Proceedings of the 2nd Croatian Conference on Earthquake Engineering - 2CroCEE
Zagreb, Croatia - March 22 to 24, 2023

DOI: https://doi.org/10.5592/CO/2CroCEE.2023.124

EXTENSION OF SYSTEMS FOR SEISMIC SECURING OF HEAVY FAÇADES THROUGH REFURBISHMENT, STRENGTHENING AND RETROFITTING

Samuel Hine [(1)], Matthias Roik [(2)]

[(1)] *Research & Development, Leviat LTD, sam.hine@leviat.com*
[(2)] *Research & Development, Leviat GmbH, matthias.roik@leviat.com*

Abstract

Recent earthquakes have shown that existing older buildings are not sufficiently safe against seismic loads. This applies to both structural and non-structural elements of buildings. Damage to so-called 'heavy' façade structures is of particular concern, as falling components can cause personal injury and block important traffic and escape routes.
Heavy facades made of masonry, natural stone cladding or concrete panels with dead loads exceeding 100 kg/m² are usually anchored to the supporting structure by steel anchors that transfer the loads from the cladding panels.
Although new façades are very secure against earthquakes, the field of seismic strengthening of heavy façades is largely unproven, although several product systems are available on the market that enable repair and strengthening.
These systems will be investigated to see if they are suitable to take the additional loads caused by earthquakes.
Ongoing trials are expanding the range of fastening systems suitable for heavy façade retrofitting as well as repair. This will utilise the experience already presented at the last 1CroCEE conference. An independent test series will allow the knowledge already gained to be reflected in a range of products for repair.
This paper presents a method for repairing existing facades. This method can be used to preserve the fabric of historic buildings but can also be used to strengthen façade structures with the aim of meeting seismic design requirements, such as protecting human life after an earthquake or enabling rescue operations. As an alternative to large-scale shake table tests, so-called mesoscale tests for checking load-bearing capacity are described. The technical background is explained, and the test results are presented.

Keywords: seismic retrofitting, seismic repair, façade systems; testing methods, non-structural elements

1. Introduction

The façade of a building not only defines the building's appearance by harmonising it with other buildings or making it stand out, but also serves a number of other purposes, such as protecting the internal structure and occupants from the effects of weather, including rain and wind. For example, cavities can improve ventilation and thermal performance can be improved by adding a layer of insulation.

Facade fixings are an integral part of this structure and must safely transfer dead loads (of the facade itself) and loads (wind, earthquake, etc.) to the structure, while at the same time maintaining the distance between the support layer and the facade layer. 'Heavy' façades, such as brickwork, natural stone and concrete, with dead loads in excess of 100 kg/m² which place high demands on the façade fixings. Not only do fixings need to carry high point loads back to the structure, but the nature of the structure means that the distance the fixings have to span between the inner and outer layers can be significant (up to 300 mm or even more).

BS EN 1998-1 [2013] classifies façades and façade fixings as non-load-bearing components, i.e. lumps without inherent stiffness attached to load-bearing structures. Such items can be designed against seismic loads by using static equivalent horizontal loads acting in the most unfavourable direction.

Proceedings of the 2nd Croatian Conference on Earthquake Engineering - 2CroCEE
Zagreb, Croatia - March 22 to 24, 2023

DOI: https://doi.org/10.5592/CO/2CroCEE.2023.124

In the following, as a first step, only masonry facades will be considered, as the range of these repair products has been examined. However, the lessons learned can also be applied to other façade materials, such as natural stone and concrete.

Hairline cracks and other minor damage can occur to masonry facades as a result of earthquakes. Although the aesthetics of the building will be compromised, such damage does not usually pose an imminent hazard. However, major damage, such as the partial or total collapse of a façade, creates greater risks and hazards for occupants attempting to escape and for emergency services trying to access a building. As well as the imminent danger from falling masonry, important access routes in and around the building may be blocked. Damage to facades and falling stones is evident in post-earthquake photographs from Christchurch (2011) and Zagreb (2020), see Figure 1.

Figure 1. Masonry façade damage – Zagreb 2020 (Photo credit REUTERS/Antonio Bronic).

Damage to the façade may indicate that the structure itself has been weakened, reducing its potential seismic performance during aftershocks and subsequent earthquakes. In order to restore the seismic integrity of the building and the façade, damage (including to the structure and façade itself and associated fixings) should be assessed quickly to identify where repairs are required.

Once damaged, the seismic performance of a building can be restored through repairs, but retrofitting existing facades with new components can improve their seismic performance and reduce the likelihood of damage occurring in the first place. This reduces the human risk in the event of an earthquake and reduces the time and cost of repairs.

Seismic retrofitting is particularly applied to older historic facades that were built before modern standards were introduced and usually do not include any seismic fixings. Retrofit methods can be carried out with minimal or no visual impact, which can improve seismic performance while preserving the aesthetics of the façade.

Rather than assessing façade fixings in isolation, the interaction of fixings with other components such as the structural frame and façade should be considered. Analysing fixings in this way allows load-bearing capacity and ductility to be assessed. In addition, different scale tests can be carried out to assess the load-bearing capacity of the system in different scenarios. Macroscale testing offers the opportunity to accurately replicate field conditions, but requires large, expensive test facilities and can be very time-

DOI: https://doi.org/10.5592/CO/2CroCEE.2023.124

consuming. On the other hand, small-scale testing, such as mesoscale and microscale testing, provides a viable alternative where representative results can be obtained at a lower cost.

This paper discusses methods for seismic repair and retrofitting of existing masonry facades. Different approaches for testing façade fixings are presented and evaluated.

2. Brickwork Façades

Modern buildings with brick facades usually rely on several layers to achieve the necessary weather resistance, thermal performance and ventilation. The external-facing façade layer is generally separated from the insulation layer by a clear air gap or cavity, with the structural frame located behind the insulation layer. Shelf angles or brick support brackets (Fig. 2) are used to support the dead loads on brick façades, and these must span between the layers and be firmly fixed to the frame through the insulation. They are usually designed as cantilever or tension members with spacers and are fixed using suitable anchor bolts or channels.

Loads acting perpendicular to the façade, such as wind loads, are separately accommodated by horizontal restraints. These members transfer tensile and compressive loads between the masonry facade and the structure and limit movement between them. The anchorage method shown in Figure 2 is not designed to transfer loads parallel to the façade layers. If seismic loads are anticipated, load-bearing members must be added. This is important not only for new buildings, but also for repairs and refurbishments.

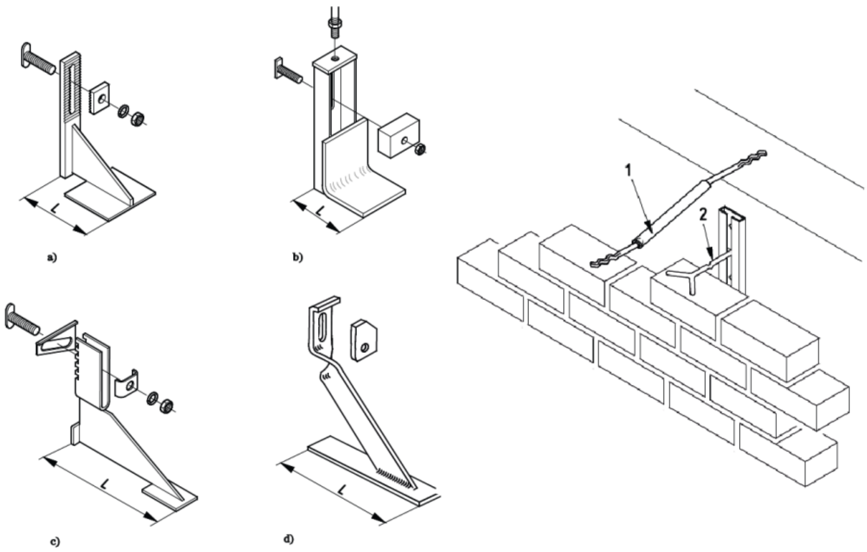

Figure 2. Examples of brickwork support brackets and movement-tolerant wall ties [xxx].

3. Seismic strengthening Methods

Strengthening methods fall into two main categories: repair and retrofit; BS EN 1990 [2005] defines repair as *'activities undertaken to maintain or restore the function of a structure that fall outside the definition of maintenance'*. Whereas repairs are carried out in response to damage to a building, retrofitting is a more proactive approach and is carried out in anticipation of the occurrence of an event, such as an earthquake. The ultimate aim is to reduce or completely eliminate damage. This has the dual benefit of lower risk to health during an event and reducing the amount and cost of repairs required after the event. A variety of retrofit strategies exist, ranging from simple single components to more

Proceedings of the 2nd Croatian Conference on Earthquake Engineering - 2CroCEE
Zagreb, Croatia - March 22 to 24, 2023

DOI: https://doi.org/10.5592/CO/2CroCEE.2023.124

complex connected systems. Many methods can be installed sympathetically and with minimum disruption to the existing façade – this can be of great importance when working with older buildings of historic significance. A number of such methods are presented below and assessed for their ability to secure masonry façades against seismic loads..

3.1 repair methods for masonry façades

Repair methods are important to restore the structural integrity of stone facades after damage has occurred. If building damage is left unchecked, the facade's seismic integrity will be compromised in the event of a subsequent earthquake, increasing the likelihood of damage and loss of life. It is therefore important to repair cracked, damaged or collapsed masonry as soon as possible.

One method of repairing cracked masonry is to insert long twisted (helical) stainless steel bars into horizontal mortar joints and grout them in place (see Figure 3). The helical bars and thixotropic cementitious grout bond tightly to the existing masonry, redistributing the tensile load down the length of the panel and minimising the occurrence of cracks. With careful consideration of the mortar to be used in the grouting process, façades can be repaired technique in a very aesthetically sympathetic manner.

Figure 3. Thixotropic cementitious grout applied to a horizontal slot in preparation for insertion of helical bar.

Another use of helical stainless steel bar for façade repair is the creation of deep masonry beams. In a similar way to crack stitching, bars are grouted in place in horizontal slots cut in the mortar joints. By using pairs of bars installed a number of courses apart, structural integrity and load-bearing capacity of the façade can be restored.

Masonry façades which are bowing out of plane can be repaired by using threaded or helical stainless steel bars to reinstate the connection between the façade and the structural frame – see Figure 4. By driving the bars through the façade and into the internal timber joists (either into the ends or the sides), the masonry can be stabilised and further movement prevented. As external spreader plates are not required, this method is again easily concealed and presents a quick, permanent repair solution.

For masonry façades which have suffered more significant damage or have high load applications, a more robust system of threaded stainless steel bar, heavy duty mesh fabric sleeves and cementitious

Proceedings of the 2nd Croatian Conference on Earthquake Engineering - 2CroCEE
Zagreb, Croatia - March 22 to 24, 2023

DOI: https://doi.org/10.5592/CO/2CroCEE.2023.124

grout may be required. The bars and sleeves are inserted into the walls through drilled holes, grout is then pumped into the sleeves which expand and form a strong chemical/ mechanical bond with the existing masonry ad internal structure – see Figure 4. Again, with good detailing and workmanship to fill the drilled cores this solution is fully concealed and can leave the façade looking virtually un-touched.

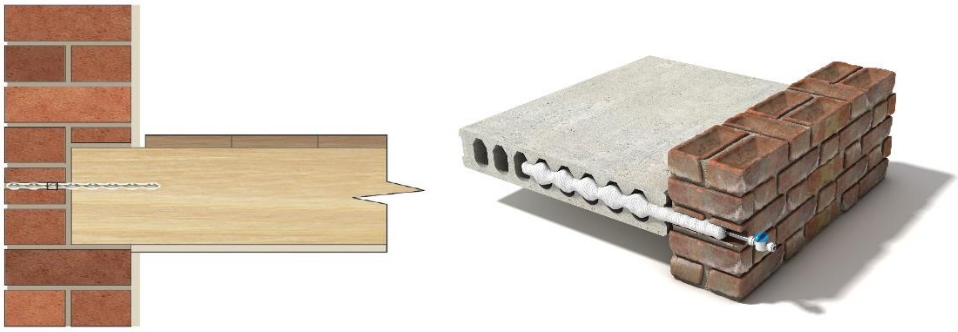

Figure 4. Brickwork façade restrained from bowing out of plane and heavy duty repair to masonry façade.

If complete masonry collapse has occurred and the façade is to be re-built, cavity wall ties can be employed to join the leaves of masonry together. This improves the wall stability by tying the layers together and allowing them to act as one homogenous unit. Many different wall tie profiles and end types are available to suit different applications – ties can be bedded in mortar at both ends, mechanically fixed using screws or bolts, or resin-bonded directly to the masonry. Typically wall ties are made from stainless steel but pultruded basalt fibre ties are also available when even lower thermal conductivity is required.

3.2 retrofit methods for masonry façades

When retrofitting stone facades to improve their seismic performance, a different philosophy is utilised. Instead of waiting for damage to occur and then repairing it, retrofitting is a proactive approach that spends time and money up front, with a view to reducing future expenditure.

On brick facades, a similar effect to crack stitching can be achieved by installing stainless steel helical bars at mortar joints. These long bars can be connected via stainless steel components to short helical ties driven vertically through the façade and into the internal structure (see Figure 5). By connecting the bars and ties in this way, long repair masonry can be installed to improve the in-plane and out-of-plane performance of the façade with minimal increase in seismic strength. If required, the anchorage strength can be verified in situ by a simple tensile test.

Stainless steel helical ties may also be used to mechanically (or chemically) fix brick facades, render and masonry to the structural frame. Ties are driven into small pre-drilled holes inside the bricks to hold the brick layers together and prevent the masonry from collapsing due to earthquakes (see Figure 5). Depending on the application, cementitious grout or fabric sleeves can also be used with ties. The technology can be used on both cavity walls and solid walls and is suitable for fixing to brick, block, concrete and timber.

Tests have shown that retrofitting stainless steel helical ties can effectively improve the out-of-plane performance of masonry walls [EQ Struc. 2013], and Newcastle Innovation [2010] found that the Australian Standard AS/NZ2699.1 medium load for earthquake It has also been shown that the requirements for ties can be met in this way.

DOI: https://doi.org/10.5592/CO/2CroCEE.2023.124

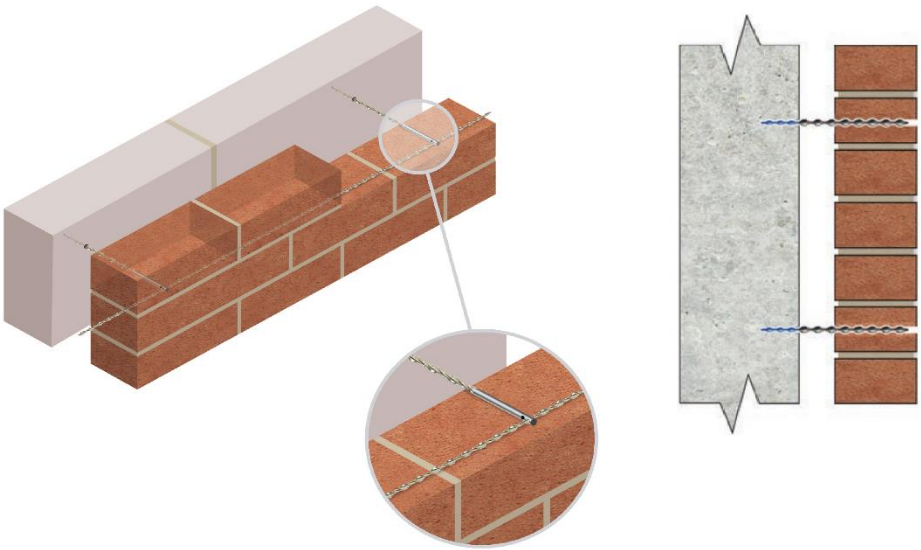

Figure 5. Long helical bars connected to perpendicular helical ties and a mechanically pinned masonry façade.

Seismic performance can be further improved by the use of 'rigid' and 'ductile' anchors. Typically these require more invasive installation procedures; individual masonry support brackets ('rigid' anchors) can be installed to carry horizontal seismic loads whilst angled wall ties ('ductile' anchors) can transfer both transverse and longitudinal loads back to the structure. This has been shown to be an effective method of limiting damage to heavy façades during shake-table testing [Roik and Piesker, 2017].

4. Testing of Repair & Retrofit for Masonry Façades

4.1 Introduction

Roik and Piesker [2019] describe the different test scales that are suitable for heavy façade fixings; macro, meso and micro. Each scale has various advantages and disadvantages but, generally, the larger the scale, the greater the expense and time required. For this reason, meso-scale testing presents a good compromise where the full representative façade system and inter-linked components can be evaluated without requiring large-scale testing facilities.

4.2 Meso-scale Testing

Mesoscale tests are much easier to carry out than large-scale shake table tests, as they utilise an area of approximately 1 m2 representative of the façade. Importantly, even with an area of 1 m2, all components of the façade anchorage system can be assessed together, so that important interactions between elements are not lost. The low cost makes it more practical to carry out project-specific tests with relevant predefined static equivalent loads.

As there are no specific regulations on test methods for façade systems subjected to seismic loads, the regulations in Annex E [2013] of ETAG 001 are proposed. The only exception is that the calculated horizontal equivalent loads (taken from the relevant seismic design standards) are used as the maximum load N max in tension and compression and V max in shear.

Proceedings of the 2nd Croatian Conference on Earthquake Engineering - 2CroCEE
Zagreb, Croatia - March 22 to 24, 2023

DOI: https://doi.org/10.5592/CO/2CroCEE.2023.124

Figure 6 shows an example of a mesoscale test where a 1 m2 masonry façade section was supported on brickwork support brackets and fixed back to a concrete frame. Vertical wall ties were placed as the bricks were stacked and the mortar was left to cure. Once the design strength was reached, two helical bars were driven diagonally from the bricks into the concrete frame and resin-fixed with 'ductile' anchors to accurately represent the retrofit scenario. Horizontal loads were applied in the plane of the wall, in accordance with ETAG 001, Annex E [2013], at a continuous loading rate, with load increments. Horizontal displacements of the facade were measured using displacement transducers.

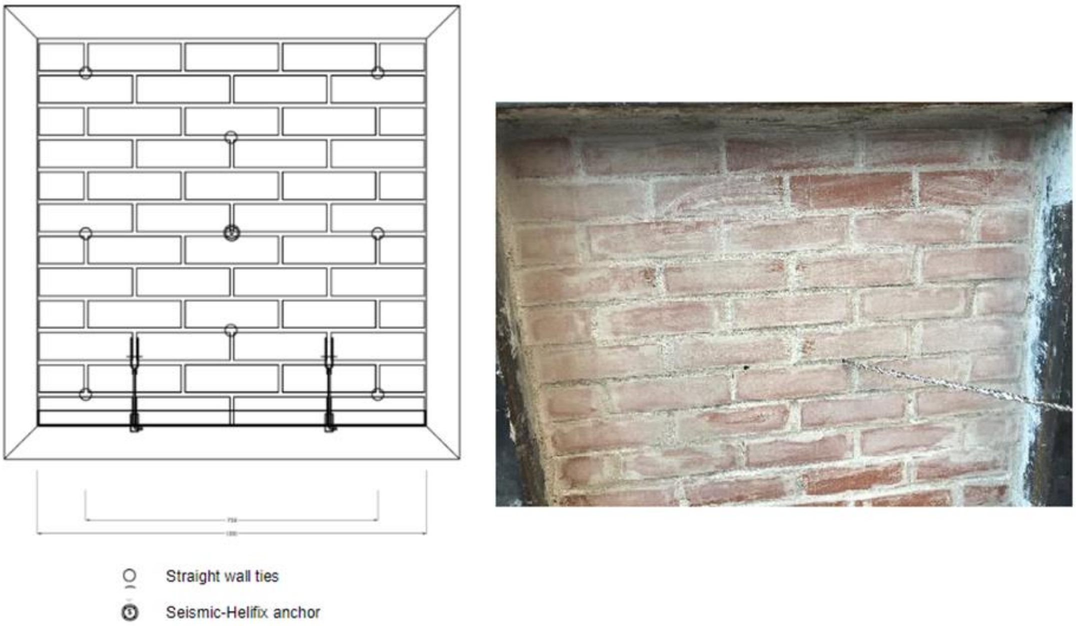

Figure 6. Meso-scale test concept and installation of helical bar through brickwork.

The test results show minimal horizontal displacement (less than 1mm) is exhibited with load application Vmax = ±2.0kN (equivalent to 1 x G). Plastic deformation starts to become apparent around Vmax = ±4.0kN (2 x G) with horizontal displacement of ±9mm. With further load increases the displacement grows strongly up to around 50mm (applied loading in the region of 4 x G). However, even at ‘failure’ when the wall ties have buckled and bent the masonry is still held together and does not collapse – suggesting that in the event of an earthquake such a design would reduce the risk of falling masonry.

4.3 Macro- & Micro-scale Testing

Macroscale tests are usually carried out on a one-to-one scale using a shake table, allowing the entire façade and anchorage system to be tested in as-built conditions. The behaviour under load can be accurately investigated, giving a very good representation of the building's performance in the 'real world'. However, due to the large scale of the tests, it is very costly and time-consuming to repeat them in new scenarios.

Microscale testing, on the other hand, focuses on a single component only and analyses its behaviour and performance individually. Microscale testing can be easily carried out in the laboratory or on site, is quick and inexpensive, and can test many different scenarios. However, the results do not take into account interactions with other building components and should therefore be considered carefully.

4. Conclusion

The latest seismic design standards classify façades and façade fixings as non-structural members. Static equivalent horizontal loads acting in the most adverse direction are used in the design of these members.

DOI: https://doi.org/10.5592/CO/2CroCEE.2023.124

Damage to façades caused by earthquakes can range from small hairline cracks to more dangerous partial or total collapse. It is crucial to prevent major damage in order to reduce the risk of injury to people in the vicinity of the building and to aid rescue efforts in the immediate aftermath. Following an earthquake, any damage sustained by the stone façade must be assessed and repaired as soon as possible. Even if the damage is apparently not aesthetically displeasing, the building's seismic resistance may have been compromised and must be addressed as soon as possible. The longer a building remains in a damaged state, the greater the risk of future earthquakes, including danger to human life and increased repair costs. Depending on the use of the masonry, different repair methods are available.

Seismic strengthening of existing buildings can reduce the risk to human life by taking action before damage occurs, or at least reduce repair work after an earthquake. By combining components such as stainless steel helical bars, resin, grout and sleeves, a suitable seismic reinforcement system can be constructed and installed quickly and with minimal disruption.

When assessing the seismic performance of façade fixings, the interaction of all components in the system should be considered. Elements such as the façade fixings, the façade itself and the structural frame must all be included in the assessment to ensure that the load-bearing capacity and ductility meet the requirements. Physical testing is a valuable way of determining the actual performance of an element or system, whereas theoretical calculations can only give a partial picture. Tests can be carried out to local standards if required, and specifications can be modified to suit specific project conditions.

Testing can be carried out at different scales, depending on the space, time and cost limitations applied; macroscale testing, carried out at 1:1, can give a very accurate representation of overall load-bearing performance, but is very time-consuming and costly. Microscale tests tend to be much easier and cheaper to carry out, but focus only on isolated components and may miss important system interactions. Mesoscale testing is a compromise between the two. A facade test area of approximately 1 m2 is used to keep costs low, but it is still possible to analyse the interactions between different elements.

Tests carried out at the meso-scale have been used to show the success of retrofitted façade fixings in limiting deflection of brickwork when subjected to cyclical horizontal loading. Even when taken to ‘failure’ with large plastic deformations, the façade fixings were able to provide sufficient integrity to the test wall to prevent any collapse of the masonry.

References

[1] BS EN 845-1 (2016) Specification for ancillary components for masonry - Part 1: Wall ties, tension straps, hangers and brackets, British Standards Institution, UK.

[2] BS EN 1990 (2005) Eurocode: Basis of structural design, British Standards Institution, UK.

[3] BS EN 1998-1 (2013) Eurocode 8: Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings, British Standards Institution, UK.

[4] “Seismic performance of twisted steel bars used as wall ties and as remedial wall stitching: 2010/2011 Canterbury Earthquakes”, Commissioned report, New Zealand.

[5] ETAG 001, Annex E (2013) Metal Anchors for Use in Concrete, Annex E: Assessment of Metal Anchors under Seismic Action, European Organization for Technical Approvals, Belgium.

[6] Roik, M., Piesker, C. (2017) “A concept for fixing “heavy” façades in seismic zones”, Proceedings of 16th World Conference on Earthquake Engineering, Santiago de Chile, Chile.

[7] Roik, M., Piesker, C. (2019) “Streamlining the Test Methods for Seismic Verification of Façade Anchors”, Fourth International Workshop on the Seismic Performance of Non-structural Elements (SPONSE), Pavia, Italy.

[8] Simundic, G. (2011) “Helifix wall ties testing”, Individual Study, University of Newcastle, NSW, Australia.