Experimental Pull-Out Test Program of Wall-to-Diaphragm Adhesive Connections and Observations from 2010/2011 Canterbury Earthquakes

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ABSTRACT: The connections between walls of unreinforced masonry (URM) buildings and flexible timber diaphragms are critical building components that must perform adequately before desirable earthquake response of URM buildings may be achieved. Field observations made during the initial reconnaissance and the subsequent damage surveys of clay brick URM buildings following the 2010/2011 Canterbury, New Zealand earthquakes revealed numerous cases where anchor connections joining masonry walls or parapets with roof or floor diaphragms appeared to have failed prematurely. These observations were more frequent for adhesive anchor connections than for through-bolt connections (i.e. anchorages having plates on the exterior façade of the masonry walls). Subsequently, an in-field test program was undertaken in an attempt to evaluate the performance of adhesive anchor connections between unreinforced clay brick URM walls and roof or floor diaphragm. The study consisted of a total of almost 400 anchor tests conducted in eleven existing URM buildings located in Christchurch, Whanganui and Auckland. Specific objectives of the study included the identification of failure modes of adhesive anchors in existing URM walls and the influence of the following variables on anchor load-displacement response: adhesive type, strength of the masonry materials (brick and mortar), anchor embedment depth, anchor rod diameter, overburden level, anchor rod type, quality of installation and the use of metal mesh sleeve. In addition, the comparative performance of bent anchors (installed at an angle of minimum 22.5^{o} to the perpendicular projection from the wall surface) and anchors positioned horizontally was investigated. Observations on the performance of wall-to-diaphragm connections in the 2010/2011 Canterbury earthquakes, a snapshot of the performed experimental program and the test results and a preliminary proposed pull-out capacity of adhesive anchors are presented herein.

1 INTRODUCTION

The connections between flexible timber diaphragms and the walls of unreinforced masonry (URM) buildings are critical building components that must perform adequately before desirable earthquake response of URM buildings may be achieved. These connections typically consist of steel anchors installed either at the time of construction or post construction. The diaphragm-to-wall connections are typically considered as tension and/or shear force resisting anchor connections. Tension anchors are designed to prevent out-of-plane wall failure and transfer out-of-plane induced lateral loads into the diaphragms. Shear anchors are designed to transfer forces from the diaphragm and out-of-plane walls into the walls resisting in-plane forces. Through-bolt connections (i.e. anchorages having plates on the exterior façade of the masonry walls) and adhesive anchors are the two most common anchor types in use (FEMA 2006). In addition to wall-to-diaphragm connections, similar anchorage systems are also used for parapet bracing and veneer restraint. Field observations made following the 2010/2011 Canterbury, New Zealand earthquakes revealed numerous cases where tension anchor connections joining masonry walls or parapets with roof or floor diaphragms appeared to have failed prematurely. Subsequently, an in-field test program was undertaken in an attempt to evaluate the performance of adhesive anchor connections between roof or floor diaphragm and clay brick URM walls. The test program consisted of almost 400 test anchors being installed in eleven existing URM buildings that are located in Christchurch, Whanganui and the Auckland region and was conducted in order to obtain accurate data on the pull-out capacity (POC) of adhesive type anchors in existing clay brick URM walls.

Anchoring rods that are bonded to the substrate material using non-shrink grouts or chemical adhesive are referred to as adhesive anchors herein. Most adhesive materials that are in use are described as a two-component pre-packaged chemical setting adhesive (referred to hereafter as epoxy) that are mixed together prior to installation. Non-shrink cementitious grouts are another form of adhesive that is commonly used for anchoring steel rods. Grout is more cost effective in comparison to epoxy yet it is not commonly used in New Zealand as an adhesive for anchorages installed in URM walls mainly due to the absence of a standardised reliable installation method in order to utilise this material outside of controlled conditions. Furthermore, there appears to be limited research conducted on the POC of anchors installed in URM walls using grout as adhesive (Gigla 2012). Horizontal (straight) and 22.5^{o} to the horizontal (bent) are the two common installation orientations of adhesive anchors that are recommended in FEMA (FEMA 2006). Horizontally installed anchors are specified for only resisting shear forces and bent anchors are indicated to be more suitable for resisting tension forces due to the engagement of multiple courses of masonry (FEMA 2006). Recommendations made in the NZSEE Guidelines on Assessment and Improvement of the Structural Performance of Buildings in Earthquakes suggest the use of design POC for adhesive anchors in tension as 11 kN (NZSEE 2006), whereas in FEMA (FEMA 2006) the POC for adhesive anchors in tension is suggested as 5.3 kN (bent anchor with 330 mm embedment at the allowable stress design force level).

2 PERFORMANCE OF ANCHOR CONNECTIONS DURING THE 2010/2011 CANTERBURY EARTHQUAKES

Field observations made during the initial reconnaissance and the subsequent damage surveys of clay brick URM buildings following the 2010/2011 Canterbury earthquakes revealed numerous cases where anchor connections joining masonry walls or parapets with roof or floor diaphragms appeared to have failed prematurely (Dizhur et al. 2010; Dizhur et al. 2011). These observations were more frequent for the case of adhesive anchors than for the case of through-bolt connections (i.e. anchorages having plates on the exterior façade of the masonry walls). Punching shear failure of the through-bolt connections was a common failure type observed, and was mainly attributable to failure along weak mortar joints. In Figure 1(a) it is shown that the successful performance of anchors does not necessarily prevent out-of-plane wall failure, as the potential for one or two way spanning out-of-plane wall bending failure is not necessarily precluded. The out-of-plane failure of URM walls was in many cases also attributed to the low shear strength of masonry (see Figure 1(b)), wide anchorage spacing and/or insufficient embedment depth of anchors (see Figure 1(c)). In some cases, the reasons for the adhesive anchor failures were apparent. As shown in Figure 1(f), the top anchor shown is an example of anchor pull-out due to insufficient embedment length, while the remaining anchors shown in Figure 1(e and f) indicate a lack of bonding between the anchor and the substrate material. In other cases, the reasons for such failures were not evident from visual observation. The construction quality of adhesive type anchorages was commonly observed to be poor, due to insufficient anchorage depths and poor workmanship, as shown in Figure 1(c-f).

Most of the adhesive anchor systems that were observed used threaded steel rods ranging from 10 mm to 20 mm in diameter. These rods were typically embedded into the URM walls to a depth equal to the wall thickness less 25 - 50 mm. Although less common, deformed reinforcement bars with a diameter of up to 20 mm and with one threaded end were also observed to be used in adhesive anchor systems.

Although at times hard to identify, there appears to be little evidence suggesting the use of bent anchors (having an angle of minimum 22.5° to the perpendicular projection from the wall surface), and the majority of observed anchors were positioned horizontally (Dizhur et al. 2011).

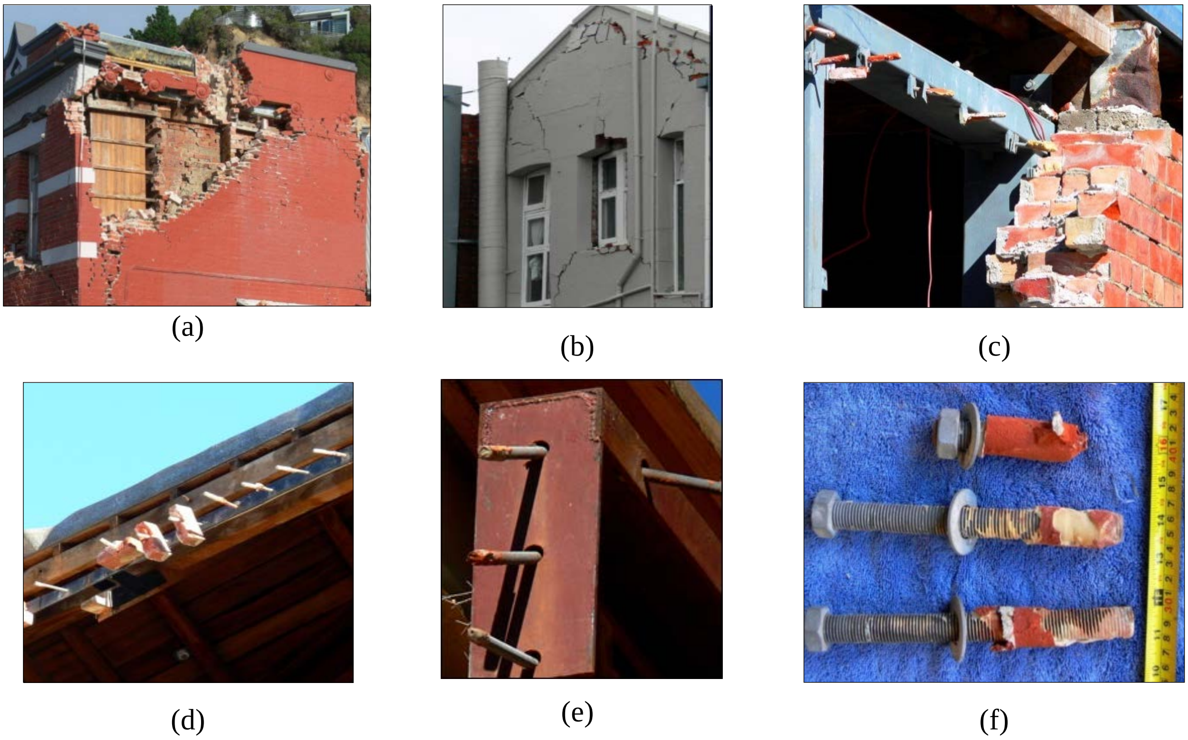


Figure 1: Wall-to-diaphragm anchors: a) Row of successful wall-to-diaphragm anchors, with wall failure beneath; b) Failure of the gable due to low shear strength of masonry, despite sufficient anchorage; c) Insufficient embedment depth of adhesive anchors; d) Large number of adhesive anchors unsuccessful at preventing out-of-plane collapse of URM wall; e) Insufficient adhesive used only at the tip of anchors; f) Recovered adhesive anchors that performed inadequately.

3 IN-FIELD TESTING OF ADHESIVE ANCHOR CONNECTIONS IN EXISTING CLAY BRICK MASONRY WALLS

An in-field test program was undertaken in an attempt to evaluate the performance of adhesive anchor connections. A team of researchers was deployed, first to Christchurch and later to Whanganui to conduct the in-field tests in order to obtain accurate data on the POC of adhesive type anchors in existing clay brick URM walls. Testing was also conducted in selective buildings located in the Auckland region.

3.1 *Brief description of tested buildings*

The in-field test program in Christchurch was conducted on three buildings located in the Wards Brewery Historic Area, nestled between Fitzgerald Avenue, Kilmore Street and Chester Street East. The buildings included the original malt house (c. 1881, Figure 2(a)), a malt lot storage building (c. 1910, Figure 2(b)), and one of the barrel storage buildings (c. 1920). All three buildings suffered significant damage during the 2010/2011 earthquakes, and at the time of the in-field test program they were scheduled for demolition.

A building that is part of the former Phoenix Wine and Spirits complex located in the Whanganui central business district was made available for the purposes of research and was subsequently utilised for pull-out testing of adhesive anchor connections. The test building had large unaltered URM walls that were originally constructed in 1913 and was considered representative of many URM buildings constructed in the same era. The testing of adhesive anchors in the former Phoenix Wine and Spirits building (see Figure 2(c)) was conducted in two stages. In addition, epoxy anchor connections were installed and tested in seven buildings located in the Auckland region (see Figure 2(d) for an example) and a further building located in Christchurch.

(a) (b) (c) (d)

Figure 2: Selected examples of tested buildings: a) Wards Brewery Building 2, Christchurch; b) Wards Brewery Building 3, Christchurch; c) Phoenix Wine and Spirits Building, Whangnui; d) Mt. Albert, Auckland.

3.2 *Test program*

A total of 170 adhesive anchors were installed and tested in three buildings located in Christchurch and a total of 93 adhesive anchors were installed and tested during stage one of testing in the former Phoenix Wine and Spirits building, Whanganui. Approximately 50 additional adhesive anchors were installed and tested during the second stage of testing in Whanganui. Furthermore, 86 adhesive anchor pull-out tests were performed in seven URM buildings located in the Auckland region. The main aim of the testing program reported herein was to apply a direct tension load to the test anchors and record the force exerted on the anchor and the displacement relative to the wall, with the peak resistance force that the adhesive anchors were able to achieve being of particular significance.

3.3 *Test parameters*

Specific objectives of the in-field test program presented herein included the identification of failure modes of adhesive anchor connections in existing URM walls and the influence of the following variables on anchor load-displacement response: adhesive type (epoxy or grout), strength of the masonry materials (brick and mortar), embedment depth, anchor diameter, the overburden, anchor rod type, and quality of installation. In addition, the comparative performance of bent anchors and anchors positioned horizontally (see Figure 3(a)) was investigated. Table 1 lists the range of values for the selected variables. Metal mesh sleeves, which are placed in the drilled out hole before inserting the anchor rod and adhesive, were also used as a test parameter. Typically, for each combination of test parameters, at least 5 anchors were installed and tested.

Table 1: Range of values for test parameters in adhesive anchor tests (see also Figure 3(a))

Parameter	**Range of Values**
Adhesive type	6 epoxies and 2 cementitious grout
Masonry material strength	Weak to intermediate strength
Anchor embedment depth, e	100-400 (mm)
Anchor diameter, d	12, 16, 20 (mm)
Rod type	Threaded metric, threaded rebar
Metal mesh sleeve	Yes, No
Orientation of anchor	Horizontal and 22.5^{o} to perpendicular projection from wall
Overburden weight	4 different heights

3.4 *Installation procedure*

Standard steel metric threaded rods and threaded reinforcing steel bars were cut onsite to the required length according to the anchor embedment depth. Six epoxy adhesive products from different manufacturers were used and were injected using a proprietary dispensing gun for each product. Cementitious grouts from two different manufacturers were used and were mixed onsite.

To achieve an effective bond between the anchor rod, the adhesive, and the encompassing masonry, installation manufacturer's specified procedure (when available) was strictly followed. As per manufacturer's specifications, epoxy anchors were installed in holes having a diameter of the anchor rod plus 2 mm. The hole diameter that was adopted for grout anchors was the result of a compromise between the manufacturers' recommendations and the equipment that was available at the time of installation. The holes for grout anchors were drilled at 22 mm and 24 mm diameter for 12 mm and 16 mm anchor rods respectively. It was ensured that the holes were thoroughly cleaned and that sufficient volume of adhesive was injected.

Installation of anchors with grout as adhesive proved to be difficult, mainly due to the rapid absorption rates of clay bricks. The non-saturated surrounding clay brick rapidly absorbed the moisture from the grout causing it to harden prematurely, making it difficult to fully insert an anchor rod. Three installation techniques of anchors with grout as adhesive were attempted. The first attempted installation method involved mixing grout with a high water content ratio and applying the grout onto the anchor rod as it was being slowly inserted with rotational motion into a water saturated hole. The second method involved a network consisting of perforated hoses that were inserted into the drilled holes for approximately one hour of continuous water spraying prior to injecting grout and inserting anchor rods. The third method involved insertion of an anchor rod and a small tube simultaneously. The tube was then slowly withdrawn from the hole as the grout was injected. Due to time frame restrictions on-site, grout anchors were tested 72 hours following installation. All anchors installed using epoxy products were allowed to cure prior to testing for at least 24 hours as specified. A typical testing arrangement is illustrated in Figure 3(b and c).

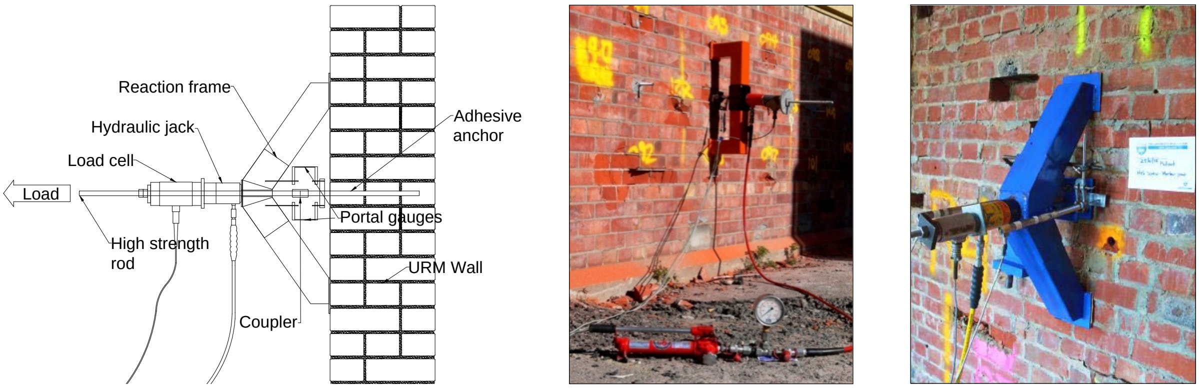
(a) (b) (c)

Figure 3: Testing arrangement of adhesive anchors: a) Test parameters; b) Wards Brewery Building 2, Christchurch; c) Phoenix Wine and Spirits Building, Whaganui.

3.5 *Test apparatus*

Adhesive anchors were installed and tested using the test set-up and loading procedure used to satisfy the New Zealand (NZS1170.0 2002) and US (ASTM A488 (ASTM 2003)) standards. The tests employed a steel load frame, a manual hydraulic pump, a loading hydraulic actuator, a load cell, and two displacement transducers (see Figure 4) to evaluate the effectiveness of various adhesive anchor connections. Applied tensile force and the corresponding displacement/slip were recorded using a digital data acquisition system. Peak pressure was also recorded manually, and photographs (before and after testing) were taken of all the tested anchors.

The reaction frames used in the adhesive anchor study were designed with sufficient capacity in order to prevent yielding and excessive deflection of the frame when subjected to expected magnitude of load. This increased capacity and stiffness of the reaction frame ensured that the tension loads remained parallel to the anchor being tested and that the displacement of the anchor rod could be measured using the reaction frame as a reference point. In order to avoid interference with an assumed 45^{o} failure cone (NZSEE 2006), the reaction frame was designed with a total clear span of 600 mm based on a maximum embedment depth of 300 mm (Figure 4(b and c)).



(a) (b) (c)

Figure 4: Test setup for adhesive anchor pull-out tests: a) Schematic view of the typical pull-out test apparatus; b) Typical test set-up used for pull-out anchor testing used in Christchurch; c) Typical test set-up used for pull-out anchor testing used in Whanganui.

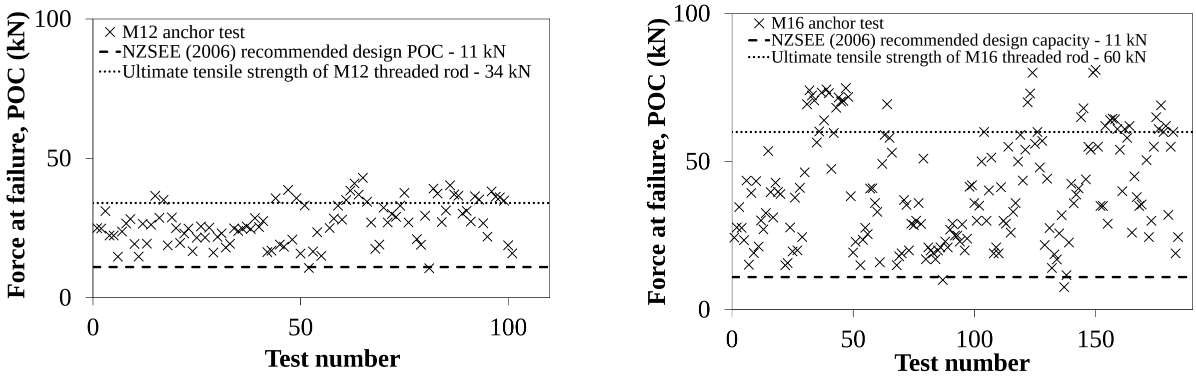
3.6 *Material properties*

The masonry properties of the buildings tested as part of experimental study reported here cover a wide range of clay brick and mortar properties and are considered comparable to the majority of URM buildings located in New Zealand (Lumantarna et al. 2013). A representative number of bed joint shear tests were conducted in each tested building, and brick units and mortar samples were extracted and later tested in laboratory compression. Testing was conducted in the form of irregular mortar compression tests, half brick compression tests and bed joint shear tests in accordance with Ingham et al. (2011). Due to paper length limitations, detailed building material data is not included herein.

The majority of the anchor rods that were used in the adhesive anchor connection experimental program were of DIN 975 grade 4.6 class steel with experimentally determined average ultimate tensile yield strength of 296 MPa. A small number of anchors were cut from DIN 975 grade 8.8 (high-strength) steel. The average experimentally determined ultimate tensile yield strength of 12 mm and 16 mm diameter threaded reinforcing steel bars was 597 MPa and 696 MPa respectively. Three day compressive strength of 37.8 MPa was achieved for grout blocks prepared and tested in accordance with ASTM C1019.

4 RESULTS

The overall POC results are shown in Figure 5(a) and (b) and the plots are separated into M12 and M16 rods respectively. The majority (96%) of the adhesive anchors exceeded the NZSEE (NZSEE 2006) recommended design capacity and all tested anchors exceeded FEMA (FEMA 2006) recommended design capacity (excluding grout anchors in Building 3, Christchurch). The performance of adhesive anchors below the NZSEE (NZSEE 2006) recommended design capacity was attributed to the epoxy anchors being installed in excessively damp masonry, an excessively high water content of cementitious grout and insufficient volume of adhesive. In approximately 1% of the cases excessively low POC could not be attributed to any known parameter and was considered as an outlier and removed from the dataset.



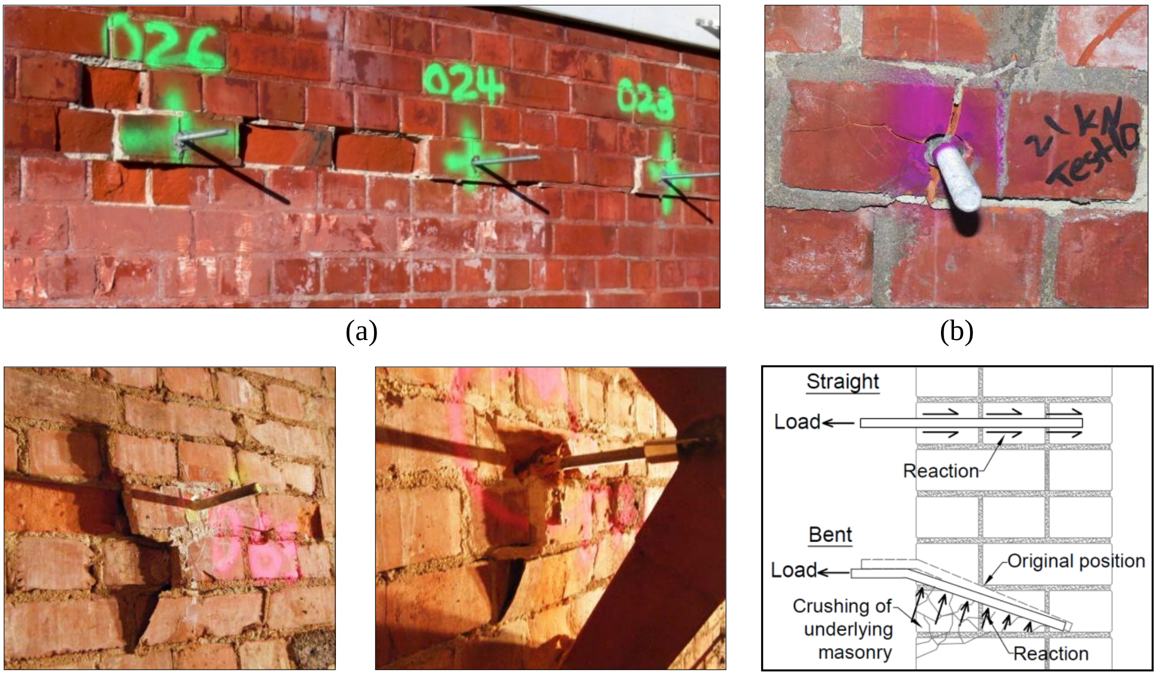
(a) (b)

Figure 5: Overall threaded rod adhesive anchor test results: a) Force at failure for M12 adhesive anchors in overall data set; b) Force at failure for M16 adhesive anchors in overall data set.

4.1 *Failure modes*

No failures of adhesive anchor connections approximating the ideal breakout of masonry, in which rupture occurs in a roughly conical masonry failure surface, were observed in any of the tests. Failure of the masonry occurred in 91% of the tests. Failure modes included pull-out of the adhesive plug (particularly in weaker brick and mortar and shorter embedment depths), masonry breakout/anchor pull-out (where the leading brick, or part of it, is pulled out with the anchor as shown in Figure 6(a)), failure of the bond between the adhesive and the rod with localised splitting of bricks (Figure 6(b)), and yielding of anchor rods.

Figure 6(c-e) shows the typical failure modes observed for straight and bent anchors. Crushing of the masonry below the bent anchors was typically observed. Tension loading of the bent anchor rod causes the rod to straighten, resulting in bearing of the rod against the underlying masonry and causing crushing. Furthermore, it was observed that the bent anchor lost the bond between the top side of the rod and the surrounding masonry as it moves out of position (see schematic representation in Figure 6(e)).



(c) (d) (e)

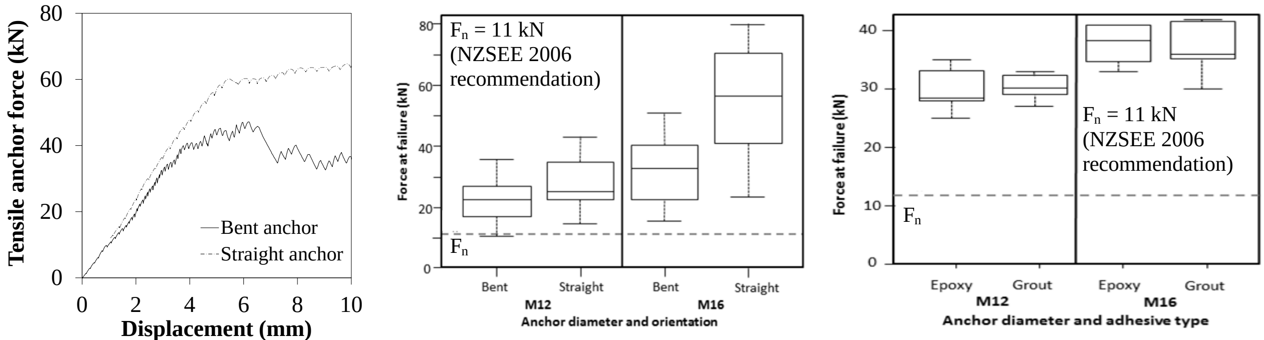
Figure 6: Typical failure modes: a) Typical masonry pull-out type failure observed; b) Localised splitting of brick; c) Straight anchors; d) Bent anchors; e) Schematic view of observed failure modes.

4.2 *Parametric study of pull-out capacity*

4.2.1 *Orientation*

Adhesive anchors installed having an angle of minimum 22.5° to the perpendicular projection from the wall surface had a lower POC compared to anchors that were installed horizontally. Straight anchors had a larger force at failure and typically had a larger residual strength, as opposed to bent anchors where following the peak force resistance, the residual strength diminished at a greater rate. Furthermore, straight anchors typically had a higher stiffness than bent anchors as shown by the gradients of the linear portions of the force-displacement response (see Figure 7(a)). A typical force-displacement response curve for M16 epoxy anchors installed with 300 mm embedment in the Phoenix Wine and Spirits Building, Whanganui is shown in Figure 7(a).

From Figure 7(b) it is evident that for the 300 mm embedment depth, the average force at failure for straight M16 anchors was higher than for the bent M16 anchors. The large sample spread was attributed to the varying nature of URM material properties.



(a) (b) (c)

Figure 7: a) Typical force-displacement response for epoxy anchors with 300 mm embedment depth; b) Force at failure for bent and straight epoxy anchors embedded to 300 mm; c) Force to failure for epoxy and grout straight anchors embedded to 200 mm.

4.2.2 *Adhesive type and metal mesh sleeve*

When installed using the second and third methods (see Installation procedure section) the anchors with grout as the adhesive had a similar average POC compared to the POC of the anchors with epoxy as the adhesive, for all combinations of parameters tested (see Figure 7(c)). The comparable POC between grout and epoxy adhesive material is applicable to threaded metric anchor rods as well as to threaded reinforcing steel bars. However, it was found that installing anchors using grout as the adhesive was a more difficult exercise than when using epoxy due to the extra effort involved in drilling a larger hole. Moreover, grout requires mixing onsite and correct water content is essential in order to achieve full strength capacity of the grout. With acquired experience in the installation technique, the grout anchors provide a comparable POC results to the more expensive epoxy based systems.

The effect of incorporating a metal mesh sleeve as part of the epoxy anchor installation was investigated in Building 1, Christchurch. Based on the attained experimental results it was concluded that the presence of a metal mesh sleeve appears to have no beneficial effect on the POC of adhesive anchors.

4.2.3 *Embedment depth, rod diameter and rod type*

The POC of an adhesive anchor increased with increasing embedment depth. Nevertheless, the results show that when anchor embedment was 100 mm (fixed to a single brick) the POC was in excess of current capacity recommendations (FEMA 2006; NZSEE 2006). Adhesive anchors embedded to 100 mm have larger average bond stress compared to anchors embedded at a greater depth (see Figure 8(a)). Figure 8(b) shows the POC of adhesive anchors with increasing rod diameter, with the maximum attained POC being for 16 mm anchor rod diameter. The reduction in POC for anchor rods having a 20 mm diameter was attributed to the clay brick propensity to split (see Figure 6(e)) at a lower POC as a result of a larger diameter hole and subsequent reduction of the brick cross-sectional area. It is therefore evident that the use of anchor rods having a large rod diameter is detrimental to the POC and hence is counterproductive.

Based on the similarities in experimentally attained POC it was concluded that both the metric threaded rods and the threaded reinforcing steel bars performed satisfactorily and are suitable to be used as anchoring rods with adhesive systems. However, there is a cost advantage in using threaded reinforcing steel bars as anchor rods in comparison to the use of the metric threaded rods.

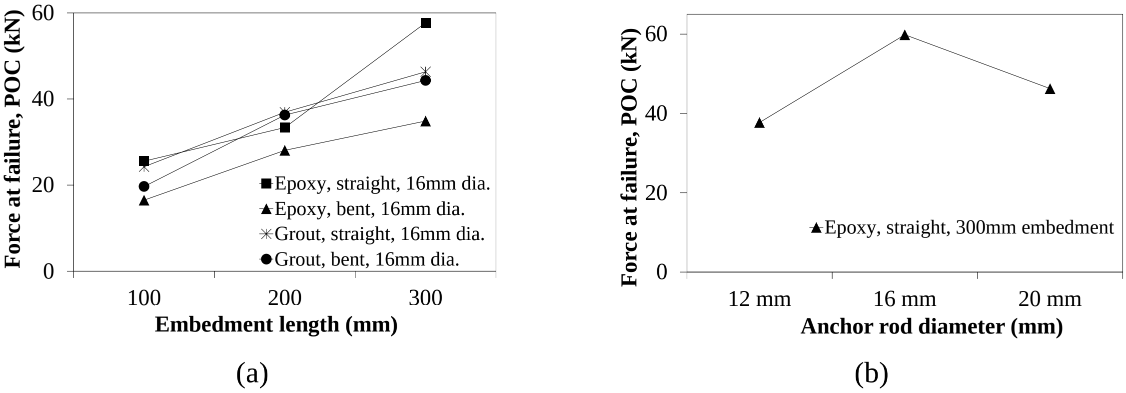


Figure 8: a) Effect of embedment length on the average POC; b) Effect of anchor rod diameter on the average POC (epoxy anchors).

4.2.4 *Overburden level, vertical accelerations and dynamic loading*

Overburden weight is of significance for adhesive anchors used in applications such as for parapet restraints, where low levels of overburden are present. The adhesive anchor test results acquired as part of the research presented herein show a clear reduction in the POC for anchors installed at upper building levels compared to the ground and basement levels of a building (see Figure 9(a)).

Where high earthquake induced vertical ground accelerations are experienced (i.e. as observed during the 2010/2011 Canterbury earthquakes) the axial overburden level is greatly reduced. In some cases, where the vertical ground acceleration is greater than gravity, the wall can be put into tension and the effect of friction on the bed joint shear strength is reduced to zero. Adhesive anchors subjected to tensile loads applied dynamically with varying level of overburden are yet to be investigated.

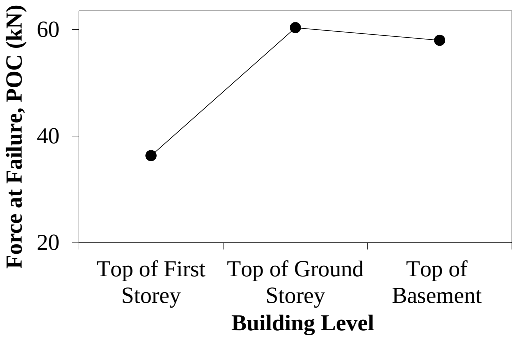
4.2.5 *URM material properties*

The material properties for the seven buildings in the data set were plotted against the average bond stress for all straight epoxy anchor connections. Of the three material properties considered (brick and mortar compressive strength and bed joint shear strength), the bed joint shear strength had the strongest linear correlation with the average bond stress of tested adhesive anchors, with an R^2 value of 0.341. The second strongest linear correlation was attained between the average bond stress and the mortar compressive strength with an R^2 value of 0.252. A weak linear correlation was identified between brick compressive strength and the average bond stress with an R^2 value of 0.064. These correlations, although weak, indicate that anchors installed in stronger mortar achieve a higher bond stress and therefore a higher POC and confirm site observations. The weak correlations are partially attributed to the high level of variability of the constituent material properties of masonry that were observed even within the same building.

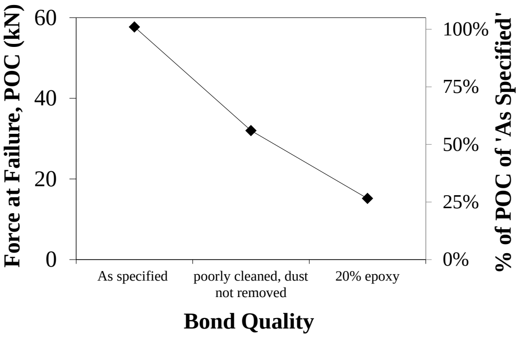
4.2.6 *Installation quality*

The correct installation of adhesive anchors is important in order for an anchor to perform to full capacity. Installation into the horizontal mortar joints resulted in marginally greater average POC in comparison to adhesive anchors positioned in the middle of a brick. The marginal increase in average POC was attributed to the increased resistance to splitting provided by the full height of the bricks located directly above and below the adhesive anchor.

To address the poor quality of installation of adhesive anchors observed during the reconnaissance following the 2010/2011 Canterbury earthquakes, three sets of anchors where installed and tested with varying quality of installation. From Figure 9(b) it can be observed that the average POC dramatically decreased with decreasing quality level of installation. It was concluded that with poorly cleaned holes, such as dust from hole drilling being only lightly brushed (no air blowing), the average POC was reduced by 55% when compared to the capacity of epoxy anchors that were installed per manufacture's specifications. A reduction down to 26% of the average POC of the epoxy anchors that were installed per manufacture's specifications was observed for anchors that had approximately 20% of the hole filled with epoxy.



(a)



(b)

Figure 9: a) Effect of overburden on the average POC, Building 7 Auckland, M16 epoxy anchors with 200 mm embedment; b) Effect of bond quality on the average POC, M16 epoxy anchors with 300 mm embedment.

5 PROPOSED PRELIMINARY POC CAPACITY

Based on the results attained from the adhesive anchor connections experimental program, the POC capacity of adhesive anchors embedded into URM walls is preliminary proposed in Eq**.** 1. The proposed equation was empirically derived based on observations of the encountered failure modes, and the numerical relationship between POC and anchor orientation, embedment depth, anchor rod diameter and masonry material properties. The proposed equation was applied to 240 of the relevant test results contained within the database, with 93% of the predicted POC being below the experimentally obtained results (see Figure 10). The overall average factor of safety was obtained as 2.29. It is recommended that the design engineer reduces the POC obtained using the proposed POC equation (Eq. 1) when ultra-weak masonry material properties are encountered and/or adhesive anchors are being designed to restrain the top of URM walls or parapets where overburden loads are particularly low.

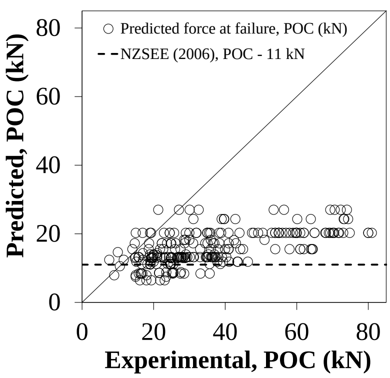


Figure 10: Experimental versus predicted POC for 240 tested adhesive anchors

$$POC = K_o \times K_e \times K_\phi \times K_m \times e \times n_{tp} \qquad \text{(Eq. 1)}$$

K_o is the anchor rod orientation factor, which can be taken as 1.0 for all horizontally orientated adhesive anchors, 0.9 for bent 16 mm diameter anchor rods and 0.75 for bent 12 mm diameter anchor rods. K_e is the embedment length factor which can be taken as 1.3 for anchor rods embedded to 100 mm, 1.15 for anchor rods embedded to 200 mm and 1.0 for anchor rods embedded to 300 mm or greater. K_ϕ is the anchor rod diameter factor which can be taken as 1.0 for 16 mm diameter anchor rods and 0.9 for 12 mm diameter anchor rods. e is the anchor rod embedment length in millimetres. K_m is the masonry material reduction factor which can be taken as 0.65 if $c \leq 0.25$ MPa (where c is the masonry bed-joint shear strength determined on-site under in-situ axial compression) and in all other cases K_m is taken as 1.0. n_{tp} is the force per millimetre of anchor rod embedment length and can be taken as 67.5 N/mm. Where necessary, linear interpolation between provided values should be used.

For example, an adhesive anchor installed as a wall-to-diaphragm connection on a ground floor of a URM building with a rod diameter of 16 mm horizontally embedded to 300 mm into strong masonry substrate will have a characteristic tensile POC of $1.0 \times 1.0 \times 1.0 \times 1.0 \times 300 \times 67.5 = 20.3$ kN. An adhesive anchor installed as a wall-to-diaphragm connection on a ground floor of a URM building with a rod diameter of 12 mm embedded at an angle of 22.5^o to the perpendicular projection from the wall surface to 200 mm into strong masonry substrate will have a characteristic tensile POC of $0.75 \times 1.15 \times 0.9 \times 1.0 \times 200 \times 67.5 = 10.5$ kN.

6 CONCLUSIONS

- Field observations made following the 2010/2011 Canterbury earthquakes revealed numerous cases where tension anchor connections joining masonry walls or parapets with roof or floor diaphragms appeared to have failed prematurely;
- An in-field test program was undertaken in an attempt to evaluate the performance of adhesive anchor connections between roof or floor diaphragm and clay brick URM walls with almost 400 test anchors being installed in eleven existing URM buildings;
- No failures of adhesive anchor connections approximating the ideal breakout of masonry, in which rupture occurs in a roughly conical masonry failure surface, were observed in any of the tests;
- Cementitious grout was identified as a suitable anchor adhesive. However, a detailed installation procedure needs to be developed;
- Metric threaded steel rods and threaded reinforcing bars perform satisfactorily when used as anchor rods in adhesive anchoring systems;
- Adhesive anchors oriented horizontally were found to have a higher POC and stiffness compared to the bent anchor equivalent;
- While the POC of an anchor increases with increasing embedment depth, the average bond stress at failure decreases with increasing embedment depth;
- 16 mm anchor rod diameter is considered to be the optimum rod size. Varying the rod diameter will decrease the POC of adhesive anchors;
- A low overburden weight was identified to have significant detrimental effect on the POC of adhesive anchors;
- As expected, adhesive anchors installed in strong masonry achieved a higher bond stress and therefore achieved a higher POC of the adhesive anchor connections;
- Installing adhesive anchors as per the manufacturer's instructions is critical to achieving an adequate POC;
- A proposed preliminary method to calculate POC for adhesive anchors installed in URM walls was presented and was based on on-site observations of encountered failure modes, and the numerical relationship between POC and the anchor orientation, embedment depth and anchor rod diameter;
- Further research is required in order to investigate the effects of adhesive anchors loaded dynamically and the effects of vertical accelerations on the POC of the adhesive anchors.

7 ACKNOWLEDGEMENTS

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