Behaviour of square steel anchor plate in autoclaved aerated concrete block masonry

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Abstract. This research was conducted to study the mechanical behaviour of square steel anchor plate mounted in thin-bed masonry, which was made of autoclaved aerated concrete (AAC) blocks of D400 density grade. The research objectives were to determine the failure mechanism in static push-in tests and suggest the best way of structural design for anchor plate in lightweight concrete masonry, and in particular to calculate its bearing capacity. As the behaviour of small size (40×40×5 mm) anchor plate used in the research depends on the mechanical properties of the masonry units as well as on the distance to edges and joints, these properties and factors were also studied. Low strength of aerated concrete under local compression was the main reason of failure for the investigated type of anchor plate and masonry. Graphical dependencies between anchor plate displacements and applied vertical load are presented. The highest and the lowest bearing capacities of anchor plate were observed when it was mounted in the middle of the block and at the joint, respectively. The design values of the vertical concentrated load resistance of the wall, $N_{Rdc}$, calculated according to EN 1996-1-1, are in good agreement with experimental failure loads.

1. Introduction
Masonry units made of autoclaved aerated concrete (AAC) have been used in civil engineering for many years. The manufacture of blocks started in Sweden in 1929 and spread internationally through Western Europe with the introduction of technology licensing after 1937. Nowadays mass production of blocks is popular also in Central and Eastern Europe, China, India, the Middle East and other countries [1]. AAC masonry reduces the dead load of the walls, which could result in a decrease in cross-section of other structural elements of the building, thus leading to further savings in construction and maintenance. Due to their lighter weight AAC blocks are simpler and more economical to transport, they make construction easier and faster [2]. Blocks can also be handled by plain tools on the construction site with low wastage.

Along with other numerous advantages of AAC block masonry such as being environmental friendly, fire resistant and having good thermal and sound insulating properties [3], it has some disadvantages. One of the major problems is the brittleness of the blocks, which require long thin screws or other expensive plugs or anchors for fastening [2]. The topic of anchors’ behaviour in light-weight concrete masonry is more or less described in technical literature [4], design codes [5,6,7], but mostly by manuals for design and construction of buildings using cellular concrete masonry made by AAC blocks or anchors manufacturers [8, 9].

The analysis of these sources showed some problem questions that were not covered. Research of connectors in masonry construction, which are usually classified as anchors, ties or fasteners and which
are generally addressed in structural masonry design standards where the strength of these anchors is determined [10], don’t cover all known fastener types. Most research and codes deal with headed or expansion anchors, undercut anchors, and bonded anchors, but omit tie rods with anchor plates, which have been a common masonry structural element since Ancient Rome [11].

A tie rod with an anchor plate transmits the tensile forces applied to it to a masonry. It consists of three main parts: 1) the head, transmitting the anchor force to the masonry via the bearing plate (anchor plate, wall washer); 2) the tie rod or bolt, piercing through significant or usually the whole width/depth of the wall; and 3) the end anchorage or nut that holds another wall layer, structural element or appliance etc. (fixture). There are several working principles which make a tie rod with anchor plate bear the load in a masonry: 1) load bearing by the stratum of masonry, which is subjected to local compression under the anchor plate (if the masonry layer subjected to compression is thick enough then we should obtain crushing of material under the plate, which can cause splitting of the wall, if the masonry bearing layer is thin, then a masonry cone breakout will occur after exhausting of tensile strength of masonry with tensile stresses, distributed uniformly on the 45° angle stress cone surface radiating from the free end of anchor plate towards the unloaded edge of the wall); 2) stiffness of the anchor plate (insufficient anchor plate thickness will cause its failure by bending, this should be calculated using the elastic theory of thin plates [12]); 3) strength capacity of welded, bolted or other type of connection between tie rod and anchor plate; and 4) tensile strength of steel rod. Preliminary analysis showed the lack of codes’ guidance or recommendations for values of load bearing capacity of anchor plates in AAC masonry, which leaves the design community to improvise the design of these anchors. In this research the authors will only concentrate on aspects dealing with the load bearing of stiff steel anchor plates, where the failure mode and bearing capacity of the anchor plate depend on the strength properties of the materials used in masonry and the position of the anchor (distance to joints, edges etc.).

2. Aim and Objectives
The aim of perfect design is achieved if the load bearing capacity of the steel anchor plate, AAC blockwork and tie rod are about equal, and so all the materials are fully exploited. The main objective of this research is to get better understanding of the failure mode and the load bearing capacity of a steel anchor plate in AAC block thin-bed masonry. A secondary objective is to discover whether the distance of vertical masonry joints from the anchor plate influences the strength of the fastening. In order to achieve this, it was proposed to perform experimental tests of bearing capacity of square steel anchor plate in AAC block masonry on laboratory models of masonry with investigation of compressive strength and other physical properties of cellular concrete. As above, there is no particular design code for the bearing capacity of anchor plates in aerated concrete blockwork. We predicted that the best match for estimation of bearing capacity of plate anchor in masonry would be the calculation formula (6.10) of EN 1996-1-1:2005 [7] for calculation of masonry resistance to local vertical load.

3. Methods and Materials
The experimental tests were carried out on two identical masonry fragments, which were simultaneously prepared in a laboratory. Each sample consisted of four cellular concrete blocks. One masonry unit was divided into two equal pieces and set at the ends of the second row. The design of test masonry fragments is shown on figure 1. As masonry units we took prefabricated autoclaved aerated concrete blocks, available in the local market – AEROC EcoTerm (D400 density grade) with smooth edges 200x200x600 mm. The physical characteristics of masonry units are summarized in table 1.
The thickness of perpend and bed joints of the masonry was set to 3 mm. We used pre-mixed cement-based AAC adhesive Baumit PlanoFix. The mortar was received by mixing 25 kg of dry adhesive with approx. 6 litres of potable water. The common view of masonry fragments can be seen in figure 2. The exposure before the start of the tests was 7 days, storage was carried out indoors at ambient temperature of 18±2°C and at a relative humidity of 50-60%.

Anchor plates were made from the ordinary 4 mm thick sheet carbon steel. All tested anchor plates were of square shape and their size was 40×40 mm.

The preparation of experiments included the drilling of three holes in masonry fragments, the diameter of which (12 mm) corresponded to the size of the rod used in tests. The drilling of the holes ensured that there was no effect on the results of experiments of any grip or friction between the rod and the wall. Figure 3 indicates the sequence in which tests of the bearing capacity of the steel anchor plate were conducted.

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The first test point was located at the weakest point of the masonry – the perpend. The second anchor was tested at a distance of 100 mm from the perpend in the middle block, and the third anchor plate was tested in the middle of the experimental masonry fragment. All tests were carried out for anchor plates, located in the bedding plane of masonry.

Traditionally, anchor plates transmit tensile force from the rod, causing local compression in the masonry, therefore our experiments were organized in the form of a push-through test, applying compressive force to the outer end of the rod. Plate anchors and the surrounding masonry behaved in the same way as we would apply the tensile force to the opposite end of the rod.

The load was created with the help of a hydraulic jack with a capacity of 12 tons. The process of loading was carried out in steps of 0.1-0.2 from the planned destructive load and controlled by a circle spring compression dynamometer 4 (figure 4) with a dial indicator clock gauge. The vertical displacements of the anchor plate 5 were measured in the middle of its edge by a dial indicator 7 with 0.01 mm accuracy and 10 mm measuring range. The tests were conducted until the load values stopped growing.

![Figure 4. The cross-sectional view of the anchor plate in AAC masonry bearing capacity test: 1 – 200 mm wide masonry; 2 – drilled hole (12 mm in diameter) in the middle of the wall; 3 – threaded stud; 4 – compression dynamometer with dial indicator clock gauge; 5 – carbon steel anchor plate 40×40×5 mm; 6 – a nut to hold the anchor plate; 7 – dial indicator, measuring vertical displacements between anchor plate and the upper surface of the aerated concrete block masonry.](image)

Along with the main experiments, there were several tests conducted, aiming to examine the mechanical characteristics of AAC and masonry. The testing methods used for this include compression, splitting and flexural tensile strength tests of the masonry units. The exact quantity of specimens and purpose of each test in this study gathered in table 2.
Table 2. Experimental program.

| Type/shape of sample | Dimensions, mm | Quantity of samples | Test purpose                                          |
|----------------------|----------------|---------------------|------------------------------------------------------|
| AAC block masonry    | 200×403×1206   | 2                   | Bearing capacity of steel anchor plate in AAC block masonry |
| Cube                 | 200×200×200    | 3                   | Compressive strength grade of AAC                     |
| Prism                | 200×200×600    | 5                   | Splitting and flexural tensile strength of AAC        |
| AAC block unit       | 200×200×300    | 3                   | Compressive strength of masonry unit                  |
| AAC blockwork fragment | 200×403×300   | 2                   | Characteristic compressive strength of masonry $f_k$  |

4. Results and Discussion

The mean value of AAC compressive strength was 2.83 MPa with minimal value observed in experiments at 2.57 MPa. Due to the significant variation of strength values, guaranteed strength grade of AAC, used in masonry, was set to LC 2 (not LC 2.5, as was suggested by the manufacturer). Tests of the masonry units showed compressive strength $f_b = 2.6$ MPa. The characteristic compressive strength of the masonry, calculated using empirical expression (3.3) [7] was

$$f_k = K \cdot f_b^{0.85} = 0.8 \cdot 2.6^{0.85} = 1.8 \text{ MPa.} \quad (1)$$

The compressive strength of masonry, obtained from the experiment, was equal to 2.06 MPa. The difference between experimental and predicted values was 14.4%, which is acceptable due to the high variability of properties in lightweight concretes. Mean values for splitting tensile and flexural strengths were 0.42 MPa and 0.49 MPa, respectively. The failure mode for all specimens was ordinary.

The bearing capacity of the anchor plate was measured as its resistance (value of applied force) at the moment when residual deformations under anchor plate began to grow rapidly. It was found that fastener destruction with investigated type of block masonry and size of anchor plate was caused by the exhaustion of the aerated concrete strength at local compression – we observed the crushing of aerated concrete under the anchor plate without any damage or bending of the steel plate (figure 5). Test results are represented here in the form of the applied load vs. anchor plate vertical displacements diagrams (figure 6).

![Figure 5](image1.png) **Figure 5.** Crushing of aerated concrete under anchor plate. View after experiment held.

![Figure 6](image2.png) **Figure 6.** Applied load vs. anchor plate vertical displacements diagram.
For the anchor plates at position 1 (at the perpend), the observed destructive load was expectedly lower than the one for anchor plates at positions 2 and 3 and equal to 5 kN. We also noticed some declination of anchor plates at position 1 from the horizontal plane of masonry surface.

We did not find any essential difference in behaviour or bearing capacity between anchor plates, tested at positions 2 and 3 (100 mm from the perpend and in the middle of the block, respectively). Both positions showed 6 kN bearing capacity before the crushing of aerated concrete.

The mean values for vertical displacements of anchor plates at ultimate load, which correspond to testing positions 1, 2 and 3, were 0.355 mm, 0.220 mm and 0.145 mm, respectively.

For further study of anchor plate behaviour in AAC block masonry we decided to find a good fit for calculation of its predicted bearing capacity. After analysis, we accepted the working hypothesis that the best match would be provided by formula (6.10) of EN 1996-1-1:2005 [7],

\[ N_{\text{Rac}} = \beta \cdot A_{c} \cdot f_{d} \]  

usually employed for the calculation of masonry resistance to local vertical load. The value for enhancement factor for concentrated loads \( \beta = 1.5 \), obtained, utilizing instructions and limitations of design code [7], was the same for all testing positions of the anchor plate (actual values were 1.80; 1.91 and 2.13 for each testing position, but final value for \( \beta \) should be less than 1.5). In order to be able to compare the experimental bearing capacity with the prediction in the formula above we used experimentally obtained compressive strength of masonry \( f_{d} = 2.06 \) MPa, which resulted in a characteristic bearing capacity of stiff anchor plate [13] in AAC block masonry \( N_{\text{Rac}} = 1.5\cdot 1600 \cdot 2.06 = 4944 \) N = 4.94 kN. The difference between the predicted bearing capacity and experimental bearing capacity at the weakest position of anchor plate is 1.2%, which shows good agreement with the experiment of the proposed design method.

5. Conclusions

Most design manuals for AAC masonry construction recommend mounting wall top plates and other beams with fasteners anchored in reinforced heavyweight concrete elements. We suppose such recommendations are caused by low strength of AAC as well as inadequate scientific research on the topic of anchoring in AAC block masonry. The current study sheds more light on the design of anchor plates in AAC masonry. The bearing capacity of stiff small-sized square steel anchor plates loaded parallelly to the wall plane is determined only by the plate’s position relatively to edges and joints and the mechanical characteristics of masonry. We propose to use formula (6.10) of EN 1996-1-1:2005 [7] for the calculation of predicted bearing capacity of studied anchor plates, which proved its workability. The experimental data confirmed the assumption that the anchor plate is more efficient when it is mounted in the middle of the AAC masonry unit, in comparison with behaviour of the anchor plate at the masonry joint. Consequently, we propose a recommendation for the installation of anchor plates in the central zone of bearing AAC block (marked as position 3 in this research).

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