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Rehabilitation and strengthening methods for masonry façades

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Abstract

Due to the earthquake on 22 March 2020 serious damage to thousands of buildings occurred above all in the historic centre of Zagreb. People were injured and escape routes were blocked by falling facades or parts of buildings. Significantly mainly older and badly preserved buildings were damaged, whereas buildings built after 1964, which had to meet the requirements of the regulations for earthquake protection in the former Yugoslavia, showed minor damage. Especially in earthquake zones, the history of the country in the form of historic buildings needs to be preserved, and accordingly it is precisely these buildings that need to be surveyed and assessed in terms of their performance in the event of an earthquake. Any previous damage should be repaired immediately so that in the event of an recurrent earthquake, there is no more danger to human life. There is a need for repair methods that minimally disturb the building appearance in order to restore or improve the structural load-bearing capacity of existing buildings. The load-bearing capacity of a suitably strengthened facade and its fixings can be verified by tests - for these non-load-bearing elements for example, according to ETAG 001, Annex E [1]. This paper presents a method for post-repairing of façades on existing buildings to restore their structural load-bearing capacity. This method can be used to preserve historical building material on one hand, but also to upgrade the façade construction with the aim to meet requirements of earthquake design like protection of life and enabling rescue work after an earthquake. So called Meso-scale tests to check the load-bearing capacity are described as alternative to large shake table tests. The technical background is explained and the experiment results are illustrated.

Key words: seismic retrofitting, façade systems; non-structural elements, testing methods

1 Introduction

The façade of a building serves numerous purposes: it characterizes the appearance of the building, but also protects it from weather influences such as rain and wind. It contributes to the building's physical properties insofar as, in addition to the facing layer, it consists of an adequate insulation layer and an optional air gap or cavity.

As a result of this structure, the task of the façade fixing is to safely transfer the dead load of the façade and the loads acting on it into the supporting structure and to maintain the distance between the supporting and façade layers. Especially in the case of "heavy" façades, i.e. façades with a dead load of more than 100 kg/m² such as brickwork, these façade fixings must transfer high point loads over large distances between the layers.

In the current earthquake standardization such as [2], façades and their fixings are classified as non-load-bearing components . These components are usually defined as masses without any inherent stiffness that are attached to the load-bearing structure. Their design for the seismic load case is carried out by static equivalent horizontal loads acting in the most unfavourable direction.

Minor damage to the façade can occur as a result of an earthquake, but in particular the falling of façade parts should be prevented in order to avoid injury to persons and blocking of escape routes. Damage to the façade of a building represents a weakening of the structure and reduces the possible seismic performance during future earthquake events. Therefore, this damage, such as cracks or deformed façade fixings, must be assessed and repaired immediately.

Historical buildings without any seismic fixings whose construction took place before seismic standards were introduced, can be retrofitted with appropriate horizontal bearings. In terms of preserving the visual impression, this is possible without significantly disturbing the building's appearance.

To assess the seismic performance of a fixing, it is mandatory to analyse the interaction of all components, i.e. the façade fixing, the support structure and the façade itself, to ensure sufficient ductility with adequate load-bearing capacity. In addition to calculations, the load-bearing behaviour of the system is usually determined by tests, as in each case there are individual conditions concerning the building and loadings. Since macro-scale tests – such as shake table tests – are very time-consuming and cost-intensive, detailed tests on a smaller scale can be a good alternative.

In the following, methods for repairing after an earthquake as well as for retrofitting a façade to support seismic loads without causing major disturbance to the building's appearance are described. Test methods to verify the suitability of the fixing at different scales are presented and evaluated.

2 Brickwork Façades

Modern curtain façades usually consist of a facing façade layer, a layer of insulation and, if necessary, an additional air gap and are fixed to the supporting layer. The distance between the load-bearing layer and the facing façade can reach values of more than 300 mm. This façade construction requires on the one hand that the fixings of the façade layer are either designed as cantilevers or as tension members in combination with spacers and on the other hand that the fixings have to penetrate the insulation. In the following, systems of common fixings for non-load-bearing brickwork façades are presented.

Fig. 1a shows an example of a brickwork façade. The dead weight of the brickwork panels is taken up by support anchors such as support angles – or in the case of larger cavities – brickwork support brackets, which are fixed to the supporting structure with suitable fixings such as anchor bolts or anchor channels (Fig. 1b). Horizontal loads perpendicular to the plane of the façade, such as wind loads, must be absorbed separately by special horizontal restraint anchors, such as brick ties, as shown in Fig. 1c.

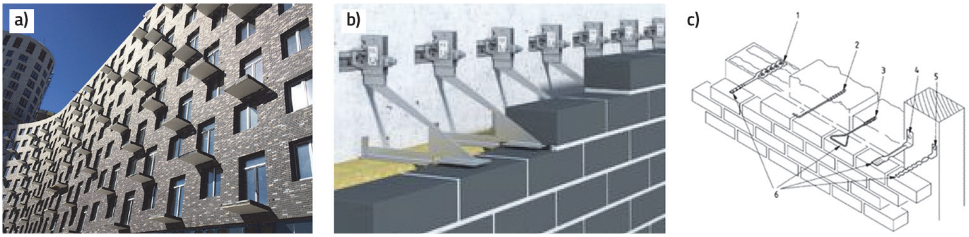

Figure 1. a) Brickwork façade; b) Brickwork support brackets; c) Various wall ties [3]

3 Methods for repair and seismic retrofit of façades

Repair is defined in EN 1990 as '*Activities performed to preserve or to restore the function of a structure that fall outside the definition of maintenance*' [4]. Typically repair will be undertaken when a structure has been damaged and is a response to an event or events that have already occurred. Retrofitting is also concerned with preserving the function of a structure, however it is generally carried out in anticipation of an event occurring with the aim of limiting damage to the structure in the first place. Strategies for retrofitting can comprise a single type of component or a system of linked components which combine to increase the structural capacity or reduce the demand on the structure due to a seismic event. Numerous methods exist for both seismic repair and retrofit, some of which are explored below.

3.1 Methods of repair

After a seismic event, brickwork façades can display relatively minor damage, such as cracking, or more major damage such as partial or full collapse of masonry panels. It is vital that even 'minor' damage is repaired promptly to ensure that the structure's seismic performance does not remain impaired. This is important as, with the structure in a weakened state, aftershocks or subsequent earthquakes have the potential to cause more serious structural damage, personal injury or disruption to escape routes and rescue attempts.

Where masonry façades have been cracked, lengths of flexible twisted (helical) stainless steel bar can be used to 'stitch' the brickwork back together and provide near-surface masonry reinforcement. Helical bars are placed in the horizontal mortar joints and thixotropic cementitious grout is injected to form a strong bond between mortar, bar and masonry (Fig. 2a). The helical bars effectively redistribute tensile loads along the length of the masonry to minimise further crack development. This is a low-disruption and permanent repair method which stabilises the masonry and has been shown to be an effective method of repairing cracking in URM (unreinforced masonry) walls [5]. Pairs of long helical bar can also be used to form deep masonry beams. These reinforce and stabilise existing masonry and can restore structural integrity where masonry has failed and lost its load bearing capabilities.

Cracked or unstable masonry can also be repaired by using threaded stainless steel bars, cementitious grout and heavy duty mesh fabric sleeves working in a composite action. Threaded bars and sleeves are installed into pre-drilled holes in the structure and the sleeves filled with grout; this causes them to expand and form a strong chemical/ mechanical bond with the substrate (Fig. 2b). This repair method has been shown to be suitable for heavy duty and high load applications such as stitching cracked solid or multi-leaf walls and stabilising rubble-filled walls, parapets and arches. This is a fast, permanent, non-disruptive and fully concealed method of repairing masonry which allows the building's original appearance to be retained; particularly important for buildings of cultural or historical value.

Where masonry has collapsed and needs to be re-built, cavity wall ties can be used to effectively tie the inner and outer leaves of brickwork together, allowing the two parts to act as a homogenous unit and thus improve the wall stability. Various profiles and shapes of tie can be used depending on the specific building make-up and structural requirements. Stainless steel ties with shaped ends can be built into the outer leaf and either mechanically fixed or resin bonded to the inner leaf. Where thermal performance is important, pultruded basalt fibre ties can be used – these perform the same function of tying the two leaves together but reduce the transfer of heat across the cavity due to their low thermal conductivity.

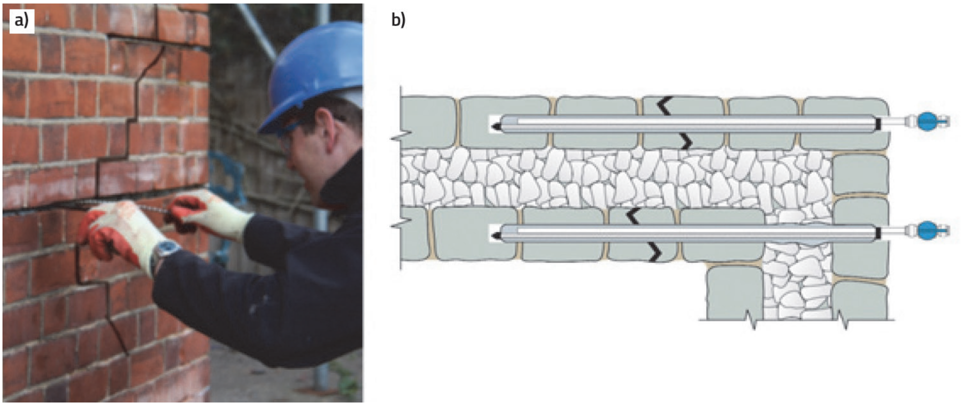

Figure 2. a) Helical bar installation. b) Threaded bars, sleeves and grout used to repair cracked masonry

3.2 Methods of retrofit

Seismic retrofitting aims to increase the overall level of security of a building to resist a seismic event. One method of achieving this is to use short lengths of stainless steel helical bar to mechanically pin or tie brickwork façades as well as masonry walls, render (stucco) and delicate masonry features (such as terracotta). These ties can be used effectively in a variety of materials such as brickwork, blockwork and concrete and are suitable for cavity and solid wall constructions – Fig. 3a shows an example of natural stone cladding fixed back to a solid brickwork wall. They can also be used in conjunction with cementitious grout and fabric mesh sleeves to stabilise and secure walls, lintels and decorative fascias. Installation is quick and the masonry is left virtually unmarked. These helical ties have been shown to be effective in improving the out-of-plane performance of masonry walls and meet the requirements of an earthquake medium duty tie according to Australasian standard AS/NZS2699.1 [5], [6].

Helical ties installed perpendicular to the masonry can be joined to lengths of horizontal helical bar in the external leaf mortar joints by use of stainless steel connectors – see Fig. 3b. The horizontal helical bars can be overlapped and grouted in place to provide long runs of remedial masonry reinforcement, improving both in and out of plane performance. This allows the structure to be upgraded whilst minimising the addition of seismic mass and does not require the wall to be taken down and rebuilt. In-situ testing can easily be undertaken to confirm the security of the fixing/s in the substrate.

'Rigid' and 'ductile' anchors are further methods that can improve seismic performance of a structure. Rigid anchors consist of individual masonry support brackets installed to transfer horizontal seismic loads in the plane of the façade. Ductile anchors are achieved by installing additional wall ties at an angle across the cavity – Fig. 3c shows two cross-section examples of ductile anchors.

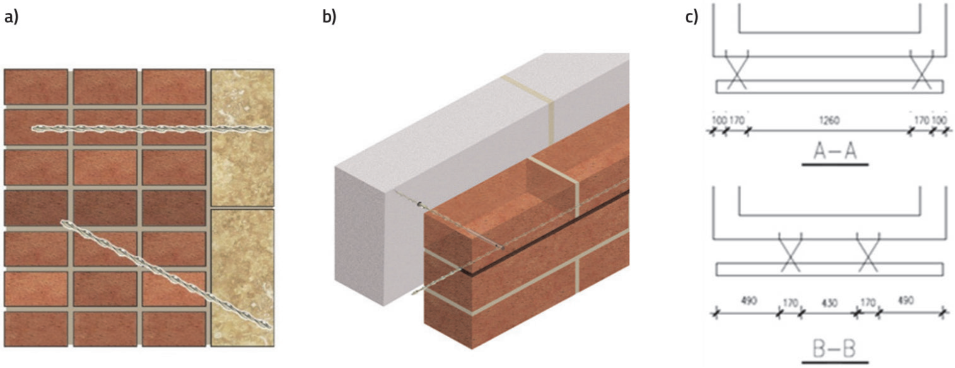

Figure 3. a) Helical bar used to pin masonry. b) Stainless steel connector. c) 'Ductile' anchors

4 Experimental evaluation of repair and retrofit methods

4.1 Macro-scale testing

A macro-scale test is a system analysis on a 1:1 scale on a shake table, requiring that the whole structure, including fixing and façade, is loaded with a series of artificial and natural waves of increasing intensity. Applied loads and resulting deformations are recorded.

For further illustration, a shake table test carried out on a modified brickwork support system [7] is described below. A cast-in-place concrete tower simulated the load-bearing structure (Fig. 4).

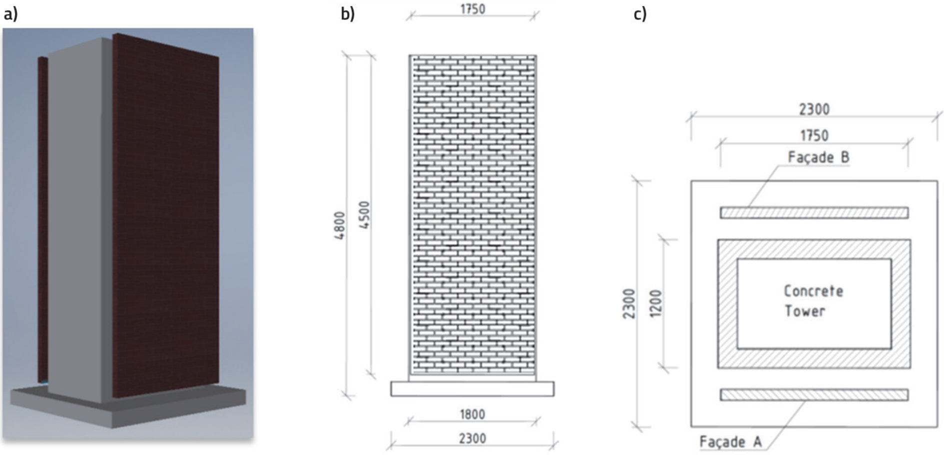

Figure 4. a) 3 D model of the test object; b) Elevation of the test object; c) Floor plan

Brickwork facades with different fixing concepts were attached to two sides of the tower. Support brackets carried the dead load at the bottom and distributed horizontal wall ties took the horizontal loads perpendicular to the façade, e.g. wind load etc.

Additional horizontal wall ties angled at 60° (i.e. ductile anchors) were distributed on wall A, and additional horizontal support brackets (i.e. rigid anchors) were installed on wall B to transfer the horizontal seismic loads in the plane of the façade. After applying accelerations by the shake table to simulate specific seismic events, the construction was examined to see if it could carry the loads without damage to the façade. Another example of a macro-scale test is the in-situ out-of-plane bending test described in [8] on a full-scale unreinforced masonry wall that was seismically retrofitted with twisted steel inserts.

The test setup consisted mainly of steel sections, a rigid wooden reaction frame, air cushions, an air compressor, four load cells and two linear variable displacement transducers (LVDT) with a tripod. Air cushions were used to apply a uniformly distributed load that simulated the seismic load generated in the out-of-plane direction. Fig. 5 shows the test setup.

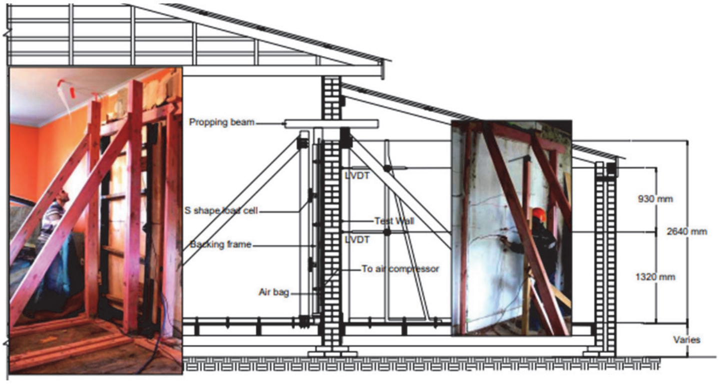

Figure 5. In-situ macro-scale test setup [8]

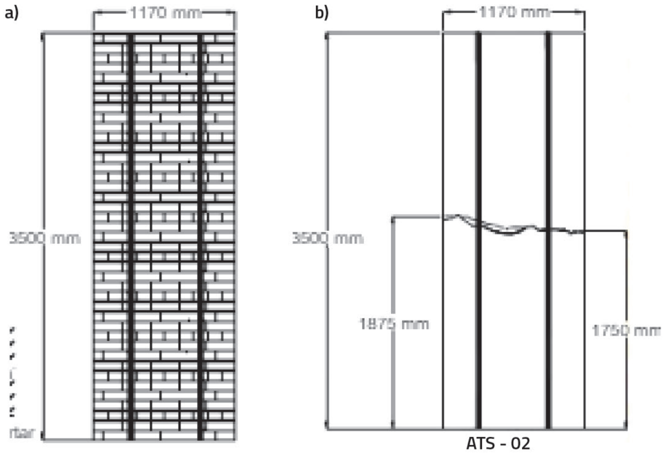

Figure 6. a) Retrofit detail; b) Failure mode of the test wall [8]

The test wall was retrofitted as follows: surface grooves were made on one side of the wall. After cleaning and moistening the grooves, an approx. 10mm thick layer of injection mortar with high adhesive strength was injected. Twisted stainless steel rods were then inserted and the grooves filled with mortar. The test subject was retrofitted with two evenly spaced D6 rods inserted into 50 mm deep grooves. Fig. 6a shows the details. The test wall was subjected to several loading and unloading cycles by inflating and deflating the air cushion until failure within a safe displacement limit was achieved. When comparing the results of the non-retrofitted and retrofitted wall, it was found that the nominal out-of-plane flexural strength of the test wall was 5.7 times that of the non-retrofitted URM wall, respectively.

The advantage of these macro-scale tests is the ability to determine for a specific design what earthquake resistance can be provided while respecting the serviceability limits. The major disadvantage of macro tests is that they are material-intensive, time consuming, expensive and do not provide any conclusion for deviating constructions.

4.2 Micro-scale testing

Micro-scale tests describe the experimental investigation of an individual fixing with regard to its suitability for the expected seismic design load. These tests can be carried out in a laboratory or on site with static or static equivalent loads which makes the tests faster to carry out at a manageable cost. For example, it is possible to simulate the dead load of a façade using weights and apply a horizontal alternating load simulating seismic actions. These micro-scale tests are inexpensive and quick to carry out, but do not provide any information about the interaction of all façade components, particularly with regard to the connection between fixing and load-bearing layer or fixing and façade.

4.3 Meso-scale testing

Meso-scale tests allow an evaluation and verification of all components of a façade system. A representative façade surface – e.g. of 1m² – is attached with suitable fixings to a support layer corresponding to the building and static equivalent loads determined according to local standards for seismic design are applied.

Since there is no standard regulating the test procedure for façade systems under seismic loading, the regulations of ETAG 001, Annex E (2013) [1], for example, are proposed, with one exception: the calculated horizontal equivalent loads according to the relevant seismic design standard are used as maximum loads N max (tension/compression load) and V max (shear force).

A 3D model and a picture of an exemplary test object are shown in Fig. 7. In this example, the brickwork rested on support angles with two brackets, which were fixed to the lower part of a concrete slab with anchor bolts. The brickwork and the concrete support layer were connected by straight wall ties according to [3, 9] and two wall ties angled at 60° as an additional horizontal bearing (ductile anchor).

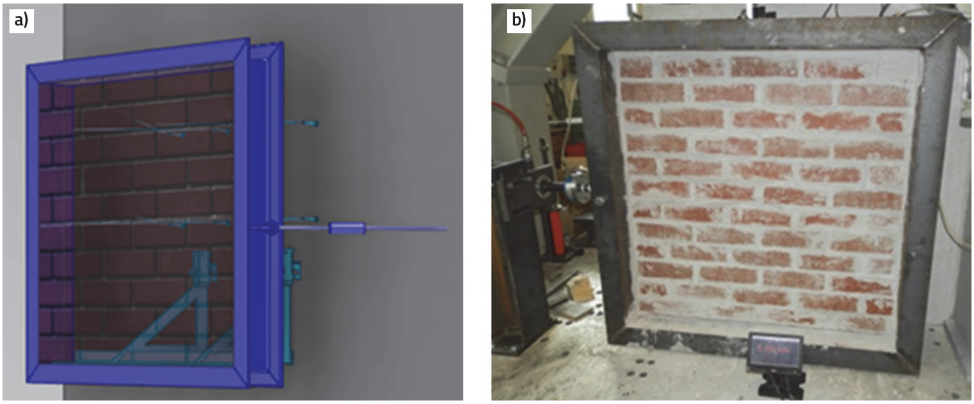

Figure 7. a) 3D model of a meso-scale test setup; b) Photo of exemplary test setup

The load application height corresponded to the centre of gravity of the facing layer, whilst the horizontal load direction complied with that of a horizontal load in the façade plane from earthquakes on the real component. The load application was carried out according to [1] in increasing load steps on the same component. Deformations and displacements under load were measured throughout.

In case of failure, the serviceability limit was exceeded here, but it could be observed that even after the stability failure of the fixing after a load of 4xg, there was no pulling-out of the wall ties or the anchor bolts. The façade would not have collapsed in the event of an earthquake – escape routes would be clear and people would not be at risk.

With the help of meso-scale tests, different fixing concepts, i.e. not only the fixing but also the connection to the supporting layer and to the façade, can be comprehensively tested and compared according to various criteria such as load-bearing capacity, deformation or ductility. Before, during and after the test, all façade components are clearly visible and can be assessed. Deformations for different load levels and the failure behaviour can be observed and documented.

Meso-scale tests are easy to carry out and allow important statements to be made on the assessment of the earthquake resistance of a corresponding overall construction quickly and at low cost.

5 Conclusion

Current earthquake standards classify façades and their fixings as non-load-bearing components. Their design for the seismic load case is carried out by static equivalent horizontal loads acting in the most unfavourable direction. Minor damage to the façade can occur as a result of an earthquake, but in particular the falling of façade parts should be prevented in order to avoid injury to persons and blocking of escape routes. Damage to the façade of a building represents a weakening of the structure and reduces the possible seismic performance during future earthquake events. Therefore, this damages must be assessed and repaired immediately. Buildings without any seismic fixings can also be retrofitted with appropriate horizontal bearings without significantly disturbing the building's appearance.

Appropriate methods for masonry repair and retrofitting are available. Combinations of stainless steel bars, grout, sleeves and connectors can be used to stitch together cracked masonry, stabilise and reinforce existing masonry walls and improve their out-of-plane performance during a seismic event. The methods discussed are relatively quick, non-disruptive and can be easily concealed, ensuring the building aesthetic is not compromised.

To assess the seismic performance of a fixing, it is mandatory to analyse the interaction of all components, i.e. the façade fixing, the support structure and the façade, to ensure sufficient ductility with adequate load-bearing capacity. Along with calculation methods, tests are still the most meaningful method to determine the loadbearing capacity and ductility, because every building provides different conditions for seismic hazard and more general structural make-up.

The most commonly used test method is the shake table test, because test results are reliable and describe the overall load-bearing behaviour relatively accurately. But these tests are very time and cost intensive and the results are only valid for the actually applied boundary conditions. Simpler test methods are needed to reduce the size of the test specimens and effort.

A test on only one anchor represents the smallest possible test size. Tests in "micro" scale can show the bearing behaviour of a single anchor, its deflections and its ductility. In order to evaluate the interaction of several potentially different anchor types, a test arrangement on the so-called "meso" scale represents the most sensible alternative. A representative façade field – in the discussed examples 1m² was chosen – is installed and subjected to alternating or pulsating static equivalent loads. The results obtained in this way show good correlation with the far more complex shake table tests.

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