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A CONCEPT FOR FIXING "HEAVY" FAÇADES IN SEISMIC ZONES

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Abstract

So called "heavy" façades with a dead load of more than 100 kg/m² are usually constructed in brickwork, natural stone cladding or using concrete panels. Load bearing steel anchors are used to transfer the load to the main load bearing sub-structure.

According to current standards, façades are defined as non-structural elements. Previously, the calculation of these anchors only assumed static loads such as dead-loads, wind loads and constraining forces. In countries with seismic risk the façade's seismic load can be replaced using a static equivalent load acting in a horizontal unfavorable direction.

Façade components must be appropriately designed to prevent unintentional tipping (tilting), falling or from hitting other elements; including swaying of components on hoist or tearing of pipes. On the one hand, the intention is to prevent physical injuries during an earthquake, and on the other hand to ensure that rescue operations after an earthquake are not hindered by fallen or falling façade segments.

Current design practice (e.g. numerical simulations) assumes that façade constructions are a mass fixed to a building with zero stiffness. However, seismic design should not only focus on the load bearing structure; in fact there is significant interaction between main structures and façades, which can seriously influence the bearing behaviour of the whole structure.

Experience with earthquake damage to building-façades, which are fixed according to current standard solutions, illustrate clearly that this concept does not work properly.

Cladding panels fastened to a building are part of the whole structural system; these provoke a seismic response with the main sub-structure. The higher stiffness of this "resistance system" results in forces that are greater than those calculated based on frame models. Therefore the panels themselves have to be dimensioned according to these resulting stresses and the anchors have to be designed accordingly.

Fixings should be designed according to these assumptions. They form the link between the two systems (façade / load bearing structure) and have to be adequately dimensioned. It also has to be examined whether the fixings should be designed as ductile or rigid; this influences the interaction significantly.

In general, new methods for modeling the behavior of heavy façades during earthquakes need to be developed. Suitable recommendations are illustrated in this paper. Results from shake table tests support this technical approach.

Additional shake table tests were provided to compare rigid and ductile (load) bearing behavior of fixings for heavy façades.

This paper provides an overview of the calculation methods and test methods. Shake table tests are used to show the (load) bearing behavior of the system structure/façade. The technical background is explained and the experiment results are illustrated.

Keywords: façades; fixing constructions; heavy façade systems; nonstructural elements

1. Introduction

Façades of building constructions have two main tasks: like an envelope they are part of the aesthetic design of a building and they are part of the insulation. To provide an effective influence on the building physics façades do not only consist of the outer skin but also of an adequate insulation layer and optional ventilation. The corresponding task of the fixing constructions is therefor to introduce the loads into the building construction safely and to provide sufficient space for all needed components. Especially for "heavy" façades i. e. façades with a dead load of more than 100 kg/m² such as brickwork layer, natural stone claddings or concrete panels, the fixings have to carry high punctual forces over large wall cavities.

Fixing constructions are defined as attachments, including anchor bolts, welded connections and mechanical fasteners [1]. Dependent on the importance of the considered component being attached, the fixing is classified in different design categories. Façades and their fasteners usually are classified similar to nonstructural wall elements, i.e. as architectural components or elements. As well as partitions, nonstructural elements usually are treated as masses attached to the structure without consideration of their possible stiffness. Those architectural features contribute to the damping of the whole building and may modify the structural response in ways detrimental to the safety of the building. Regardless of whether it is increasing or decreasing the damping of the structure, this interaction will surely raise the forces to be transferred by fixtures.

European regulations for attachments can be found in [2]. This Annex E describes the required resistance and the corresponding test methods for metal anchors under seismic actions. It contains the qualification of anchors to introduce seismic loads into concrete safely.

DIN CEN/TS 1992-4 [3] sets new standards for assessing fixing constructions to concrete and masonry and will be adopted in the Eurocode series in the near future. Since the design provisions in the CEN/TS 1992-4 series are not consistent with the assessment according to ETAG 001, Annex E and the EN 1992-4 has not yet been published, the need for a publicly available document rises [4]. The design method for anchors to resist seismic loading in this Technical Report (TR 045) [4] is intended to bridge the time span until the publication of EN 1992-4.

TR045 covers the seismic design of fastenings including the attachment. To gain sufficient ductility, a yield mechanism is required. This can be assured either by developing a ductile yield mechanism in the attached steel component or in the steel base plate taking into account material over-strength effects, or on the capacity of a non yielding attached component or structural element. Additionally ductility can be gained by using ductile anchors.

For a proper design it is essential to examine all components of a fixture i.e. the anchor, the baseplate and the attachment to assure sufficient ductility with adequate bearing capacity at the same time.

In this paper fixtures for heavy façades are examined due to these requirements. Methods are described and test results are provided.

2. Façade anchors for heavy façades and their application

All further mentioned façade types have in common that they should leave sufficient space between the bearing construction and the façade layer to accommodate insulation and optionally an air gap.

To provide this space, fixings of the façade layer need to be designed either as a cantilever or as tension members combined with spacers. All fixing components such as load bearing members as well as spacers need to penetrate the insulation. Systems of common fixings for nonstructural façades are introduced in the following.

2.1 Concrete façades

Besides cast-in-place façades - which are not further subject of this article - there are two general types of precast façades: Façade Panels and Sandwich Panels, see Fig. 1 and Fig. 2.

Fig. 1 – Concrete Façade Panel

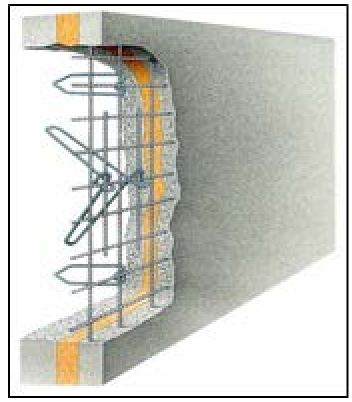

Fig. 2 – Concrete Sandwich Panel

Concrete façade panels will be fixed after the bearing construction is erected. For their handling and support the following inserts are necessary:

- Transport anchors to enable the handling of the slabs during fabrication and transport and for lifting the panels into their final position,
- Bearing members to carry vertical loads,
- Spacers to adjust the panels and to carry horizontal loads
- Pins to align and connect the plates.

In contrast to these panels, sandwich elements consist of a bearing layer and a façade layer which are produced simultaneously. Usually the facing concrete is brought into the formwork first. Therefore the reinforcement is placed in the prepared mold and supporting anchors and stirrup ties or pins are installed. Then concrete is poured evenly in the formwork and will be compacted. Subsequently the heat insulation layer is placed onto the concrete with the anchors penetrating it. After connecting the reinforcement of the bearing layer with the anchors, the concrete can be poured into the mold.

2.2 Brickwork façades

Brickwork façades can be masoned following the process of erecting the bearing construction or it can be installed subsequently. The façade layer is installed in the above mentioned distance to the bearing construction, therefor the brickwork is supported either by steel angles or – for larger cavities – by brackets.

Fig. 3 – Brickwork façade

Fig. 4 – Supporting Construction

Brackets and angles support the brickwork layer in vertical direction. They are fixed to the construction by appropriate attachments such as dowels or anchor channels.

Horizontal loads are to be carried separately by special horizontal anchors such as cavity wall ties or brick ties.

2.3 Natural stone façades

This type of façade consists of at least 30mm thick stone panels which are attached to the building by special anchorages or channel sub constructions. The panels are fixed to the anchorages either by special dowels or by special pin bearings. The fixings should be adjustable to align the façade plate accurately.

Fig. 5 – Natural Stone Façade

Fig. 6 – Fixing Construction

3. Static resistance

All above mentioned support constructions need to ensure a defined space between the outer surface and the bearing construction. This space is depending on the requirements to the insulation and can reach values of more than 300 mm. To transfer the loads safely the fixing constructions have to be designed and tested properly. Not only the bearing capacity has to be ensured but also the maximum deflection to provide a sufficient serviceability. All fixing constructions have in common to be designed for vertical and horizontal loads perpendicular to the façade panel. Forces parallel to the façade surface usually can be neglected to prevent constraint forces.

4. Seismic resistance

Façades usually are defined as non bearing, nonstructural elements [5].

Besides the primary functions of façades i.e. to resist environmental conditions like wind, rain and temperature as well as to define the aesthetic image of a building, the secondary function is to provide sufficient fire resistance.

Façade fixings must be designed in a way that they can adjust to movements caused by wind or thermal expansions.

As seismic impact includes loads in horizontal directions these loads need to be absorbed safely at the same time without loss of flexibility.

Common façade fixings act as a pendulum with the dead load providing stability. To gain flexibility and adjustability it is helpful that the fixings can compensate on-site tolerances. Those fixings are not able to carry horizontal loads without corresponding deflections. For use under seismic conditions horizontal deflections shall be limited to the serviceability limits which in most cases means additional bearings. Depending on the resistance of the façade element either additional fixings should be introduced (a) or the existing bearings need additional horizontal support (b).

(a) Brickwork façades usually are supported by angles or brackets laid on grout to generate a linear bearing which usually cannot provide a horizontal support.

(b) Façade elements with sufficient shear resistance such as concrete layers or natural stone plates can be supported by punctual bearings such as single dowels or pins. Those bearings can be fit up with additional horizontal binding conditions, if necessary.

Façade elements which are used as shear walls or infill walls are not subject of this paper.

To evaluate these above mentioned additional horizontal binding conditions tests on strengthened components had been carried out. For all façade types tentative tests on fixing details lead to a construction whose seismic performance should be verified by full scale tests. In the following a full scale test on a Brickwork support system and a tentative test series on natural stone fixings are presented.

4.1 Full scale test

To verify the safety of HALFEN brickwork support system under earthquake loading, the Institute of Earthquake Engineering under China Academy of Building Research (CABR) carried out tests with the HALFEN brickwork support system. For the test a 6m×6m earthquake simulation shaking table in the engineering seismology laboratory of China Academy of Building Research was used.

The tests were performed in accordance to Code for seismic design of buildings GB50011-2010 [7]. In [8] is shown, that results according to this code are comparable to results according to American and European standards.

A cast-in-place reinforced concrete wall served to simulate the main structure during the test. Two different connection methods were adopted to test masonry wall A and masonry wall B with brick dimensions of 215mm×102mm×65mm (L×W×H). Refer Fig. 7 to Fig. 8 for elevation and plan of the test specimen.

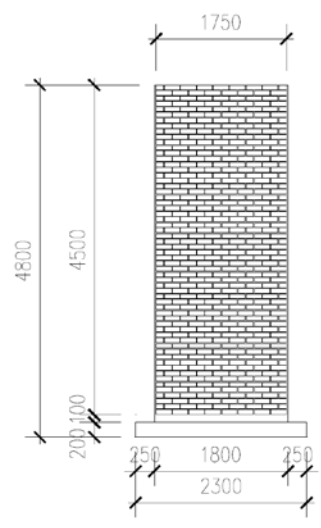

Fig. 7: Elevation of the test specimen

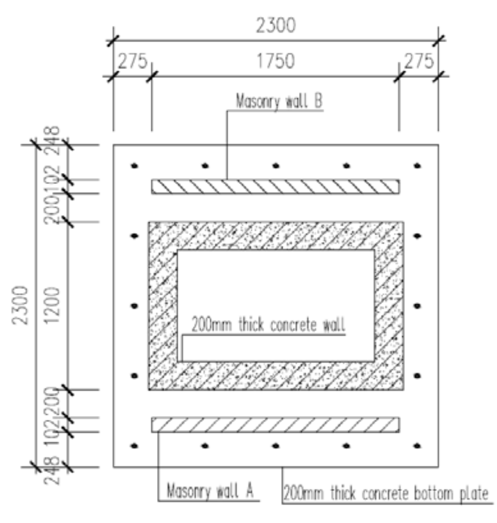

Fig. 8: Plan of test specimen

The masonry walls A and B were supported separately by 2 HALFEN brackets with a load range of 7.0 kN.

HALFEN cast-in channels and HALFEN T-bolts were used for the connection between HALFEN HK4 bracket of masonry wall A and the concrete wall. Horizontal brick ties (bended 60°) were distributed on both masonry walls. Refer Fig. 9 and Fig. 10 for the layout of brick ties of masonry wall A.

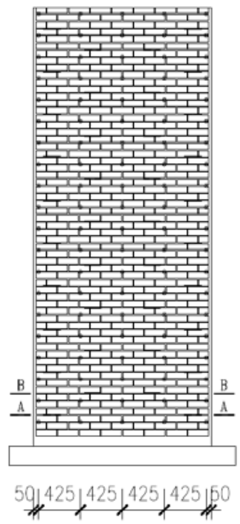

Fig. 9: Layout of brick ties on masonry wall A

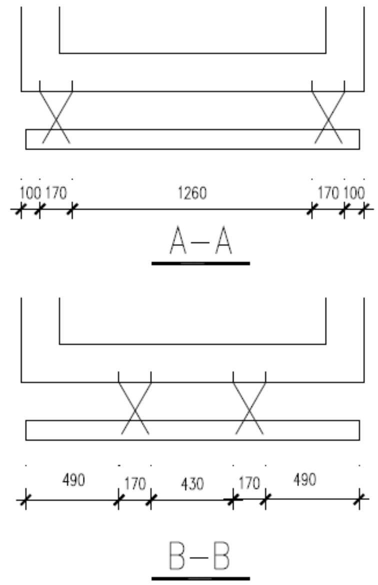

Fig. 10: Sectional details of brick ties on masonry wall A

Like in common applications HK4 brackets in the bottom row carry the dead load and brick ties distributed over the masonry wall are designed to carry the horizontal loads perpendicular to the façade e.g. of wind etc. In addition further horizontal HK4 brackets were installed to carry horizontal seismic loads in the façade plane. See Fig. 11 and Fig. 12 for the layout of brick ties and horizontal HK4 brackets of masonry wall B.

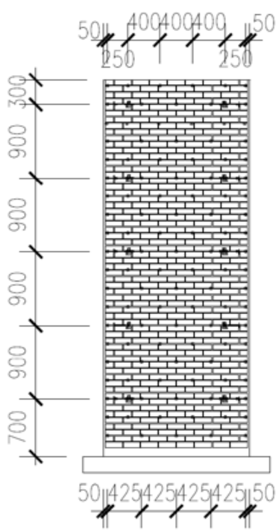

Fig. 11: Elevation of brick ties and horizontal HK4 bracket on masonry wall B

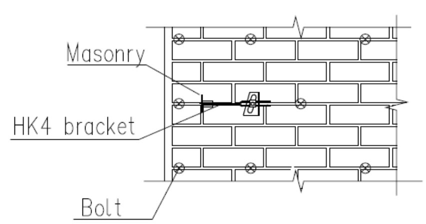

Fig. 12: Detail of brick ties and horizontal HK4 bracket on masonry wall B

Three groups of seismic waves were selected to simulate earthquake loads. Refer Fig. 13 and Fig. 14 for two groups of natural waves, and Fig. 15 for one group of artificial wave. White noise input was adopted for the detection of natural frequency vibration.

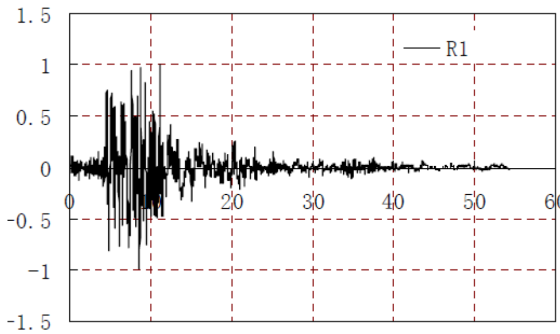

Fig. 13: Normalized time interval curve of natural wave 1

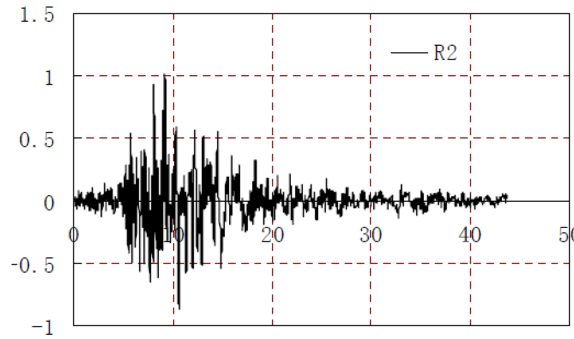

Fig. 14: Normalized time interval curve of natural wave 2

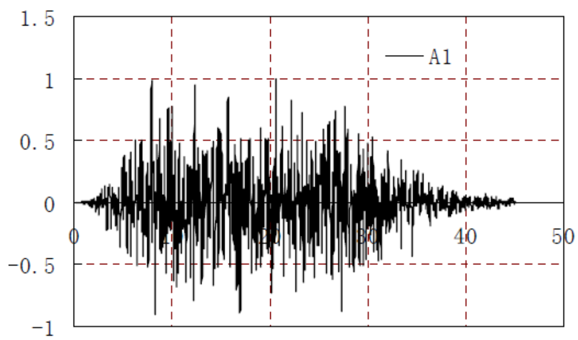

Fig. 15: Normalized time interval curve of artificial wave

The acceleration input on the test started from 7-degree seismic fortification intensity. The peak input acceleration of the shaking table was increased level by level. The maximum value for peak input acceleration of the shaking table is 3 times of 8-degree rare earthquake, considering the amplification action of the actual structure on acceleration. Small-amplitude white noise excitation was introduced after the input of each grade of seismic wave in order to measure the change in dynamic characteristics of the test system.

The peak input acceleration of the test table started from 0.100g (7-degree seismic fortification intensity), and was increased to 0.200g (8-degree seismic fortification intensity), 0.300g (8.5-degree seismic fortification intensity), 0.408g (8-degree rare earthquake) and 0.633g (9-degree rare earthquake). X-direction (Perpendicular to wall plane) and Y-direction (parallel to wall plane) seismic wave input was applied for each fortification intensity. The peak input acceleration of table under 32 and 34 working condition was respectively 0.816g (2 times of 8-degree rare earthquake) and 1.224g (3 times of 8-degree rare earthquake), and only X-direction seismic wave input was applied. The observations during the test were:

- The brick wall showed no sign of damage (cracks etc.) during the entire test procedure. Refer Fig. 16 and Fig. 17 for pictures of right side and side face of the wall.
- HALFEN brackets and brick ties as well as the connection of brackets to both (concrete and brick wall) did not show any sign of damage. Refer to Fig. 18 and 19.
- After loading condition No. 34, the mortar surface showed slight cracks only for a few brick tie connections, refer Fig. 20 and Fig. 21. However, through inspection, there was no adhesion damage.

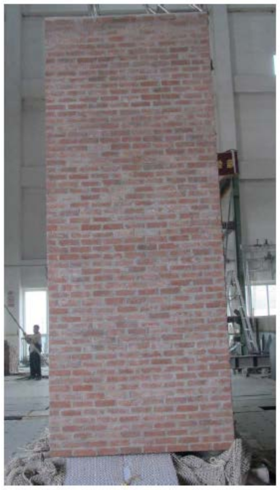

Fig. 16 Right side of the wall after test

Fig. 17: Side face of wall after the test

Fig. 18: Bracket after test

Fig. 19: Brackets and brick ties after test

Fig. 20 and 21: Crack of mortar surface at brick tie connection location

In summary the peak shake table acceleration in X-direction (Perpendicular to wall plane) reached 1.279g (equivalent to 3 times of 8-degree rare earthquake), and in Y-direction reached 0.646g (equivalent to 1.6 times of 8-degree rare earthquake). The peak acceleration at the top of the wall was magnified by factors of 2.6~3.7 compared to the peak input acceleration on the shake table. Both HALFEN masonry structure supporting system (brackets and horizontal brick ties) and the masonry wall showed no signs of damage (cracks etc.) after the described seismic loading. This results certify HALFEN masonry structure supporting system a good earthquake resistance performance under high acceleration, meeting the requirements for 8-degree seismic fortification intensity.

4.2 Tentative tests

Two types of natural stone anchors were strengthened by additional binding conditions. See Fig. 22 and 23 for pictures of anchor type 1 and anchor type 2.

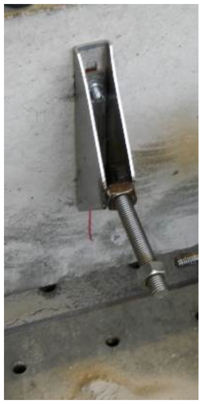

Fig. 22: anchor type 1

Fig. 23: anchor type 2

To assess the seismic resistance of these modified natural stone anchors, it was decided to choose boundary conditions that were derived from the above described brickwork-anchor tests done by CABR [6]:

- maximum ground acceleration: 1,28 g
- height of the fixing above ground: 4,5 m
- height of the building: 5,0 m

With these parameters a horizontal static substitute load in the most unfavorable direction, to be considered in addition to the dead weight, was calculated according to DIN EN 1998-1 [5]. See Table 1 for the defined loads.

Table 1 – Estimation of dead load and horizontal seismic load

anchor	**Dead load G [N]**	**Horizontal load N max [N]**	**Shear load V max [N]**
Type 1	500	2.480	2.480
Type 2	200	992	992

Since no standard exists to regulate the test procedure for façade systems under seismic loading, the regulations of ETAG 001, Annex E [4] were obtained with one exception: as maximum loads N max (tension / pressure load) and V max (shear load) the calculated horizontal substitute loads according to [5] were used.

The tentative tests were carried out in shear and tension / pressure direction in accordance with ETAG 001, Annex E [2]. The dead load was simulated by a mass hung on the anchor cantilever. The loading frequency was less than 0.5 Hz, for the load scheme see Fig. 24.

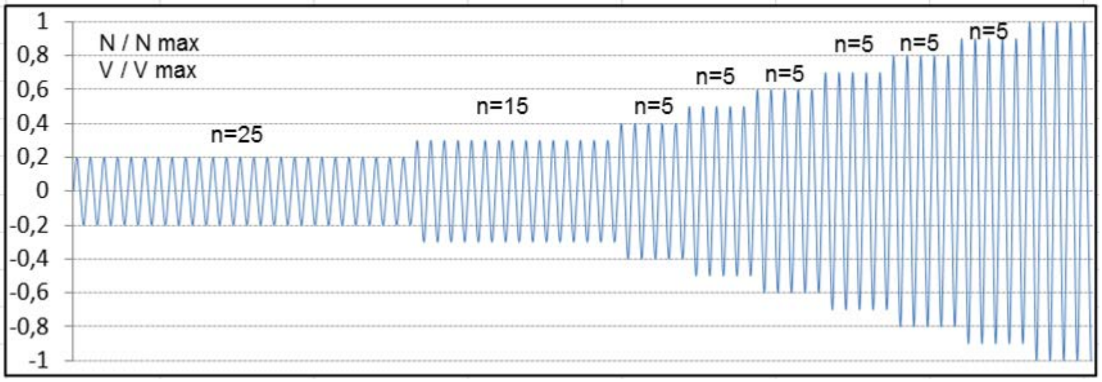

Fig. 24 – Load amplitudes for tests under pulsating pressure /tension load and alternating shear load

Two mechanical dowels were used to fix the natural stone anchors to a concrete slab. During the test displacements in load direction were measured at the anchor cantilever.

The maximum relative displacement for anchor type 1 under shear load V max was about 10 mm at the anchor cantilever. An exemplary hysteresis is shown in Fig. 25.

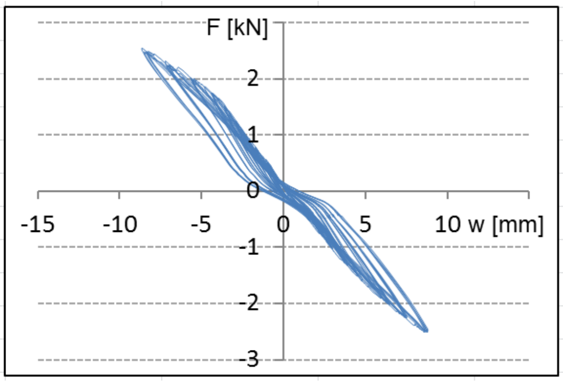

Fig. 25: anchor type 1 under alternating shear loading

The maximum relative displacement at the anchor type 2 for pulsating tension / pressure load N max was about 0,75 mm. For alternating shear load V max the maximum relative displacement was about 5 mm. Refer Fig. 26 and Fig. 27 to see exemplary hysteresis of a shear test and a pressure / tension test.

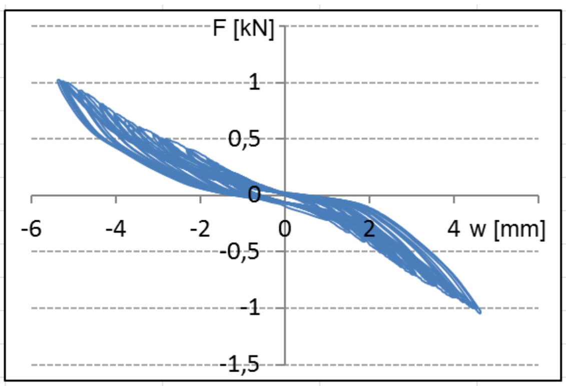

Fig. 26: anchor type 2 under alternating shear load

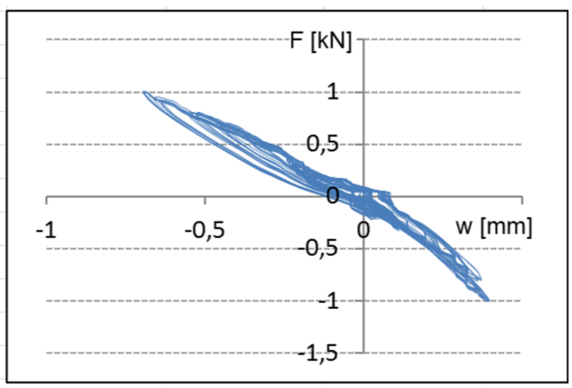

Fig. 27: anchor type 2 under pressure / tension load

These tentative tests showed a sufficient strength level of the developed natural stone anchors type 1 and type 2. For further development anchor modifications particularly with regard to anchor ductility are intended. In addition, large-scale seismic tests on a shake table are in preparation to verify the results of tentative tests and to set the borders of serviceability.

5. Summary and Outlook

Common fixings for heavy façades do not have sufficient resistance against seismic effects. Even though façades are classified as non-structural components that are not designed to contribute to the structural capacity of a building, they are to be designed for the use in seismic zones. To prevent damages of the cladding or risk from falling façade elements fixings have to show sufficient resistance and fulfill requirements of serviceability.

The construction forms of typical heavy façades are introduced. As the fixing components for those façade systems vary, their seismic performance has to be considered individually. Some methods of raising the seismic resistance were introduced and analyzed. Unlike fixings used in non-seismic areas, additional horizontal support is needed. This can be ensured either by separately installed fixings or by additional support of single fixings.

Tests were performed in accordance to international and European design rules and their results are presented. A full scale seismic test on two brickwork façade systems is presented. The results show that with appropriate methods a sufficient resistance can be gained. Tests on full scale specimen only display the current situation of stiffness and of the applied accelerations. This method takes into account the Maximum Considered Earthquake (MCE) with a defined year earthquake motion. Depending on the importance of the building the strength of the applied earthquake (in test or analysis) has to be chosen. The most influencing factor is the probability of occurrence which is regulated by the significant building code. Due to this a simulation based on MCE (Maximum Credible Earthquake) seems to be the favorite method. Even the analysis of multiple MCE's for one site, each from a different fault or seismic source, increase the reliability of the simulation. The results of these large or full scale tests shall be precise load assumptions for the façade fixings which then can be applied in complementary tests. The here presented tentative tests show the potential of developments for seismic resistant anchors. Tentative tests are a quick and economic method to compare different design methods whereas the overall performance should be proven by full-scale tests.

Buildings often receive additional strength from components, such as partitions or façades, that are not considered in a common structural analysis. To achieve a high accuracy by tests or calculations a detailed model of the structure is needed, considering the interaction between structural and non-structural elements where the façade fixings form the link between these elements.

For further development anchor modifications particularly with regard to anchor ductility are intended in the near future. In addition, large-scale seismic tests on a shake table are in preparation. These large-scale tests are necessary to prove the assumed loads of the tentative tests and to determine the borders of serviceability.

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