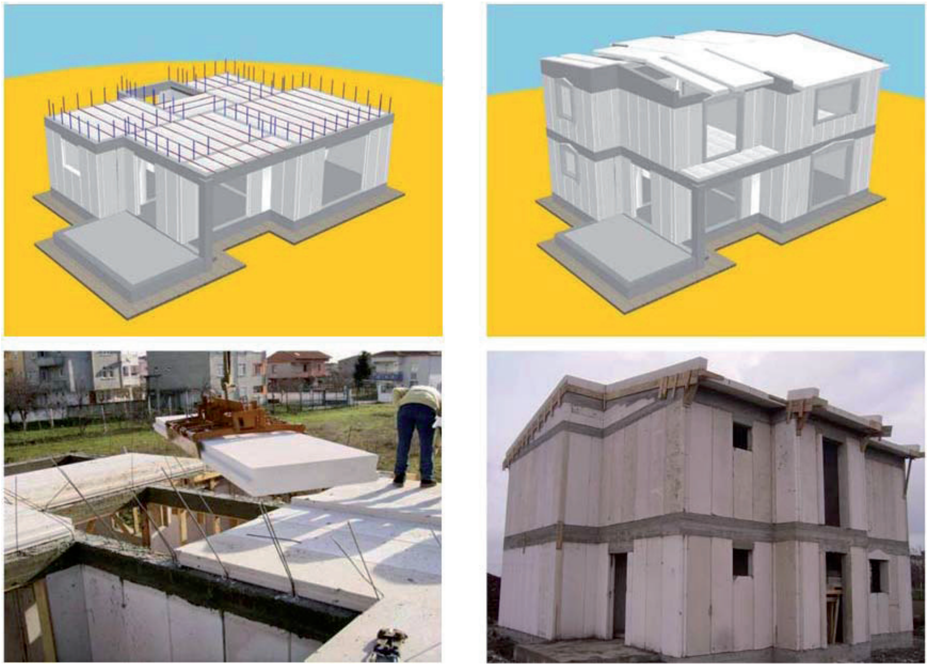

Fig. 2. YTONG Building System [2].

The focus of the present work is put on the seismic performance of residential buildings composed of reinforced vertical wall panels acting as load-bearing walls. A seismic verification concept for this special building type shall be the main outcome of the ongoing research.

## 2. State of the art and preliminary work

In the recent past, preliminary research into the field of factory-side reinforced AAC wall panels has been conducted by different universities in the USA [1, 4]. The Autoclaved Aerated Concrete Products Association (AACPA) supported a research program to investigate the in-plane behavior of different AAC masonry shear wall types. In the course of the program, a series of 19 shear wall experiments was carried out, including different AAC elements, such as masonry-type units and reinforced panels. Among the walls tested, only three were constructed with vertical wall panels and comply with the construction method to be considered here.

Based on the test results and the provisions provided by ACI 318-05 [5], design approaches and equations were derived for shear walls made of vertical AAC panels and summarized in an ACI guideline [6]. The proposed provisions are based on the conventional principles used for the design of reinforced concrete beams:

– strain compatibility between AAC and reinforcement (with some modifications),
– stress-strain behavior of AAC and reinforcement,
– equilibrium.

Although covering different aspects of panel behavior, the design provisions for vertical AAC panels available cannot be directly applied to the YTONG Building System, since they were derived from tests on panels that differ considerably in geometry and the amount of internal and external vertical reinforcement. The wall panels of the YTONG Building System are characterized by a much higher aspect ratio. They are strongly anchored to the RC ring beam and vertically reinforced in all head joints, whereas the tested shear walls were reinforced only in the joints at the walls extremities. Also the vertical loads applied were considerably higher than the vertical load levels expected in typical ground plans designated for the YTONG Building System. Therefore further research activities are needed for the development of new design rules for the YTONG Building System.

## 3. Proposed verification concepts

The goal of the ongoing research is the evaluation of the seismic performance of the YTONG Building System and the development of a force-based verification procedure in a first stage and a performance-based verification procedure in the long run.

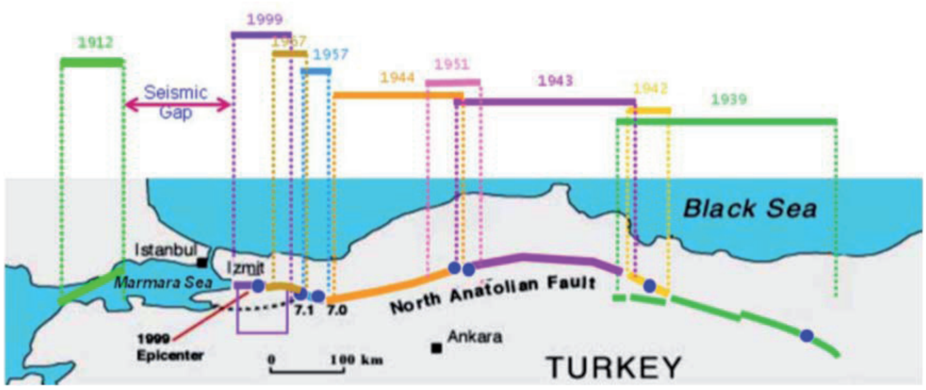


Fig. 3. Westwards propagating sequence of earthquakes on the North Anatolian Fault system since 1939 [3].

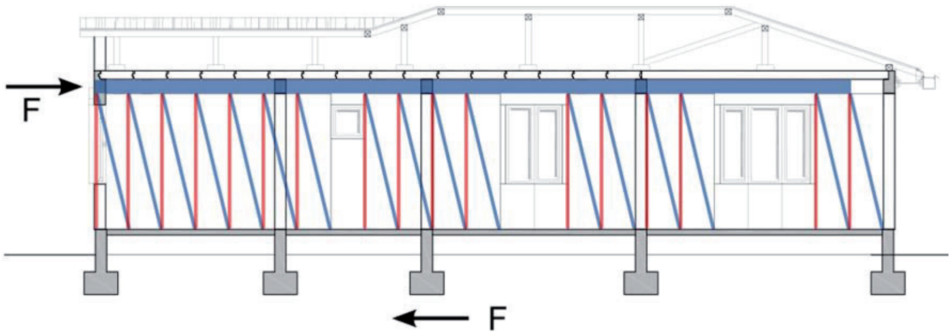


Fig. 4. Expected force distribution in vertical panels under horizontal excitation.

At the ultimate limit state, structures realized with the YTONG Building System are expected to behave similar to a strut-and-tie structure (Fig. 4). Due to the different stiffnesses of the autoclaved aerated concrete panels and the mortar grouts containing the vertical reinforcement bars, the vertical joints are likely to crack dividing the wall into several individual panels. This means that it should be possible to calculate the capacity of a wall by adding up the capacities of the individual vertical panels.

This assumption needs to be confirmed by a series of experimental tests that are yet to be carried out.

On the basis of experimental test results and complementary numerical simulations, a reliable mechanical model needs to be developed for the YTONG Building System. Using this model a force-based verification procedure and design provisions can be derived.

The findings of the investigations described above will provide a basis for an approach to approximate load displacement curves for the YTONG wall panels. The approximated capacity curves will serve as input for a performance-based design procedure, namely the capacity-spectrum-method (CSM) or the L2-method proposed in Eurocode 8 [7]. In order to determine the capacity curves, additional cyclic shear wall tests need to be conducted. Furthermore it can be necessary to investigate the influence of cross-walls through these additional tests.

The use of the deformation-based procedures will allow a seismic design check of different ground plans taking into account the available structural reserves much more extensively than it is possible with force-based methods.

Based on the results found during the development of such a nonlinear approach, the force-based design concept might be improved by introducing reduction factors taking into account the ductility of the building.

Finally, the design concepts and the developed provisions should be verified and refined through a shaking table test of a typical YTONG Building System assemblage also including floor panels and lintels.

## 4. Numerical investigations

In order to support the development of the proposed verification concepts, a numerical model based on the concrete damage plasticity constitutive law has been developed [8] which provides a strong foundation for upcoming parametric studies of geometrical aspects, constructional details and different loading conditions. In the following the numerical model is presented and the results for a ten-panel wall (Shear Wall Specimen 2) as well as for a four-panel wall (Shear Wall Specimen 15a) are given and compared to shear wall test results obtained at the University of Texas [9].

### *4.1. Modelling approach*

Regarding the material idealization, the isotropic damaged concrete plasticity model was used to represent the AAC and the grout material. Thus the two materials are assumed to fail due to the two main mechanisms ‘tensile cracking’ and ‘compressive crushing’. The concrete damage plasticity model in ABAQUS [10] is based on the assumption of scalar (isotropic) damage. It is designed for applications in which the structure is subjected to arbitrary loading conditions such as cyclic loading. The model takes into consideration the degradation of the elastic stiffness induced by plastic straining, both in tension and compression. It also accounts for stiffness recovery effects under cyclic loading.

Regarding the mechanical contacts simulation, the interactions AAC/thinbed mortar, AAC/grout and AAC/AAC were defined by assigning mechanical properties to three contact models, which include constitutive rules for pressureoverclosure relationship, damping peculiarity and frictional aspects to resist to relative motions [11].

For the Shear Wall Specimen 2 model, an assemblage of one base beam, ten vertical panels and one top beam was created (Fig. 5, Table 1). The peak value of each loading cycle is gradually increased from 2.25 mm to 31 mm.

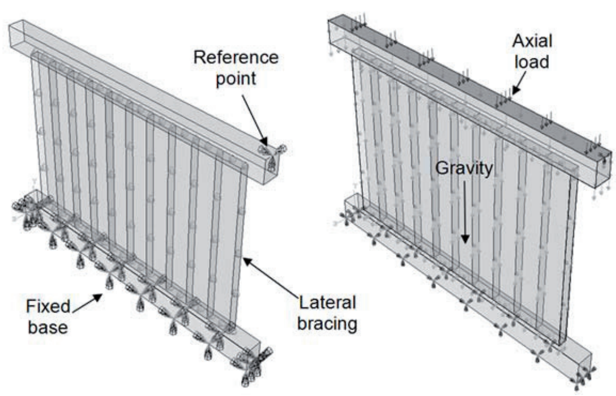


Fig. 5. Shear Wall Specimen 2 model.

Table 1

SHEAR WALL SPECIMEN 2 MODEL GEOMETRY (mm).

| Part | Length | Height | Thickness |
|---|---|---|---|
| Single Panel | 610 | 3900 | 200 |
| Base Beam | 7300 | 500 | 400 |
| Top Beam | 7300 | 500 | 400 |
| Part | Length | Height | Thickness |

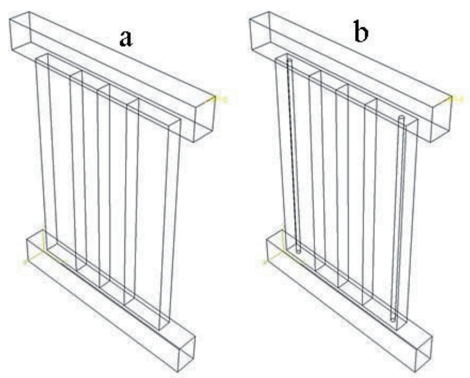


Fig. 6. Assemblage layout for Shear Wall Specimen 15a Model-1(a) and Model-2(b).

Two different models were attempted for Shear Wall Specimen 15a:

- Model-1: a simplified model with only four AAC panels of which the external two are reinforced with a single rebar (Fig. 6a).
- Model-2: a detailed model with four AAC panels of which the external two have a cylindrical hole around the reinforcement location; two instances of grout material are created to fit the holes and a single rebar is placed at the centroid of these two parts; a grout-AAC contact interaction is established to plug the grout cylinders into the holed external panels (Fig. 6b).

The assemblage was created with one base beam, one top beam and two internal jointed unreinforced vertical panels which are in turn jointed to the two external reinforced panels of plain AAC in Model-1 and coupled with the grouted reinforced cores in Model-2 (Table 2). The peak value of each loading cycle is gradually increased from 1 mm to 7 mm for Model-1 and from 1 mm to 3.3 mm for Model-2: in the former the limit was due to the excessive computational time, in the latter the plasticity/creep/connector friction algorithm did not converge after the first crack occurred.

For both models C3D8R 8-node linear bricks were used for the mesh. As the experimental procedure was quasi-static, a general static analysis was performed in each load step when the response is stable, while a dynamic implicit analysis was adopted when the nonlinearities prevented the problem to converge using the static approach [12].

### *4.2. Results*

The displacement and base shear histories for both models are presented in Fig. 7.

For the Shear Wall Specimen 2 model, accordingly to the experiment, the first major event consists of the formation of a vertical crack at the panel joints in the center of the wall while loading into the south direction, at a top displacement of 7 mm. The base shear and drift ratio are 283 kN and 0.14% respectively. The concrete material remains elastic with no damage until the end of step 31, which is on the fifth cycle loading into the north direction. The first tensile crack occurred in the following step 32 (Fig. 8).

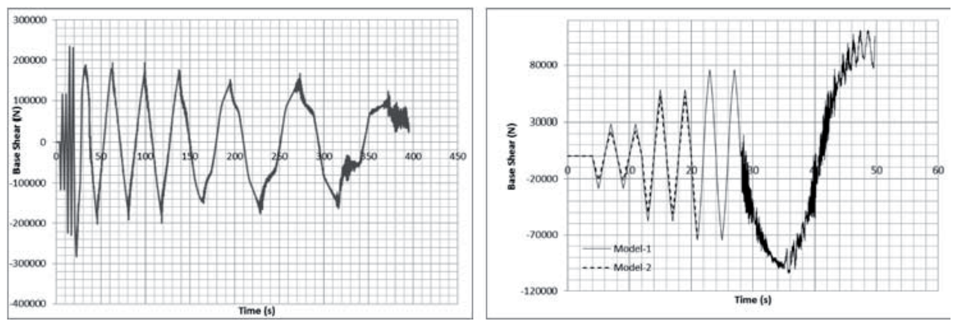


Fig. 7. Base shear history for Shear Wall Specimen 2 (left) and 15a (right).

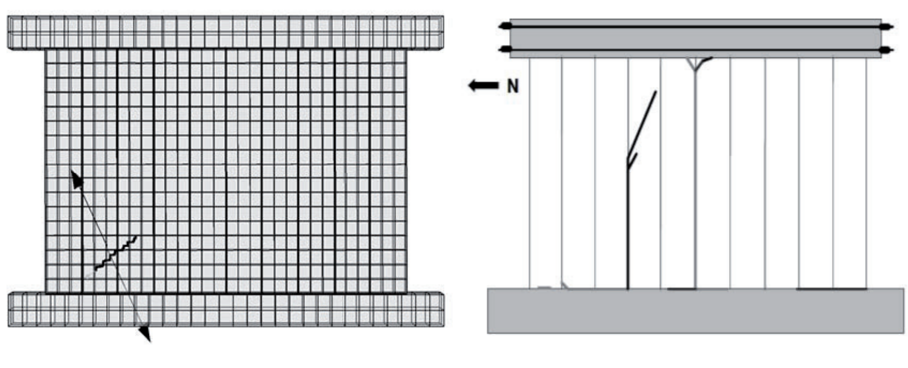


Fig. 8. Occurrence of the first diagonal crack formation in the simulation (left) and in the experiment (right) for Shear Wall Specimen 2.

Table 2

SHEAR WALL SPECIMEN 15a MODEL GEOMETRY (mm).

| | Length | Height | Thickness |
|---|---|---|---|
| Unreinforced Panel | 600 | 3700 | 254 |
| Reinforced Panel | 800 | 3700 | 254 |
| Base Beam | 7300 | 500 | 400 |
| Top Beam | 7300 | 500 | 400 |

From the sixth cycle to the end of the analysis, both in the tests and in the simulation, additional diagonal cracks formed, propagating from the previous occurrences, the damage propagates all over the specimen Fig. 9.

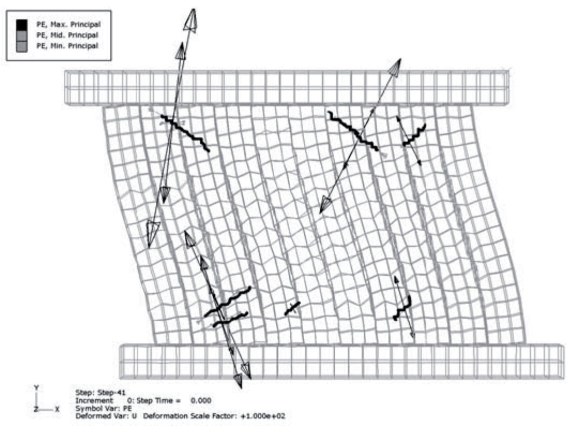


Fig. 9. Additional tensile crack in the numerical model of Shear Wall Specimen 2.

For Shear Wall Specimen 2 model, a deviation of the model behavior from the real response in the last cycles, is mainly due to the degradation of the yielding material during the crack.

Concerning Shear Wall Specimen 15a model, the first major event was the formation of flexural cracks at the base of the wall, causing a continuing failure line along the bond between the panels and the base beam.

The phenomenon described above can also be found in the experiments. In Fig. 10 (left) the opening dimensions variable, COPEN, shows the separation between the panel’s base section and the base-beam’s top surface, which is due to an excess of the bedding mortar tensile strength.

The most interesting event, which matches the wall behavior in the experiment as well, was the propagation of the tensile plastic strain. Monitoring the maximum principal plastic strain in the tensile zones, it is possible to find the flexure-shear cracking as expected during the seventh cycle. In Fig. 10 (right) the vertical plastic strain PE22 is plotted for Step 29, at a base shear of 105 KN and a displacement of 6.5 mm loading into the south direction. As shown, the cracking propagation started on the left side of the wall, near the crushing area, with a value of $3.3 \cdot 10^{-7}$.

For Model-2 a considerable gap developed due to the grout-AAC contact interaction and to the grout material behavior (Fig. 10).

The hysteretic behaviors were also analyzed and the results show that from the Shear Wall Specimen 2 model, most of the hysteretic parameters are included in the experimental ranges, confirming also a reliable response to non-monotonic loading conditions. Concerning Shear Wall Specimen 15a, only for Model-1 a value of the damaged stiffness was calculated after the formation of the first flexural cracking. The unloading stiffnesses and the stiffnesses after yielding of the flexural reinforcement were not computable, as well as the maximum displacement and the displacement ductility.

## 5. Discussion

The proposed models based on a damage plasticity model for concrete are able to simulate the general shear response of walls made of AAC wall panels, considering also the nonlinear behaviors of the involved materials.

Therefore these models may provide a strong basis for a comprehensive parametric study of geometric dimensions and construction details (links to external elements, interactions between AAC elements, amount and position of reinforcement) in order to optimize and improve the shear capacity and contribute to the development of feasible force and deformation based design concepts.

The FE software ABAQUS is deemed suitable to accurately and satisfactory represent the characteristics of the AAC-Ytong shear walls with respect to the involved materials and to the contact interactions.

Concerning the AAC, many factors are involved in the modeling procedure and each of them influences the overall behavior of the shear wall models, especially the post-failure softening of the tensile stress-strain curve.

The Shear Wall Specimen 15a model gives reliable results even if Model-1 showed some discrepancies in the compressive zone (formation of toe crushing, not exhibited in the experiment) in the nonlinear branch of the load-displacement curve, while Model-2 was only able to reproduce the undamaged response properly. For both types of models, the two load-displacement curves (FE and experimental) show an overall good match although some discrepancy at different stages of the loading history was evident.

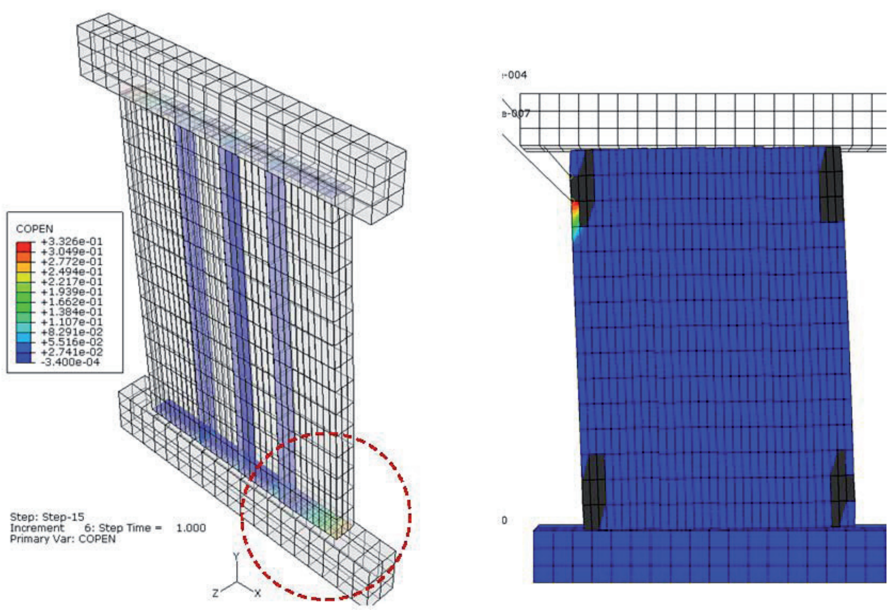


Fig. 10. Tensile failure in the bed joint for Specimen 15a Model-1(a) and Model-2(b) (left); first crack in Specimen 15a Model-1 (right).

The ductility study for the Shear Wall Specimen 2 model gives a satisfactory result for the deformability. For the Shear Wall Specimen 15a models further analyses are recommended since the results did comply well with the experimental data.

As a suggestion for further researches, new analyses are needed to investigate the effects of the boundary conditions. Furthermore, shear wall with openings or coupled shear walls need to be analyzed using the models provided in the paper on hand as a basis, in order to propose a limit value for the shear capacity of those specific systems. Experimental tests should accompany the analyses in order to ensure a close to reality modeling.

## Bibliography


[1] Tanner J.E. 2003. Design Provisions for Autoclaved Aerated Concrete (AAC) Structural Systems. PhD thesis. The University of Texas at Austin, USA.

[2] Türk YTONG Sanayi A.Ş. Ytong Building System. Presentation, July 27th, 2009.

[3] Kalkan E., Gülkan N., Yilmaz N., Çelebi M. 2009. Reassessment of Probabilistic Seismic Hazard in the Marmara Region. Bulletin of the Seismological Society of America, 99(4):2127-2146.

[4] Rivera J.L.V. 2003. Development of R and Cd Factors for the Seismic Design of AAC Structures. PhD Thesis. The University of Texas at Austin, USA.

[5] American Institute. 2005. Building Code Requirements for Structural Concrete (ACI 318-05) and Commentary. Reported by ACI Committee 318, USA.

[6] American Concrete Institute. 2009. Guide for Design and Construction with Autoclaved Aerated Concrete Panels. Reported by ACI Committee 523.

[7] Comité Européen de Normalisation. 2004. Eurocode 8. Brussels.

[8] Taddei F. 2010. Investigation of AAC vertical panel walls with the FE method based on a damage plasticity material model. Master thesis. Baustatik und Baudynamik, RWTH Aachen, Germany.

[9] Argudo J.F. 2003. Evaluation and Synthesis of Experimental Data for Autoclaved Aerated Concrete. Master thesis. The University of Texas at Austin, USA.

[10] ABAQUS 6.9 Documentation.

[11] Abdou L. 2005. Experimental investigations of the joint-mortar behavior, Laboratoire de Mécanique, Université de Marne-La-Vallée.

[12] Bathe K.J. 1996. Finite Element Procedures. Englewood Cliffs, NJ: Prentice Hall.