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# Experimental Testing of Seismically Retrofitted URM Parapets using Vertical Screw Reinforcing

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## ABSTRACT

Seismic retrofit of unreinforced masonry (URM) parapets can provide enhanced seismic performance and collapse prevention. While widely adopted retrofit methods (e.g. braced systems) have been shown to be effective, they often require tradeoffs in the form of high installation and fabrication costs, risk of water ingress due to roof penetration, and disturbance of historical aesthetic. This paper presents a simple and cost-effective retrofit system consisting of high-strength mechanical fasteners that are drilled and mechanically anchored through the top of the parapet to an effective embedment below the diaphragm-to-wall connection. To demonstrate the effectiveness of this retrofit system, a series of monotonic and cyclic tests were undertaken on as-built and retrofitted URM double-wythe parapet specimens. The results showed that retrofitted parapets had an up to 25x increase in out-of-plane strength. The ultimate strength and failure mode of retrofitted specimens was influenced by wall aspect ratio, diaphragm connection strength, anchor spacing, and effective anchor embedment.

## KEYWORDS

Unreinforced masonry (URM) parapet, mechanical anchors, out-of-plane strength, seismic strengthening, retrofit.

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## INTRODUCTION

Existing masonry buildings constructed with unreinforced masonry (URM) are highly vulnerable to seismic events due to their lack of reinforcement. Post earthquake reconnaissance of the 2010 Christchurch earthquake, highlighted that a large proportion of URM buildings were damaged due to out-of-plane actions, while structures with seismic retrofits performed well in comparison [1]. URM parapets are highly susceptible to seismic events due to their insufficient lateral support and exposure to significant accelerations [2]. Their propensity to collapse has been well-documented in numerous major earthquakes, including the 1971 San Fernando, the 1989 Loma Prieta, and the 2011 Christchurch earthquake [3]. Inventory studies of URM parapets in New Zealand and the West coast of the United States have also highlighted the high seismic vulnerability of such free-standing elements and the dangers of parapet collapse to pedestrians, occupants, and adjacent structures [4, 5]. These events underscored the urgent need for retrofitting URM buildings. Therefore, addressing the vulnerabilities of URM parapets, alongside retrofitting primary structural components, is essential for effective seismic risk reduction.

### Parapet retrofit practices

The most common practice for URM parapet repair is to continuously brace the URM parapet at the desired elevation and provide bracing or back-stays that provide a connection to the roof framing or roof-level diaphragm such that the parapet is effectively connected to the interior structural system as depicted in Figure 1 [6, 7]. Other methods for retrofit have also been developed, using materials such as epoxied FRP sheathing, shotcrete, or cementitious matrix grid [8, 9], among others.

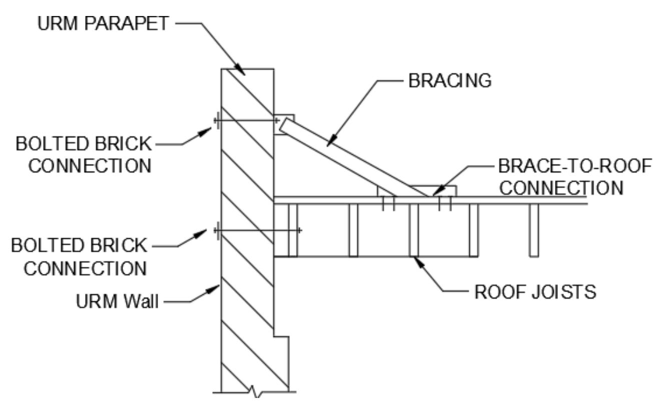


**Figure 1: Parapet wall specimen with bracing system anchored to roof (reproduced from FEMA 547 [10]).**

Although effective, retrofit techniques for URM parapets face practical challenges. Back-stays, for example, require invasive structural modifications that can compromise the architectural integrity of heritage buildings, disrupt waterproofing membranes, and reduce usable roof space. They may also be cost-prohibitive for budget-limited projects. Similarly, FRP retrofits, while viable, can be expensive, alter building facades, and are sensitive to environmental factors like heat and humidity. Surface treatments like shotcrete add weight, increasing seismic demands on the structure.

This paper describes a retrofit solution using vertical screw anchors that is cost-effective, minimally invasive, and reversible to the architecture of URM. Vertical screw anchors were drilled into parapet specimens to provide a mechanical connection between the parapet and the URM wall below, mitigating the risk of out-of-plane collapse during seismically induced shaking. These screw anchors are installed without epoxy, allowing for future removal by unscrewing the anchors. With these anchors, methods for reinforced masonry can be adapted to design URM parapets with vertical screw reinforcement.

To validate this design approach, eleven parapet specimens were constructed with heritage brick and lime mortar to represent traditional URM construction. The specimens provided an experimental data set to assess the retrofitted strength against the unretrofitted rocking strength. A simple design approach for design with mechanical anchors is proposed based on the findings of this study. Test results showed that the screw reinforcing provides substantial increases in lateral strength and increases the lateral deformation capacity.

## EXPERIMENTAL CAMPAIGN

### Test Specimens

Eleven parapet specimens with different geometric configurations were constructed using vintage brick and lime-based mortar mix. Each parapet was approximately 1000 mm wide one or two-wythe walls. The main test variables included parapet height, diaphragm elevation, mechanical anchor quantity, length and spacing, the presence or absence of a strongback, and the loading protocol. Parapet heights ranged from 400 mm to 1010 mm, resulting in height-to-thickness ratios between 1.7 and 9.2, and with varying diaphragm elevations based on parapet height. The mechanical anchor spacing was adjusted to assess the effect of the anchor reinforcement ratio on lateral strength. Wooden strongbacks were attached to the interior face of the wall to evaluate their impact on the failure mechanism. Four evenly spaced ($s_d$) diaphragm anchors were used to connect the parapet specimen to the diaphragm as seen in Figure 2a. Key details, including parapet wall dimensions, are summarized in Table 1, Table 2 and Table 3 with the specimen configuration and loading scheme shown in Figure 2a and 2b.

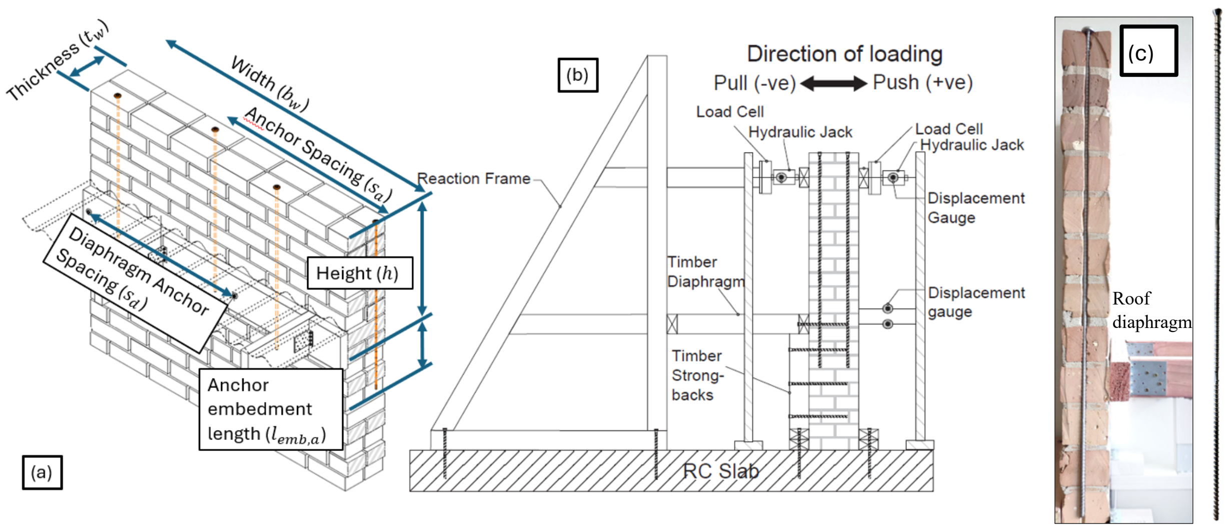


**Figure 2: (a) Specimen geometry, (b) testing configuration and (c) cross-section of single-wythe wall showing a vertically installed mechanical anchor (typ.) embedded in heritage brick parapet (Photos supplied by PYTHON Fasteners USA)**

Each test is identified by two naming formats: the Test ID format and the Parapet Name format. These separate formats help classify the parapet tests, as multiple tests were performed on a single parapet. The Test ID format is G*x*-*y*, where Gx stands for the mortar group (see Table 4) and *y* represents a specific test number (e.g. G2-4 → Group 2 mortar, 4th test in this group). The Parapet Name format is #P*xn*-S*y*, where #P indicates a parapet, *x* indicates the mortar strength level (L = Low, M = Medium, H = High), *n* corresponds to a physical parapet specimen, and S*y* corresponds to the sequence of tests performed on that specific parapet. Decimal values trailing *n* indicate a change in testing configuration using the same parapet.

**Table 1: Group 2 (0.4 MPa mortar) specimen overview and geometry**

| Test ID | Parapet Name | Wythes | Height ($h$) [mm] | Num. Anchors | Anchor Spacing $s_a$[mm] | Anchor Embedment ($l_{emb,a}$) [mm] | Loading Protocol | Strong-backs |
|---|---|---|---|---|---|---|---|---|
| G1-1 | #PL1-S2 | 2 | 500 | 2 | 480 | 360 | M-Push | No |
| G1-2 | #PL1-S3 | 2 | 500 | 2 | 480 | 360 | M-Push | Yes |

**Table 2: Group 1 (4.6 MPa mortar) specimen overview and geometry**

| Test ID | Parapet Name | Wythes | Height ($h$) [mm] | Num. Anchors | Anchor Spacing $s_a$[mm] | Anchor Embedment ($l_{emb,a}$) [mm] | Loading Protocol | Strong-backs |
|---|---|---|---|---|---|---|---|---|
| G2-1 | #PM1-S2 | 1 | 500 | 2 | 480 | 360 | M-Push | No |
| G2-2 | #PM1-S3 | 1 | 500 | 2 | 480 | 360 | M-Push | Yes |
| G2-3 | #PM2-S2 | 2 | 500 | 2 | 480 | 360 | M-Push | No |
| G2-4 | #PM2-S3 | 2 | 500 | 2 | 480 | 360 | M-Push | Yes |
| G2-5 | #PM3-S2 | 1 | 1010 | 2 | 470 | 25** | M-Push | -- |
| G2-6 | #PM3-S3 | 1 | 1010 | 2 | 470 | 80** | M-Push | -- |

**Anchor installed into concrete slab

**Table 3: Group 3 (9.7 MPa mortar) specimen overview and geometry**

| Test ID | Parapet Name | Wythes | Height ( $h$ ) [mm] | Num. Anchors | Anchor Spacing $s_a$[mm] | Anchor Embedment ($l_{emb,a}$) [mm] | Loading Protocol | Strong-backs |
|---|---|---|---|---|---|---|---|---|
| G3-1 | #PH1-S4 | 2 | 650 | 2 | 500 | 350 | M-Push* | Yes |
| G3-2 | #PH2-S2 | 2 | 650 | 3 | 250 | 350 | M-Push* | Yes |
| G3-3 | #PH2.1-S1 | 2 | 650 | 1 | -- | 350 | Cyclic | Yes |
| G3-4 | #PH2.2-S2 | 2 | 400 | 1 | -- | 600 | Cyclic | Yes |
| G3-5 | #PH3-S2 | 2 | 650 | 2 | 500 | 350 | Cyclic | Yes |
| G3-6 | #PH3.1-S1 | 2 | 400 | 2 | 500 | 600 | Cyclic | Yes |
| G3-7a | #PH4-S2 | 2 | 650 | 2 | 700 | 350 | Cyclic | No |
| G3-7b | #PH4-S3 | 2 | 650 | 2 | 700 | 350 | Cyclic | Yes |
| G3-8 | #PH4.1-S1 | 2 | 400 | 2 | 700 | 600 | Cyclic | Yes |
| G3-9a | #PH5-S2 | 2 | 900 | 2 | 500 | 300 | Cyclic | No |
| G3-9b | #PH5-S3 | 2 | 900 | 2 | 500 | 300 | Cyclic | Yes |
| G3-10 | #PH5.1-S1 | 2 | 650 | 2 | 500 | 550 | Cyclic | Yes |
| G3-11a | #PH6-S2 | 2 | 400 | 2 | 500 | 600 | Cyclic | No |
| G3-11b | #PH6-S3 | 2 | 400 | 2 | 500 | 600 | Cyclic | Yes |
| G3-12 | #PH7-S2 | 2 | 650 | 1 | -- | 80** | Cyclic | -- |
| G3-13 | #PH7-S3 | 2 | 650 | 2 | 500 | 80** | Cyclic | -- |

*M-Push: Monotonic Load Protocol, loading in the "push" direction.

** Anchor installed into concrete

### Material Properties

The mechanical anchors used in this experimental program are prototype high-strength steel anchors ($\phi$ = 8 mm, $A_s$ = 50 mm²). As prototypes, the anchor strength was limited to 24 kN for the presented experimental testing. The anchors feature a spiral thread along their circumference to create a mechanical interlocking connection with the brick when installed into a pre-drilled hole (See Figure 2c).

Reclaimed vintage bricks extracted from old masonry structures were used in the experiments to ensure the material was representative of URM parapets being retrofitted. The bricks had a tested compressive strength of 17.8 MPa, with a coefficient of variation (CoV) of 0.4. The bricks were laid with lime mortar of three different compressive strengths ($f_{cm}$). Mortar samples were extracted from the joints no sooner than 3 months from construction and tested in compression (see Table 4) following guidelines from [11] and [12].

**Table 4: Masonry material properties**

| Masonry Material | Compressive strength [MPa] | CoV [-] |
|---|---|---|
| Vintage bricks | 17.80 | 0.40 |
| Group 1 (G1) mortar | 0.40 | -- |
| Group 2 (G2) mortar | 4.60 | 0.18 |
| Group 3 (G3) mortar | 9.70 | 0.30 |

### Experimental Set-Up

As shown in Figure 2b, the parapet specimens were loaded in the out-of-plane direction at the top of the wall. Either monotonic or cyclic quasi-static load protocols were used to assess the differences in strength in each direction. There were two possible directions for monotonic loading, either away from the diaphragm, herein referred to as "push," or towards the diaphragm, herein referred to as "pull".

**Figure 4: Typical testing and boundary conditions for specimens.**

The applied load is restrained by a simulated diaphragm connection at the desired elevation, which provided an effective lateral restraint without restraining rotation. The diaphragm connection is secured to the parapet wall with timber planks and anchored with mechanical anchors passing through all brick wythes. The base of the parapet wall was restrained against lateral movement using timber members that are anchored to the concrete slab. Both the loading jack and the simulated diaphragm connection were mounted on a timber A-frame structure that resisted the force couple of the jack and diaphragm. Uplift resistance against the moment induced by this force couple was provided by anchoring the A-frame structure to the concrete slab. In this loading setup, where the diaphragm and parapet base are restrained from lateral movement and rotate freely, the applied loads are analogous to a three-point bending setup with a cantilever, resulting in a determinate structural system where diaphragm and support reactions could be calculated using the specimen geometry. Images highlighting the testing conditions are depicted in Figure 4.

To install the vertical screw anchors, a pilot hole was first drilled with the corresponding hole diameter of 8 mm. Due to the long length of the screws a vacuum hose was necessary to remove accumulated dust at the bottom of the pilot hole. Special care was taken to drill vertically along profiles that avoided vertical mortar joints. Once the pilot hole was drilled, the mechanical anchor was then installed. Specimens were first tested in as-built condition without the vertical mechanical anchors and later retrofitted with mechanical anchors to observe the increase in lateral strength.

## TEST RESULTS

### Lab Condition vs. Field Condition

To replicate the weathered and cracked conditions commonly observed in existing URM parapets, the lab-built parapet specimens were loaded either monotonically or cyclically to induce horizontal cracks in the mortar layer above the diaphragm. This was performed by loading the specimen (without vertical anchors) and with timber strong-backs, which strengthened the portion of the specimen below the diaphragm connection and ensured that flexural mortar cracking occurred at the diaphragm elevation. The rocking strength of the URM parapet was then measured and taken as the as-built strength. In existing URM buildings it is common practice to assume that nearly all URM parapets are fully cracked due to the generally long service life over which they are subjected to weather deterioration and minor seismic events. Additionally, some waterproofing details result in the membrane (DPC) or roof flashing being inserted between brick layers, resulting in an effectively unbonded surface inside a mortar layer. The cracking strength of each parapet specimen is recorded in Table 5 below. It is noted that strength comparisons are taken with respect to effective lateral strengths (rocking strengths).

**Table 5: Cracking and rocking strengths for as-built parapet specimens.**

| Parapet Name | Height above diaphragm - (mm) | Lateral load at cracking & cracking moment - (kN \| kNm) | Effective lateral strength (i.e., rocking strength) - (kN \| kNm) |
|---|---|---|---|
| PL1-S1 | 500 | 0.6 \| 0.3 | 0.6 \| 0.3 |
| PM1-S1 | 500 | -- | 0.2 \| 0.1 |
| PM2-S1 | 500 | 4.2 \| 2.1 | 0.7 \| 0.4 |
| PM3-S1 | 1010 | -- | -- |
| PH1-S1 | 650 | 4.4 \| 2.9 | 0.6 \| 0.3 |
| PH2-S1 | 650 | 5.5 \| 3.6 | -- |
| PH3-S1 | 650 | 6.7 \| 4.4 | 1.3 \| 0.9 |
| PH4-S1 | 650 | 7.8 \| 5.1 | 0.7 \| 0.4 |
| PH5-S1 | 900 | 2.9 \| 2.7 | 0.6 \| 0.5 |
| PH6-S1 | 400 | 9.6 \| 3.8 | 0.8 \| 0.3 |
| PH7-S1 | 650 | 1.0 \| 0.6 | 1.0 \| 0.6 |

### Parapets Test Observations

A total of 11 URM parapet specimens were included as part of this experimental data set. The load-displacement relations are provided below in Figure 5, Figure 6 and Figure 7. The data is also summarized in Table 6. Results generally show that loading in the positive direction ("push") was stiffer and typically resulted in failure in that direction.

**Table 6: Summary of strengthened parapet test results.**

| Test ID | Parapet Name | Peak Lateral Load ($P$) [kN] / | [g] | Improvement ratio: anchors / as-built | Improvement ratio: strongbacks / as-built | Peak Displacement ($\Delta$) [mm] | Loading Direction at Peak | Failure Mechanism |
|---|---|---|---|---|---|---|---|---|
| G1-1 | #PL1-S2 | 2.9 | 1.7 | 4.8 | -- | 30.7 | Push | FMC |
| G1-2 | #PL1-S3 | 3.9 | 2.3 | -- | 6.5 | 15.9 | Push | PO |
| G2-1 | #PM1-S2 | 1.6 | 1.9 | 8.0 | -- | 9.2 | Pull | FMC |
| G2-2 | #PM1-S3 | 3.9 | 4.5 | -- | 19.5 | 20.8 | Pull | PO/BC |
| G2-3 | #PM2-S2 | 3.2 | 1.9 | 4.6 | -- | 22.8 | Push | FMC |
| G2-4 | #PM2-S3 | 8.3 | 4.8 | -- | 11.9 | 26.6 | Push | PO/BC |
| G2-5 | #PM3-S2 | 0.8 | 1.0 | 8.8 | -- | 95.0 | Push | FMC |
| G2-6 | #PM3-S3 | 1.7 | 0.5 | 4.3 | -- | 57.0 | Push | FMC |
| G3-1 | #PH1-S4 | 9.9 | 4.4 | -- | 16.5 | 36.2 | Push | PO |
| G3-2 | #PH2-S2 | 15.4 | 6.8 | -- | 21.9 | 71.5 | Push | PO |
| G3-3 | #PH2.1-S1 | 5.1 | 2.3 | -- | 7.3 | 40.3 | Push | PO |
| G3-4 | #PH2.2-S2 | 10.9 | 7.9 | -- | -- | 39.9 | Push | PO |
| G3-5 | #PH3-S2 | 12.1 | 5.4 | -- | 9.2 | 78.1 | Push | PO |
| G3-6 | #PH3.1-S1 | 17.6 | 12.7 | -- | -- | 44.4 | Push | AF |
| G3-7a | #PH4-S2 | 5.4 | 2.4 | 7.7 | -- | 37.8 | Push | FMC |
| G3-7b | #PH4-S3 | 10.1 | 4.5 | -- | 14.4 | 51.0 | Push | PO |
| G3-8 | #PH4.1-S1 | 11.9 | 8.6 | -- | -- | 36.7 | Push | PO/BC |
| G3-9a | #PH5-S2 | 5.6 | 1.8 | 9.3 | -- | 74.5 | Push | FMC |
| G3-9b | #PH5-S3 | 5.5 | 1.8 | -- | 9.2 | 61.8 | Push | PO |
| G3-10 | #PH5.1-S1 | 11.2 | 5.0 | -- | -- | 67.7 | Push | PO |
| G3-11a | #PH6-S2 | 16.3 | 11.8 | 20.4 | -- | 50.8 | Pull | PO/FMC |
| G3-11b | #PH6-S3 | 8.3 | 6.0 | -- | 10.4 | 30.0 | Push | PO |
| G3-12 | #PH7-S2 | 12.4 | 5.5 | -- | 12.4 | 10.5 | Pull | AF |
| G3-13 | #PH7-S3 | 21.5 | 9.6 | -- | 21.5 | 17.9 | Pull | CB |

*CB: Concrete breakout (not to be considered in design equations); FMC: Flexural mortar cracking below anchors; BC: Brick crushing; PO: Pullout; AF: Anchor failure;

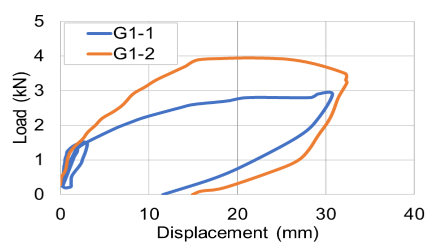


**Figure 5: Load displacement relations for G1 tests.**

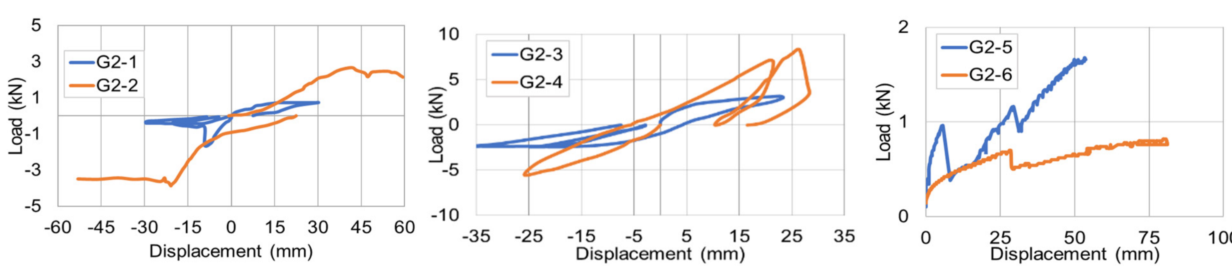


**Figure 6: Load displacement relations for G2 tests.**

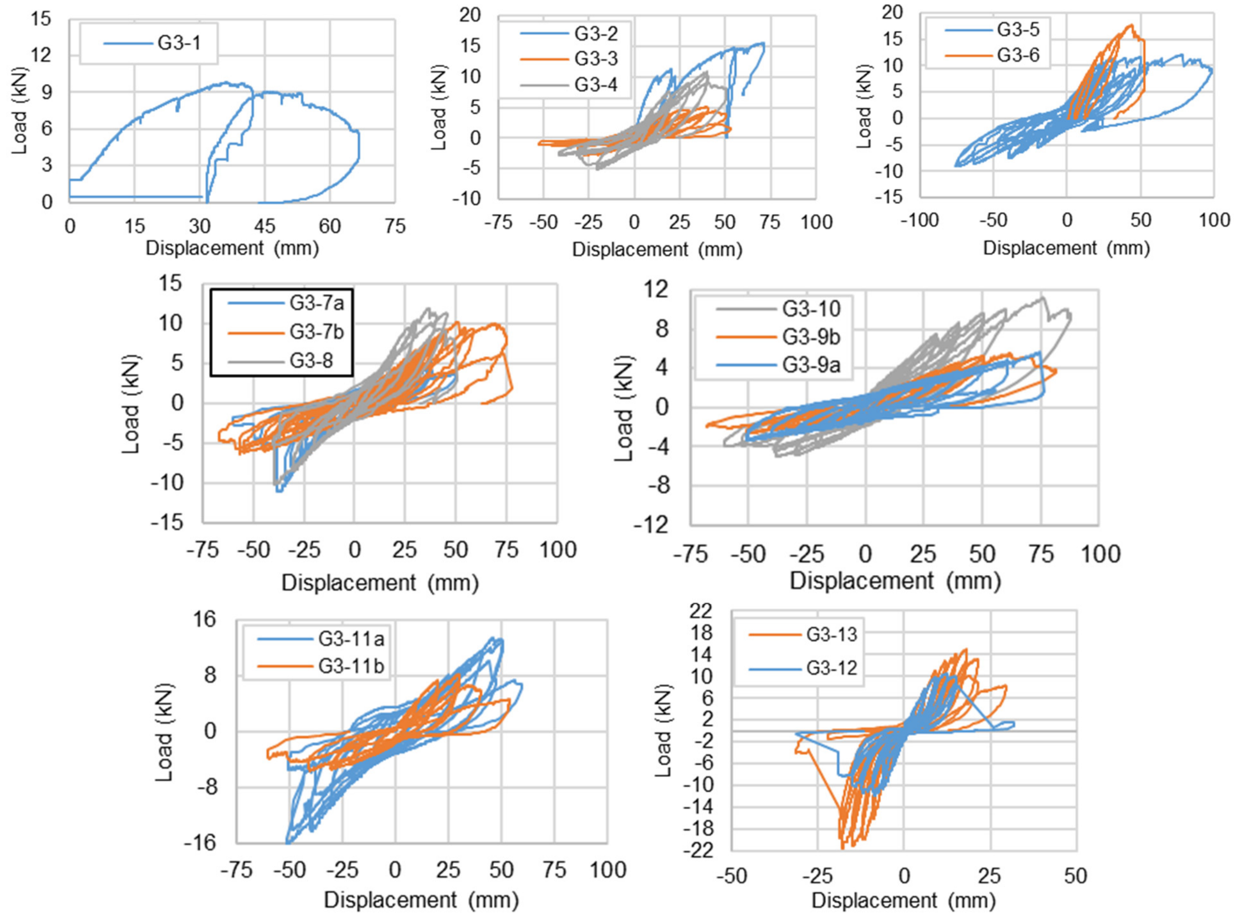


**Figure 7: Load displacement relations for G3 tests.**

In general four failure mechanisms were observed in the parapet specimens (see Figure 8 for examples).

a) Flexure mortar cracking below the anchor's embedded depth.
b) Yielding and subsequent failure of the anchor due to flexural tension.
c) Brick crushing due to flexural compression.
d) Splitting pullout of the anchor from the brick, initiating from below the diaphragm.

Since most URM parapets in service are assumed to be cracked, the increase in strength due to mechanical fixings was evaluated relative to the rocking capacity of the specimens. Initial tests were conducted to determine the cracked and rocking strength of the parapets, after which mechanical anchors were installed to assess their impact on lateral strength. In some cases, specimens were first tested with anchors but without strongbacks to study their influence on failure mechanisms. They were then re-tested with strongbacks installed to evaluate the resulting recovery in lateral load capacity.

Figure 9 provides a high-level summary of the strength increase achieved with vertical screw anchors when comparing the lateral strength of parapet walls with anchors to its strength without anchors. The results are further categorized by specimens with and without strongbacks to assess their impact on lateral load capacity. The data show that mechanical anchors significantly enhance the lateral capacity of parapet walls, regardless of the presence of strongbacks. Across all specimens, the lateral load capacity increased by at least 5 times and up to 25 times compared to the rocking strength.

(a) Flexural mortar cracking below anchors

(b) Splitting/pullout of anchors above diaphragm

(c) Crushing of brick and mortar in the push phase of the cycle

**Figure 8: Observed failure modes.**

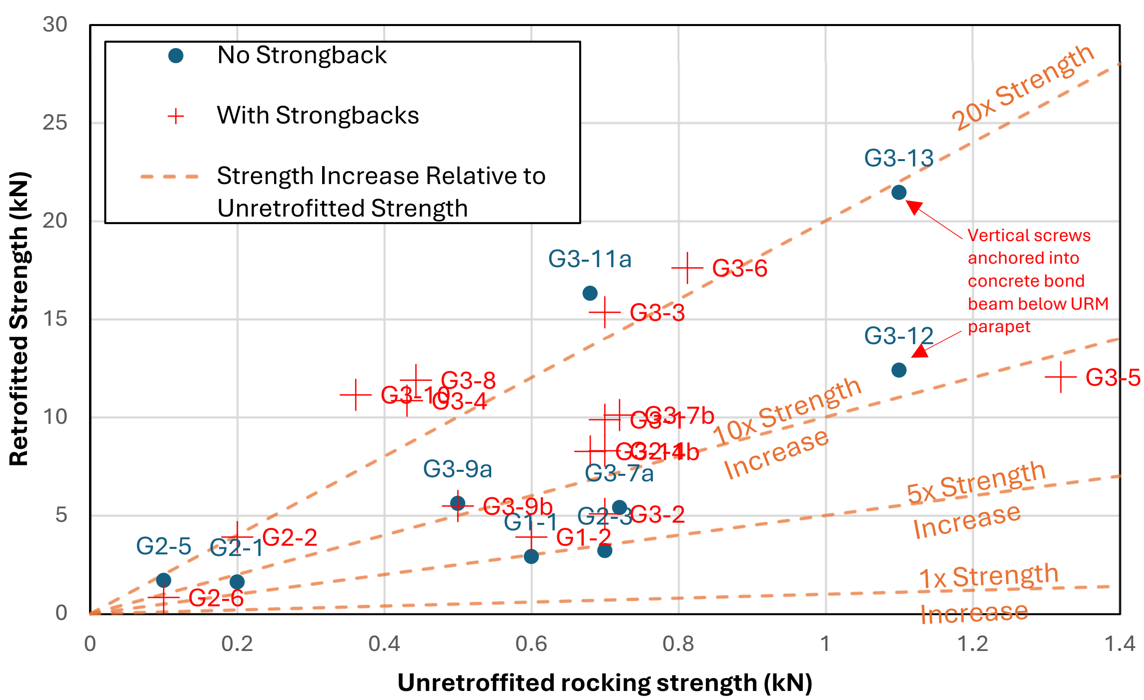


**Figure 9: Increase in lateral load capacity due to anchor with and without strongbacks. Annotated numbers indicate TestID.**

## CONCLUSIONS

This paper describes an experimental campaign where mechanical screws were post-installed to act as vertical reinforcement in URM parapet walls. This method is an alternative to traditional back-stay methods for retrofitting vulnerable parapets. Experimental tests with mechanical anchors showed that parapets can be securely connected to the roof diaphragm, significantly reducing the collapse risks while avoiding the drawbacks of back-stays, namely impacts on heritage architecture, roof usability, and waterproofing integrity. Eleven parapet specimens were tested under different configurations to assess lateral load capacity, failure modes, and key design parameters, with the following key findings:

- Mechanical anchors significantly improved the lateral load capacity beyond the rocking strength by up to an average of 9.1 times.
- A greater number of screws installed was found to increase the effectiveness of the retrofit. The effect can be seen in parapets G3-3 (1 screws), G3-1 (2 screws) and G3-2 (3 screws), that having the same properties the strength, the improvement ratio in relation to the as-built capacity was 7.3, 16.5 and 21.9 times stronger respectively.
- Strongbacks improved the lateral load capacity of the parapet by an average of 13.6 times. Strongbacks could potentially be substituted by any strengthening technique that avoids cracking below the anchors allowing the loads to transfer into the diaphragms (eg. shotcrete).
- Three critical failure modes were identified; (1) horizontal flexure cracking in URM sections below the anchor, (2) masonry crushing and compression failure, and (3) anchor pullout.
- A summary of results is shown in Figure 10 and Table 7, where the experimental design capacity is reported in terms of the equivalent component acceleration by dividing the lateral capacity by the mass of the parapet above the diaphragm.

**Table 7: Summary of results**

| Parapet height above diaphragm (mm) | Parapet thickness (mm) (# of wythe) | As-built rocking capacity (g) | Capacity when retrofitted with 2 vertical screws (g) | Capacity when retrofitted with 2 vertical screws and strong-backs capacity (g) |
|---|---|---|---|---|
| 1010 (80 mm into concrete) | 110 (1) | 0.11 | 0.96 (G2) | ** |
| 500 | 110 (1) | 0.23 | 1.85 (G2) | 4.52 (G2) |
| 400 | 230 (2) | 0.58 | 11.80 (G3) | 6.01 (G3) |
| 500 | 230 (2) | 0.38 | 1.68 (G1) / 1.85 (G2) | 2.26 (G1) / 4.81 (G2) |
| 650 | 230 (2) | 0.39 | 2.41 (G3) | 4.77 (G3) |
| 900 | 230 (2) | 0.19 | 1.80 (G3) | 1.77 (G3) |

* Anchor spacing min: 2 anchors per meter

** Anchor installed into concrete

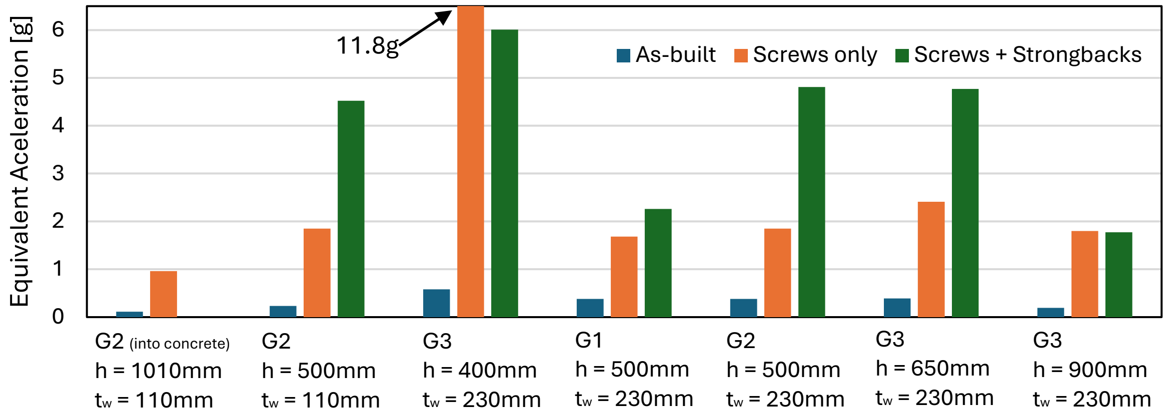


**Figure 10: Summary of results**

## ACKNOWLEDGEMENTS

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