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DESIGN AND TEST METHODS FOR SEISMIC SUITABILITY OF FAÇADE FIXINGS FROM CONSTRUCTION – PRACTICAL POINT OF VIEW

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Abstract

Building façades do not only characterize the external appearance of a building; together with an adequate insulation layer and optional ventilation, the outer skin effectively influences the building physics. The façade fixings therefore have the task to transfer the loads from the façade safely to the load-bearing structure. In particular for so-called "heavy" façades, i.e. façades with a dead load of more than 100 kg/m² such as brickwork, natural stone claddings or concrete slabs, these façade fixings must transfer high loads over large wall spacings.

In static load cases loads from dead weight of the façade, wind and temperature deformations have to be transferred. For buildings located in areas with seismic activity, additional loads from earthquakes must be taken into account. To current earthquake standards, façades and their fixings are nonstructural components. They can be dimensioned by a horizontal and an optional vertical static equivalent load, with the aim of avoiding failure of the façades and thus personal injury, as well as ensuring free escape routes after an earthquake.

In construction practice, the focus for earthquake dimensioning is essentially on the load-bearing structure. Considerations on the façade fixings are carried out later, often during the construction phase. But the seismic concept for façade fixings and the size of the static equivalent loads to be taken into account always require an individual consideration of the structure, construction site and its planned use. To verify the suitability of a façade concept various experimental methods can be used. This requires time that might not be factored in during the closely scheduled construction phase. At this late stage it is difficult to respect the interaction between construction and the nonstructural element.

The most common method for the experimental investigation of a façade concept are “Large-Scale” tests, i.e. shake table tests. Since these tests are very time-consuming, the aim is to find alternative, rational test methods.

A possibility of assessing the seismic resistance of a single anchor and its connection to the load-bearing substructure are “Micro-Scale” tests with a horizontal equivalent load in accordance with ETAG 001, Annex E. The disadvantage of this method is, it can only confirm the behavior of a single anchor, but not its interaction to the façade.

For this purpose, a special "Meso-Scale” test was developed to test all components of an anchor system instead of a single anchor. A representative façade surface - here 1 m² - is fastened with suitable fixings and static equivalent loads are applied. The test program was also based on the specifications of ETAG 001, Appendix E.

This paper gives an overview of calculation and testing methods. The role of façade fixings as connections between façade and load-bearing structure is emphasized. As an alternative to the shake table tests, further test methods are described. They all serve to obtain necessary information about the load-bearing behavior of the entire outer wall and to confirm theoretical assumptions with different experimental effort. The technical background is explained and the test results are illustrated and compared.

Keywords: façades; fixing constructions; heavy façade systems; nonstructural elements, testing methods

1. Introduction

Fixing constructions are defined as attachments, including anchor bolts, welded connections and mechanical fasteners. Dependent on the importance of the considered component being attached, the fixing is classified in different design categories. Usually façades and their fasteners are classified similar to nonstructural wall elements, i.e. as architectural components or elements, nevertheless they must be designed to withstand earthquakes to prevent personal injury during an earthquake and to ensure free escape routes after an earthquake.

2. Fixings for "heavy" façades

In this paper fixings for so called "heavy" façades are respected. These façades have a deadload of more than 100 kg/m² and usually consist of brickwork, natural stone or concrete.

Modern façade constructions are designed in such a way that there is enough 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 Brickwork façades

Brickwork façades can be installed following the process of erecting the bearing construction or they can be installed subsequently. The façade layer is installed in the above mentioned distance to the bearing construction. An example of a Brickwork façade is illustrated in Fig.1. The dead weight of the masonry panels is supported by angles or, for larger cavities, by brickwork support brackets (see Fig.2) which are fastened to the load-bearing structure using appropriate fixings such as anchor bolts or anchor channels. Horizontal loads perpendicular to the façade plane, such as wind loads, must be absorbed separately by special horizontal anchors such as brick ties as shown in Fig.3.

Fig. 1 – Brickwork façade

Fig. 2 – Example of brickwork support

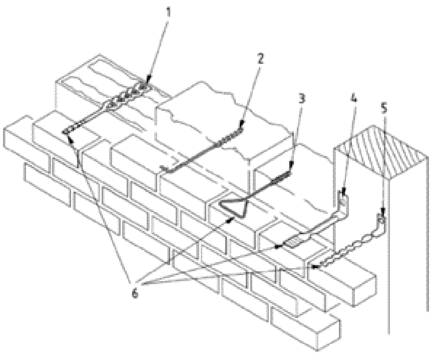


Fig. 3 – brick ties acc. to [1]

2.2 Natural stone façades

A natural stone façade like the one shown in Fig.4 consists of stone plates with a thickness of at least 30 mm, which are usually supported at four points. This support can be either in the vertical or in the horizontal joint. Load-bearing cast-in anchors, Fig.5 or bolted anchors, Fig.6 with pin bearings are used for this purpose. In case of larger wall distances or if non-load-bearing areas are to be bridged, special channel substructures are used which connect the façade with the load-bearing structure. These anchors or channel substructures absorb both the dead weight of the natural stone slab as well as the wind loads on the façade and transfer them safely to the load-bearing structure. The fixings should be adjustable in order to precisely position the façade panel.

Fig. 4 – Natural stone façade

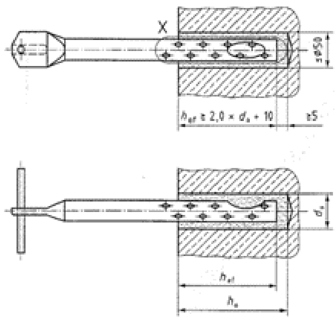


Fig. 5 – Example of cast-in anchors

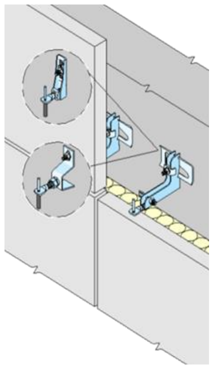


Fig. 6 – Example of bolted anchors

2.3 Concrete façades

Concrete façade panels usually are manufactured separately in a precast plant and are attached to the supporting structure after it has been erected, see Fig.7. The following inserts are necessary for their handling and support: Transport anchors to enable handling of the panels, Supporting elements for carrying vertical loads (see Fig.8), Spacer for adjusting the plates and for carrying horizontal loads and Pins for aligning and connecting the plates.

Sandwich elements as in Fig.9, on the other hand, consist of a base layer and a façade layer, which are produced simultaneously. In general, the facing concrete is placed in the formwork first. The reinforcement is installed in the prepared form and support anchors and stirrup anchors or pins are attached. Then the concrete is evenly poured into the formwork and compacted. The thermal insulation layer with the anchors is then applied to the concrete. After connecting the reinforcement of the base layer with the anchors, the concrete can be poured into the mould.

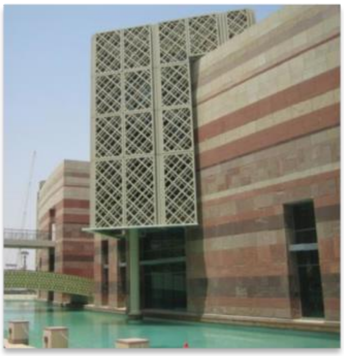


Fig. 7 – Concrete façade

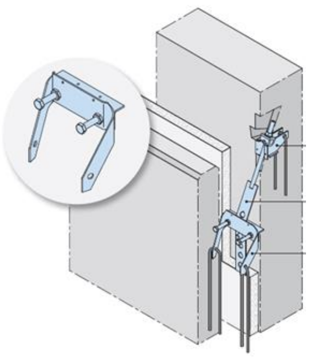


Fig. 8 – Concrete façade panel

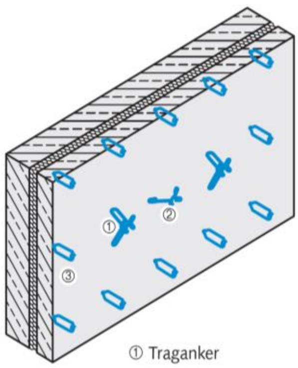


Fig. 9 – Sandwich panel

3. Bearing behavior of façade anchors

3.1 Static resistance

Heavy façades typically comprise a load-bearing layer, a thermal insulation, optionally an air layer and a facing layer. The clear distance between the load-bearing layer and the facing layer can exceed 300 mm. The façade anchors are intended to ensure the distance between the two wall layers and to absorb the loads acting on the facing layer, which are then safely transferred to the load-bearing layer. The static load case covers the consideration of the dead weight of the facing layer and the horizontal loads perpendicular to the façade surface, such as wind. Horizontal forces parallel to the façade surface can usually be neglected in order to avoid constraining forces. The anchors must not only have sufficient load-bearing capacity to support the aforementioned loads, but must also provide the proof of serviceability by maintaining maximum deflections.

3.2 Seismic resistance

In most cases, only static loads have to be considered when calculating façade anchors. In countries with an seismic risk, however, the effects of earthquakes must also be taken into account to ensure, in the event of an earthquake, falling façades do not block escape routes or injure people.

In current earthquake standardization, façades are generally regarded as non-load-bearing components. For these components, the standards specify an equivalent horizontal and, if applicable, vertical seismic equivalent load, as shown in Fig.10. These loads must be absorbed safely and without loss of flexibility.

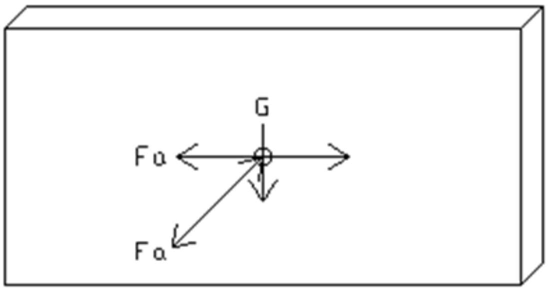


Fig. 10 – Load directions in earthquake design

A conventional façade fixing acts like a pendulum that is stabilized by the dead load of the facing layer. In order to adapt to the requirements of the installation conditions, they often have adjustment mechanisms to compensate for the tolerances on site. Horizontal loads in the plane of the façade cannot be absorbed by these anchors without appropriate displacements. However, since horizontal displacements must be limited to the serviceability limits for use under earthquake loads, additional bearings are often required. Therefore, the façade anchors must either be supplemented with additional anchors or the existing anchors must be strengthened with additional horizontal supports.

While, in the first case, brickwork façades are usually supported by brackets or angles that create a line bearing but do not provide horizontal support, in the second case, concrete or natural stone façades with sufficient shear strength can be supported by point bearings such as pins. These point bearings can be supplemented with additional horizontal bearing conditions on request.

In order to verify the applicability of these additional horizontal supports, tests on various façade fixings are useful in addition to static calculations.

4. Testing methods for seismic resistance

4.1 Macro-scale

A macro-scale test is an analysis of a supporting structure including fastening and façade at a scale of 1:1 on an earthquake shaking table. The construction is exposed to a series of artificial and natural waves with increasing intensity and the applied loads as well as the resulting deformations are documented.

The behaviour of a natural stone façade, attached to a supporting structure by a modified HALFEN natural stone anchor system, under earthquake loading was determined in a macro-scale test according to [2] Chinese Code GB/T 18575-2001 for the shaking table test method of earthquake resistant performance of building curtain wall on a shaking table for earthquake simulation in the State Key Laboratory of Disaster Reduction in Civil Engineering (SLDRCE) at Tongji University.

A concrete tower was used to simulate the load-bearing structure during the test. Natural stone slabs of granite measuring 800 x 885 x 30 mm (W×H×D) were installed with a wall distance of 120 mm. Fig.11 to Fig.13 show a 3D model, an elevation and a plan view of the tested object.

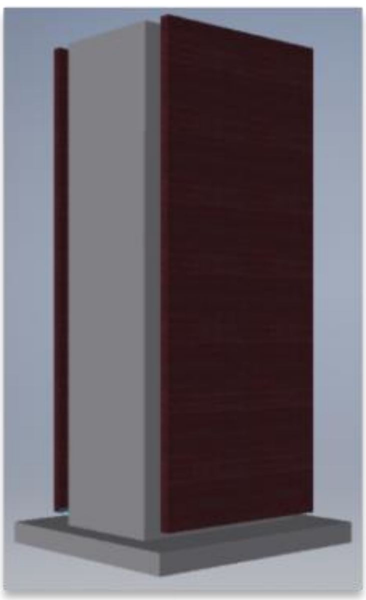


Fig. 11 - 3D model of the test subject

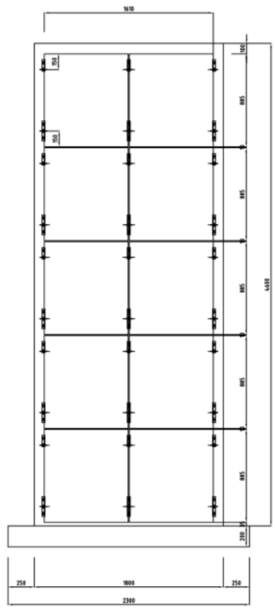


Fig. 12 - Elevation of test subject

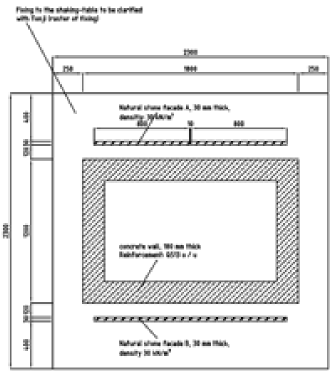


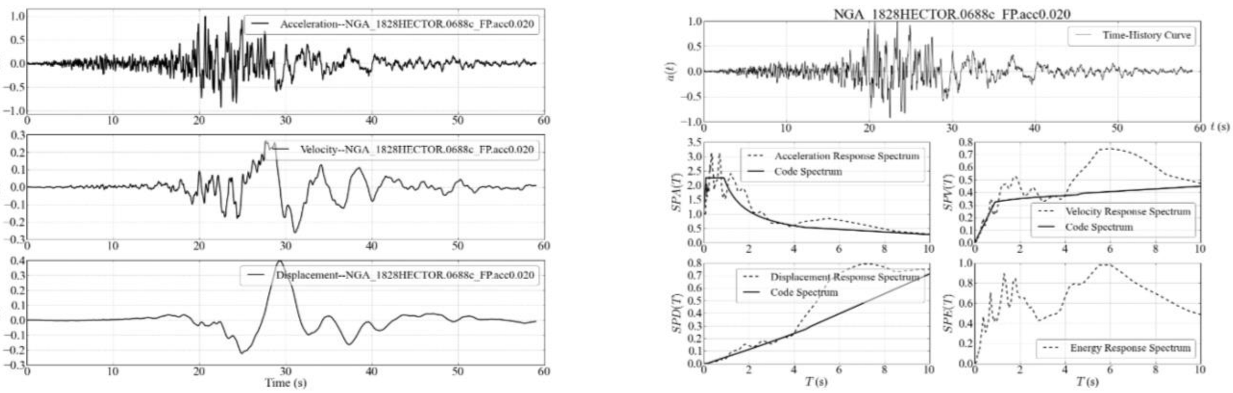
Fig. 13 - Plan of test subject

The natural stone slabs were fixed at four points of the slab using natural stone anchors in the vertical joint. The dead load of the natural stone slabs as well as horizontal loads in façade plane and vertically to it were carried by two modified support anchors, which were equipped with additional horizontal bearings. Two standard restraint anchors without horizontal bearings were used for the upper fixing points of the panels. They were able to support horizontal loads only perpendicular to the façade plane.

A total of four seismic waves were chosen to simulate the earthquake loads, including two natural waves (Hector Mine Earthquake and Chi-chi earthquake) and two artificial waves. Exemplary acceleration, velocity an displacement time-history curves and response spectra curves are shown in Fig.14.

The test started with a wave of seismic intensity of 7 degrees. The maximum input acceleration of the shake table was gradually increased. The maximum value for the maximum input acceleration of the vibration table is an 8-degree rare earth quake, taking into account the strengthening effect of the actual structure during acceleration. After entering each degree of seismic wave, a low amplitude excitation of white noise was introduced to measure the change in the dynamic properties of the test system.

Even after applying a rare earthquake of degree 8, no damage to the façade or cracks could be observed.



a) b)

Fig. 14 – a) acceleration, velocity and displacement time-history curve and b) response spectra curve as an example in X-direction for Hector Mine Earthquake

No anchor showed serious damage and all requirements for the seismic design were met. As a result, the HALFEN natural stone anchor system shows good earthquake resistance at high acceleration and meets the requirements for a seismic fastening intensity of 8 degrees.

The advantage of this type of test is that for a specific structure it can be determined which earthquake strength can be withstood according to the serviceability limits. However, this type of test is very time-consuming and cost-intensive. Another disadvantage is that no conclusions can be drawn for deviating designs. Macro-scale tests can be used for the pre-planning seismic design of an overall structure and detailed conclusions can be made. This is usually the case for bridge structures in high seismic areas. In the common practice of earthquake planning for buildings, the time factor is a major problem. Here these experiments are rarely used, alternatives to the macro-scale tests have to be found in order to avoid time delays during the planning and construction phase and to prevent additional high costs, but still to obtain confirmation of the seismic properties of the structure.

4.2 Micro scale

For a micro-scale test only a single fixing is fastened to a bearing structure, e.g. concrete, and subjected to a horizontal load in the most unfavourable direction, as specified in the current earthquake standards. There is no connection to the façade tested, but the façades dead weight is simulated by a mass suspended from the anchor cantilever arm. The regulations of [3] can be chosen for the test procedure with one exception: the calculated horizontal equivalent loads according to [4] are used as maximum loads N max (tensile/compressive load) and V max (shear force). The test procedure is shown in Fig.15.

Micro-scale tests were implemented for the first valuation of the seismic suitability of two types of natural stone anchors, which were strengthened by additional bearing conditions. The boundary requirements to simulate were chosen following the macro-scale test mentioned before:

- maximum ground acceleration: 1.28 g
- height of the fixing above the ground: 4.5 m
- height of the building: 5,0 m

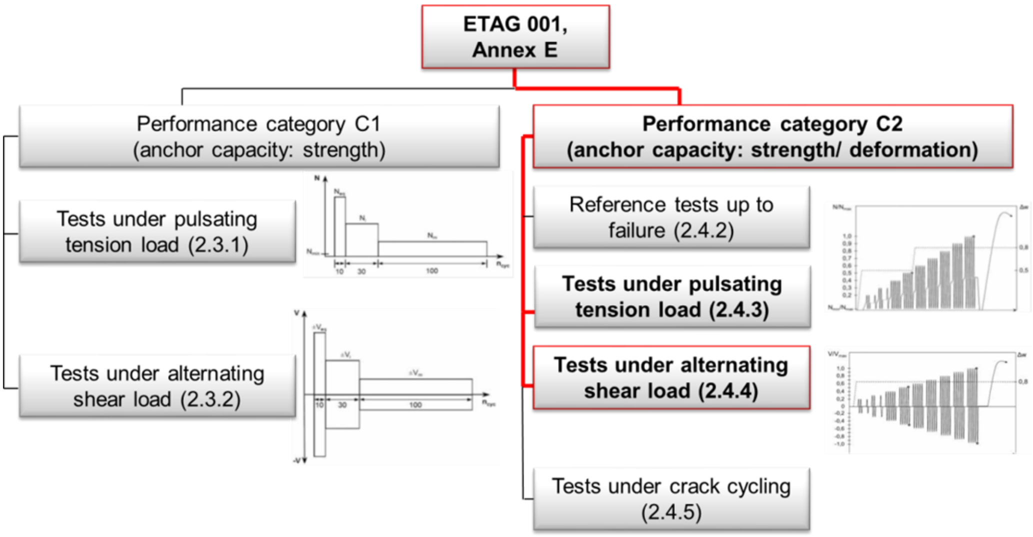


Fig. 15 - Test procedure according to [3]

On the basis of these assumptions, a horizontal static equivalent load in the most unfavourable direction, which must be considered in addition to the dead weight, was calculated according to [4] and used as maximum loads N max (tensile/compressive load) and V max (shear force). The horizontal loads were applied as well in shear direction as in tension/compression direction in according to [3].

Detailed explanations and results can be found in [5].

Quick and easy micro-scale tests are characterized by the fact that anchor modifications or further development can be checked with little time and cost. Fast conclusions can be drawn about the seismic suitability and deformation properties of a defined anchor and its connection to the bearing structure. So these tests can be very helpful for anchors selection, even in the late planning phase. A big disadvantage is the missing simulation of the connection of the fixing to the façade, for which no statements can be made during tests of this scale. Here further tests, that include the façade-fixing-connection, have to be appointed.

4.3 Meso-scale

Tests in a so called “Meso-scale” have been developed to analyze and verify all components of the façade system. A representative façade surface of e. g. 1 m² is fixed to a support structure with the intended anchors. Horizontal static equivalent loads, which have been calculated according to common earthquake standards, are applied in most unfavourable direction. For the test procedure the regulations are selected as in the micro-scale tests.

The earthquake resilience of a special masonry façade construction strengthened by additional horizontal fixings was examined by those meso-scale tests. A representative 1 m² facing brickwork façade was prepared for the tests. It was composed of a concrete slab C20/25 and a facing masonry layer of clinker bricks and NM IIa masonry mortar. The wall distance was 150 mm. Fig.16 shows a 3D simulation and Fig.17 a picture of the test setup.

The dead load of the facing brickwork was supported by a 4.0 kN masonry angle bracket with two web plates, which was fastened to the lower part of the concrete slab with anchor bolts.

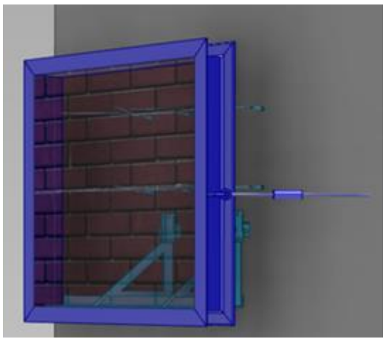


Fig. 16 - 3D model of the meso-scale test subject

Fig. 17 - Meso-scale test setup of the brickwork support system

Straight wall ties according to [6] were used to carry horizontal loads perpendicular to the façade plane. Two wall ties bent at an angle of 60° were added as an extra bearing to take up horizontal loads in façade plane. The load was applied at the height of the centre of gravity of the specimen, parallel to the façade plane. The test procedure complied with the specifications of [3] with increasing load steps. Displacements under load were measured during the tests. For load level 1 to V = 1.0 kN (corresponding to 0.5 x g), the horizontal displacements were about + / - 0.2 mm, see Fig.18. Only minor plastic deformations occurred. For load level 2 to V = 2.0 kN, Fig.19, (corresponding to 1 x g), increasing and also plastic deformations appeared. The horizontal displacements were approximately + 1.3 / - 1.0 mm (see Fig.22). Horizontal loads of + 5.0 to -8.0 kN (corresponds to 4 x g) were achieved at load level 3 to Vmax = ultimate load. In the event of failure, displacements of + 15 mm / - 60 mm occurred (see Fig.20). Failure was caused by stability loss of the wall ties as well as the brickwork support brackets as shown in Fig.21 to Fig.23.

The increasing loads also resulted in rising deformations. In case of failure, the serviceability limit was exceeded, however, it was observed that even after the stability failure of the anchorage after a load of 4xg no pull-out of the brick ties or anchor bolts were observed. The façade was damaged, but would not have fallen down in the event of an earthquake - escape routes would be free and no person would not be injured.

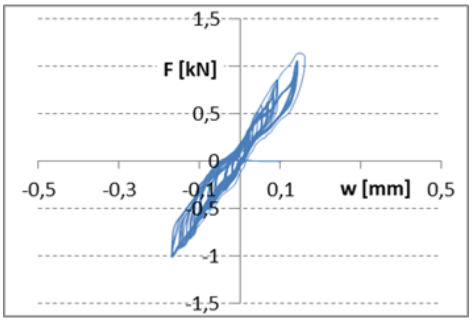


Fig. 18 - Hysteresis for load level 1 up to V = 1 kN

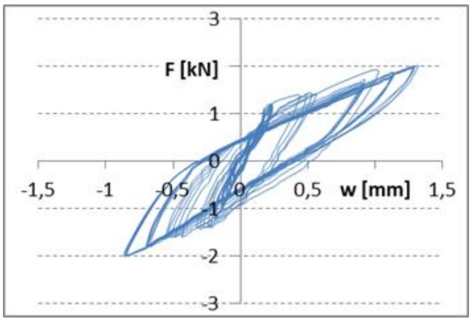


Fig. 19 - Hysteresis for load level 2 up to V = 2 kN

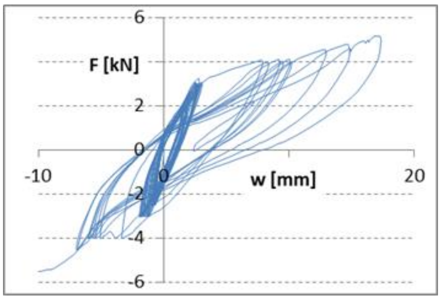


Fig. 20 - Hysteresis for load level 3 up to failure

Fig. 21 - Wall ties after load level 1 up to V = 1 kN

Fig. 22 - Wall ties after load level 2 up to V = 2 kN

Fig. 23 - Wall ties after load level 3 up to failure

Meso-scale tests can be used to fully test and compare various fixing systems, i.e. not only the fixing, but also the connection to the load-bearing substructure and to the façade, according to various criteria such as load-bearing capacity, deformation or ductility. Important information are provided on the interaction of all components. They are easy to carry out and allow important statements to be made at low cost and time, thus enabling the seismic suitability of a relevant overall structure to be assessed. These comprehensive tests are ideally suited for examining the seismic suitability of the façade including its fixing during the planning phase.

5. Concept for a seismic design

The seismic concept requires an individual consideration of the structure with regards to the planned use, the construction site, the expected earthquake load and the interaction of the load-bearing and non-load-bearing components of the structure resulting from the structural design. For the seismic design concept presented here, the façade is divided into sections and the anchors are arranged according to the calculated load. The façade anchors can either be strengthened to absorb horizontal loads in façade plane or additional bearings in horizontal parallel direction can be introduced.

This geometrical division into sections influences the architectural appearance of the building through joints and, on the other hand, has an effect on the intended supporting structure. However, in construction practice, the focus for earthquake dimensioning is essentially on the load-bearing structure. Non-load-bearing components -such as façades - are usually defined as masses attached to the load-bearing structure without an own stiffness. But these non-structural components can also influence the damping of the whole system and the performance of the building to such an extent that they must also be considered for the earthquake resistance of the building and can have a positive influence on it.

If the seismic design of the building, including all non-structural components such as the façade and its connection to the load-bearing structure, is taken into account in the early planning phase, the performance of the load-bearing structure and the façade can be harmonized. The influence of the mass of a heavy façade on the vibration response can be utilized and the damping can be positively influenced. Even if the anchorage itself is not yet exactly defined in this planning stage, a FEM simulation can be used to determine the stiffness or specific damping required for a correspondingly loaded anchor in order to achieve a certain performance of the entire building. This influence is not taken into account when considering the façade as a pure mass.

When the seismic consideration of the façade is only included in the late planning phase, time pressure often prevents the structural framework / façade and façade anchoring from being balanced. The full positive influence of the façade mass can often not be used. Nevertheless, a concept for seismic façade fixing can be developed. This is done taking into account the type of façade, the load-bearing structure and the earthquake load to be expected by strengthening the façade anchors from a static situation in such a way that horizontal loads can also be absorbed in façade plane or by additional bearings in horizontal parallel direction.

To verify the suitability of a façade concept various experimental methods can be used. On the one hand this requires time that might not be factored in during the closely scheduled construction phase and makes it difficult to respect the interaction between construction and the nonstructural element, on the other hand. Due to the tight timing of construction planning and realization, the Micro-scale tests are best suited for anchor preselection. Meso-scale tests allow an uncomplicated validation of a concept. Furthermore, anchor adaptations can be tested with regard to required stiffness or damping.

6. Summary and outlook

To examine the bearing behaviour of façade fixings, either calculations or appropriate tests are necessary. Although relatively accurate calculation methods are available for the calculation of the system façade, fastening and load-bearing structure, tests are still the most meaningful method to determine the loadbearing capacity and ductility.

The most commonly used test method is the shake table test. The results are reliable and describe the overall load-bearing behaviour accurately. However, these tests are time and cost intensive and the results are only valid for the actually applied boundary conditions.

In search of further, simpler test methods, it is obvious to reduce the size of the test specimens. A test on only one anchor represents the smallest possible test size. Tests in this “micro” scale can show the bearing behaviour of a single anchor, its deflections and its ductility. In order to evaluate the interaction of several, possibly also different anchor types, a test arrangement on the so-called "meso" scale represents the most sensible alternative. A representative façade field – in he shown examples 1 m² was chosen - is installed and subjected to static equivalent loads.

The results obtained in this way show good accordance with the far more complex shake table tests. Test setups in “micro” or “meso” are particularly suitable for comparing different anchor types with each other and controlling certain properties - such as the ductility of an anchor - without disproportionately high expenditure in the test method.

7. References

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