Strength of Unreinforced Joints of Masonry Walls Made of AAC Masonry Units

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Abstract. The paper presents the results of experimental tests performed on six wall joints. The tests were performed on the models made of AAC blocks with thin joints and unfilled head joints. The joints were constructed as traditional masonry joints. The tests were performed in a dedicated test stand in which force was transferred linearly along the whole height of the wall. Specimens were loaded in one cycle until failure. The paper discusses the mode, morphology and mechanism of failure, and analyses the load–displacement relationships which allowed to define the phases of joint behaviour. By applying code procedures, authors provide the parameters required for the design of the joints. Using the values of cracking and failure forces obtained in experimental tests characteristic strengths at the moment of cracking and failure were determined. The obtained shear strengths were compared with the code values specified by Eurocode 6.

1. Introduction
The issues related to the failure and cracking of ACC walls due to thermal and rheological loadings were rather extensively studied up to date [1, 2]. Numerous experimental studies aiming at the improvement of repairing and strengthening methods for this kind of damage have been conducted so far [3, 4]. However, in the case of joints, the situation differs considerably. The issues regarding wall joints are often underestimated and left aside, while these are the joints, where the stress concentration and failure occur. Numerical analyses presented in [5] have revealed that not only the application and magnitude of loads, but also the walls geometry strongly influences the joints failure. The problems related with the wall junctions in light of experimental research and standards recommendations were presented in [6]. The paper have indicated insufficiently clear view of the experimental investigations and scarce code guidelines, thus not allowing the safe design and construction of wall joints. The tests program enabling to bridge a highly visible gap in the current state of knowledge together with the practical application was therefore established. The tests performed so far as well as the future experiments allow the comprehensive description of:
• the cracking and failure mechanism of the wall joints made out of the most commonly applied in our country masonry units, namely ACC, calcium silicate and clay masonry units,
• load-displacement relations, stiffness, cracking and failure forces for wall joints fabricated using the traditional masonry bond and steel connectors.
The paper presents the results of the experiments performed on a series of unreinforced wall joints made out of ACC. On the basis of Eurocode 1990 [7] recommendations, the characteristic values of parameters enabling the calculations of this type of structures were determined.

2. Results of research
6 models of unreinforced T-shaped junctions were fabricated and evaluated in this study. The length of web and flange was of ca. 89 cm, while the thickness of walls was equal to 18 cm for each part of the joint – Fig. 1a. The joint models were labelled as P with following numbers. The tests have been conducted on the laboratory stand constructed specifically for this purpose and the stand consists of steel frame and horizontal tiding elements – Fig.1b. The shear load was applied to the joint by means of a hydraulic cylinder, while the measurements were recorded using an electrofusion dynamometer. The models were loaded in one cycle until the failure of the joints. In order to eliminate the in-plane bending as well as the uniform distribution of the joint loads, the vertical shear load was transferred linearly over the entire wall height. During the experiments, the loads and displacements of the loaded wall were continuously recorded in relation to the unloaded wall using a Digital Image Correlation system with inductive displacement transducers.

The tests were carried out on joints models made out of ACC masonry units with system thin layer mortar without filling head joints. The average and characteristic values of the compressive strength of masonry determined according to PN-EN 1052-1:2000 [8] and introduced in [9] were of $f_c = 2.97$ N/mm² and $f_k = 2.48$ N/mm², while the modulus of elasticity reached the value of $E_m = 2040$ N/mm². Moreover, the initial value of the shear strength calculated on the basis of PN-EN 1052-3:2004 and presented in [10] was equal to $f_{vo} = 0.31$ N/mm². Furthermore, the Kirchoff’s modulus determined in line with ASTM E519-81 [11] was of $G = 329$ N/mm².
3. Test results and discussion

3.1 Modes of failure
The behavior of all tested unreinforced models was highly comparable. At the initial stage of loading, neither crackling noises were audible to the human ear nor the loosening of material on the side surfaces of the elements was visible. This phase lasted until the emergence of first diagonal cracks near the wall joints – Fig. 2a. The increase of the loading resulted in the notable development of existing cracks at the wall joint as well as in the propagation of cracking in the direction of reinforced concrete column transferring the loads (Fig. 2b – the cracks are shown in red). The maximum load was reported in this phase. Further loading caused the considerable increase of the mutual displacement and rotations between the jointed walls. Failure crack ran through the vertical joint and crossed the concrete block (Fig. 2c). After the failure, the wall junction was demounted – Fig. 2d, e. The models have revealed the almost vertical shear failure of joint units, while the failure of other elements was hardly visible.

![Figure 2. Failure of a P series models](image)

3.2 Main results
The cracking mechanism is also highly noticeable in the curves portraying the relation between the load \( N \) and the relative (mutual) displacement \( u \) between jointed walls – Fig. 3. Until the cracking of contact elements, which occurred together with the cracking load of \( N_{cr} = 27,3 - 54,7 \) kN, the displacements \( u \) were increasing almost proportionally and this phase of wall behavior was termed as
the elastic phase. When the cracking occurred in the post-elastic phase, the reduction of stiffness has been observed. Nevertheless, even in that case, the wall junctions continued to demonstrate the capacity to carry loads.

![Figure 3. Load-displacement curves for all tested models](image)

This phase ended together with the maximum loads of $N_u = 38.6 \pm 60.4$ kN. Further attempts of loading in the failure phase resulted in the notable decrease of forces recorded by the dynamometer with the simultaneous increase of relative displacements. The forces however were not reduced to zero and the wall joint was still capable to carry some loads. In the final phase, the increase of the force was observed, the indication of the joint strengthening. The failure of the joint occurred as the complete loosening of jointed elements. The final recorded forces related to this failure, called here residual forces, were equal to $N_r = 10.2 \pm 27.9$ kN. The forces and the corresponding values of displacements are presented in Table 1, while a linear approximation of the results determined on the basis of the average values of forces and displacements is displayed in Fig. 3.

### Table 1. Main experimental results

| Model | Cracking force | Maximum force | Residual force | Displacement at cracking | Displacement for maximum force | Displacement at failure |
|-------|----------------|---------------|----------------|--------------------------|-------------------------------|------------------------|
|       | $N_{cr,i}$ kN | $N_{cr,mv}$ kN | $N_{u,i}$ kN | $u_{cr,i}$ mm           | $u_{cr,mv}$ mm              | $u_{r,i}$ mm          |
| P_1  | 27.3           | 56.3          | 20.7          | 0.07                     | 0.31                         | 6.36                   |
| P_2  | 42.6           | 50.0          | 10.2          | 0.12                     | 0.25                         | 6.97                   |
| P_3  | 31.2           | 38.6          | 13.8          | 0.12                     | 0.16                         | 5.64                   |
| P_4  | 54.7           | 60.4          | 15.2          | 0.14                     | 0.18                         | 6.72                   |
| P_5  | 37.0           | 48.1          | 15.0          | 0.07                     | 0.10                         | 5.97                   |
| P_6  | 44.9           | 52.5          | 27.9          | 0.10                     | 0.43                         | 2.22                   |

* $s = \sqrt{\frac{\sum (x-\bar{x})^2}{N-1}}$
4. Analysis of experimental results

According to EC-6 [12] recommendations, of crucial importance for the resistance verification of the junction is the determination of its characteristic shear resistance. The characteristic value was calculated according to the guidelines provided in D7.2 Annex to Eurocode [7] using the experimental results presented in Table 1 on the basis of modified equation (D.1), as follows:

\[ X_k = \eta_d (m_x - k_n s), \]

where:
- \( \eta_d = 1 \) – the design value of the conversion factor
- \( m_x \) – mean of the \( n \) sample results
- \( k_n = 2.18 \) – the factor determined based on Table D1 from PN-EN 1990:2004 [7] for the unknown coefficient of variation.

The characteristic values of cracking stress, using for instance in SLS verification, is equal to:

\[ f_{crjk} = \left( N_{cr} - k_n s \right) / A = 0.07 \text{ N/mm}^2, \]

while the shear resistance of the junction is of:

\[ f_{uvjk} = \left( N_{uv} - k_n s \right) / A = 0.133 \text{ N/mm}^2. \]

In practical design, the most advantageous approach is to express the resistance parameters of a joint as the characteristic compressive strength of masonry. Considering the above, the characteristic values of resistance are equal to \( f_{crjk} = 0.03 f_k \) and \( f_{uvjk} = 0.05 f_k \). The vertical shear resistance of the tested junction achieved in this study was two times lower, if compared with the shear strength of ACC masonry equal to \( f_{vvk} = 0.1 f_k \) according to Table Na.7 from EC-6.

5. Conclusions

The research presented in this paper are a part of research project being conducted presently in the Laboratory at the Faculty of Civil Engineering of the Silesian University of Technology involving the tests of wall junctions made out of autoclaved aerated concrete. The paper reveals the results obtained for wall junction with the traditional masonry bond. The particular phases of joint behaviour have been determined and defined, and that will further serve to establish an empirical model of joint behaviour. On the basis of the values of cracking and failure forces obtained within this study, the characteristic resistance at cracking and failure were determined. The results were further benchmarked with EC-6 recommendations. The comparison has revealed the safer estimation of shear resistance achieved in this study.

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