Seismic Capacity of Heritage Masonry Buildings in Australia – A Progress Report

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Abstract

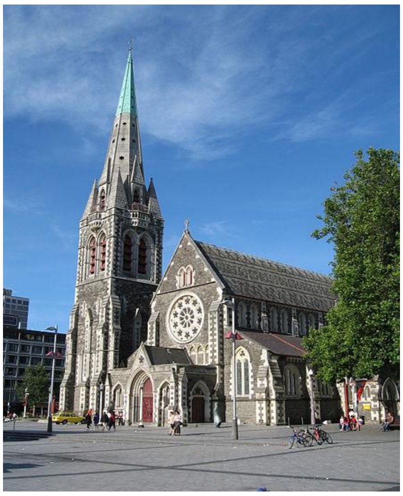
A three-year ARC funded research project featuring a collaboration between researchers at the University of Auckland in New Zealand and the Universities of Newcastle and Adelaide in Australia is now into its second year with some promising early results and exciting experimental tests to come in the near future. The overall aim of this project is to develop a practical method of analysis that accounts for the material properties used in heritage stone and clay brick masonry buildings that are most relevant to seismic response as well as the limited ductility inherent in the non-typical structural layouts used in these buildings. In order to achieve this, the first phase of the project characterised typical Australian heritage masonry buildings in terms of their most influential features for buildings listed within heritage registers in NSW and Adelaide. In the currently ongoing phase, experimental tests are being conducted to characterise the cyclic in-plane shear behaviour of clay brick and stone masonry walls as well as masonry portals with tall arched openings. This paper will summarise the project, its results to date, and the work to come.

Keywords: Heritage; unreinforced masonry; clay brick masonry; stone masonry; earthquake response

INTRODUCTION

The tragic lessons from the Christchurch earthquakes, where the two main cathedrals in the city (Anglican Cathedral and Catholic Basilica – refer to Figure 1) were both heavily damaged by the M6.3 February 2011 earthquake (Ingham & Griffith 2011, Griffith et al. 2013; Moon et al. 2014; Brower, 2017) highlight that Australia also has a substantial stock of seismically-vulnerable URM buildings that are likely to lead to catastrophic economic damage and loss of human life should a major earthquake strike any of our densely populated areas where these buildings reside such as the State capitals. Whilst these reasons already form compelling motivation in order to better understand the expected performance of URM buildings in an earthquake—so that strengthening can be applied where required—the preservation of these old buildings is further motivated by the fact that many of them which were constructed between the early 1800s to the early-to-mid 1900s represent an irreplaceable part of Australia's cultural and historical heritage.

Unfortunately there is presently a considerable lack of available technical guidance with regard to both in-plane and out-of-plane response when it comes to the assessment of heritage URM buildings. Therefore, investigation of this class of URM buildings in the Australian context is the objective of this project.



Anglican Cathedral, before Feb 2011

Anglican Cathedral, after Feb 2011 earthquake.

Catholic Basilica before Feb 2011

Catholic Basilica after Feb 2011

Figure 1: Damaged churches in Christchurch after February 2011 earthquake.

PROJECT AIMS

The overall goal of this project is to develop a practical engineering design approach to the seismic assessment of heritage URM buildings in Australia. To achieve this, the project will tackle following specific aims in a collaborative effort between the Universities of Adelaide, Newcastle and Auckland:

1) Australian URM construction will be characterised with respect to common building geometries, construction details and material properties by performing regional scale surveys; and
2) Laboratory tests will be conducted to characterise the cyclic in-plane shear behaviour of URM walls. The tests will consider wall geometries and material properties representative of documented Australian heritage constructions (output of Aim 1). Accompanying material characterisation tests under tension, shear and compression will be used to obtain material inputs for the non-linear static modelling in Aim 4 and the cyclic in-plane wall tests will be used for validation and calibration of these models.

CHARACTERISATION OF BUILDING TYPOLOGIES

An exercise to characterise Australian heritage URM buildings with respect to characteristics likely to influence their seismic performance was undertaken by concurrent studies at the Universities of Adelaide and Newcastle with each part of the project team targeting buildings listed on registers maintained by the respective regional heritage authorities.

Buildings in New South Wales

The Newcastle-based study (Howlader et al, 2016) collected data for all (total of 1275) buildings listed within the State of NSW heritage register, of which 1017 are load bearing URM buildings. Collection of data was undertaken by means of a desktop study that involved extracting information directly from the online accessible register with further supplementation using Google street view where necessary. This was made possible by the fact that the NSW heritage register statements typically provide information regarding the structural form of the building, including the wall material (brick or stone, type of stone), and roof type in terms of both shape and material. The scope of data collected is summarised in the second column of Table 1.

Table 1: Scope of information collected in the respective studies and method of collection: "HR" = directly from heritage register; "IL" = inspection on location; "ID" = desktop inspection by satellite/Google Earth 3D building imagery; "O" = other, e.g. books, online sources.

Information	Newcastle study	Adelaide study
Basic information: building name, address, GPS coordinates	HR	HR
Current building usage	HR	HR
Building type classification [1]	HR	HR, IL
Year of construction	HR	HR, IL, O
Number of storeys	HR, ID	IL, ID
Building footprint area	-	HR (GIS model)
Gravity load-bearing system: load-bearing walls; load-bearing frame (concrete or steel)	HR, ID	IL

URM wall material	HR	IL[2]
URM unit pattern (e.g. square cut stone, rubble stone)	-	IL[2]
Building connectivity (isolated or connected to other buildings, e.g. row buildings)	-	IL, ID
Regularity – plan and/or vertical	-	-
Roof shape and material	HR	-
Presence of vulnerable features (e.g. parapets, gable ends, chimneys)	-	IL, ID
Past alterations or strengthening	-	IL, HR

1. In the Adelaide survey each building was classified into three broad categories: 1) house (residential), 2) generic building - those not fitting into the other categories; 3) special – encompassing large open hall type buildings such as churches, institutional halls, factories, or arcades.
2. Documented separately for street-facing façade walls and remaining side and back walls.

Buildings in Adelaide CBD

The South Australian heritage register database provides (comparatively to NSW) only limited information relating to the structural aspects of the buildings (n.b. In general, the format of data available in the various Australian States' heritage registers are not consistent as they are each maintained by separate authorities). Therefore, the Adelaide study resorted to street level inspections to collect meaningful information relating to the structural aspects of the buildings, which was accomplished in the northern half of the Adelaide CBD (Figure 2). This meant that the Adelaide study covered fewer buildings (approx. 300), but was able to collect detailed information relating to the masonry material as well as features such as building connectivity, type of gravity load-bearing system (frame or wall only), presence of vulnerable features such as parapets, chimneys and gable end walls, and any noticeable past alterations or strengthening (Table 1).

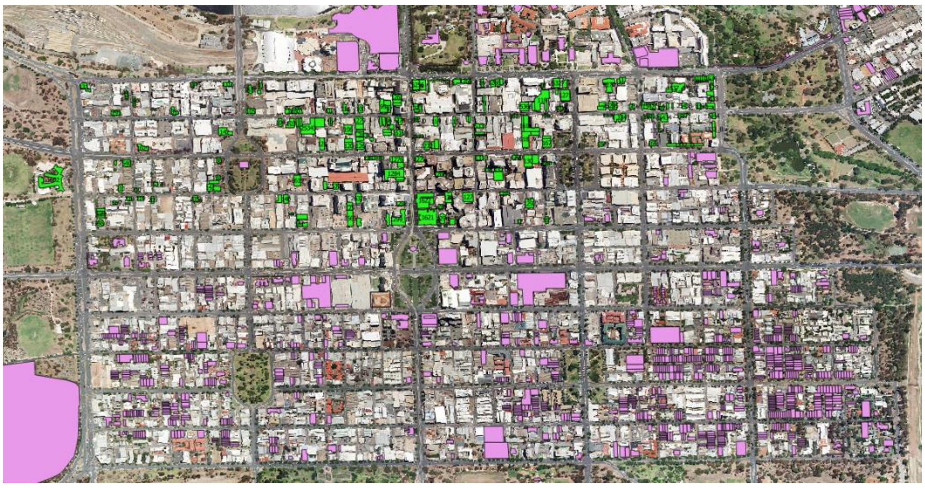


Figure 2: Survey of heritage-listed buildings across Adelaide CBD. Surveyed buildings shown in green.

Main Findings

The following findings were made on the basis of the buildings encountered across the two studies.

- The majority of buildings were constructed between 1800 to 1940 in NSW and between 1840 to 1940 in Adelaide.
- The majority of buildings range from one to three storeys with typical examples shown Figure 3. Taller buildings with four or more storeys, as well as high profile monumental buildings such as churches and institutional halls also have a strong presence in terms of their significance but are less frequent in terms of total building count.
- In terms of URM wall material, both studies encompassed buildings that were brick-only (60% in NSW, 40% in Adelaide), stone-only (20% in NSW, 30% in Adelaide) or a combination of brick and stone (15% in NSW, 30% in Adelaide) (n.b. the remaining 5% in NSW are unknown).
- The range and regional prevalence of alternate materials is a result of the fact that early construction depended heavily on locally quarried stone or the availability of clay bricks. The predominant building stone across NSW is sandstone, whereas by comparison South Australia exhibits a rather diverse range of building stones such as limestone, sandstone and the so-called ‘bluestone’, an umbrella term used to encompasses various dark stones including shale, schist and gneiss (Young, 1993). Different varieties of building stone can have vastly different compressive and tensile strength (Giaretton et al, 2015) which will therefore influence the in-plane shear capacity of the associated masonry. Further such distinctions are expected in the other Australian states based on the diversity of building stone geology (Spry, 1993).
- Among stone buildings, the quality of the stonework in terms of the regularity of the stone units and interlock between them can heavily influence the seismic in-plane shear resistance of the wall (Vanin et al, 2017). A range of masonry patterns were encountered which varied anywhere between two basic extremes: i) finely-cut, perfectly rectangular blocks typically laid in thin mortar joints and generally providing large degree of overlap between successive courses (referred to as ‘ashlar’), to ii) so-called *random rubble* comprising oblique, misshapen stones typically laid in thick mortar joints in an irregular fashion (refer to Figure 4).
- Many buildings were found to display a hierarchy in terms of street-facing facades being built with higher quality masonry and secondary side and rear walls with lower quality masonry (preference for stone > brick; ashlar pattern > rubble pattern). In terms of out-of-plane failure, failure of street-facing façade walls tend to pose a considerably greater risk to life safety (Ingham and Griffith, 2011) and thus assessment should consider specifically the particular wall typology present. With regard to the global performance of the building, the presence of different masonry types throughout the building means that building response could in many instances be influenced by variations in stiffness, strength and drift capacity of the various walls, and this is something that should be considered in any seismic assessment.

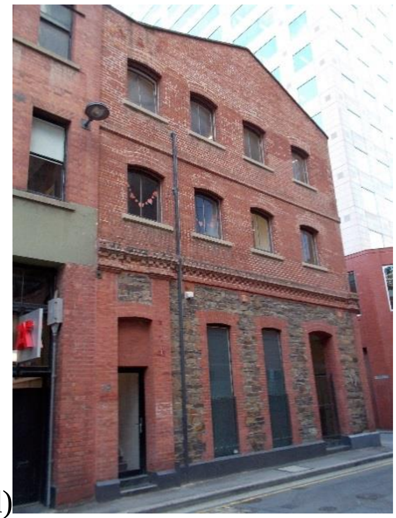
(a) 
(b) 
(c) 
(d) 

Figure 3: Typical heritage buildings encountered in the Adelaide survey.


(a) sandstone ashlar


b) bluestone rubble with brick quoins

Figure 4: Various type of stonework encountered in Adelaide

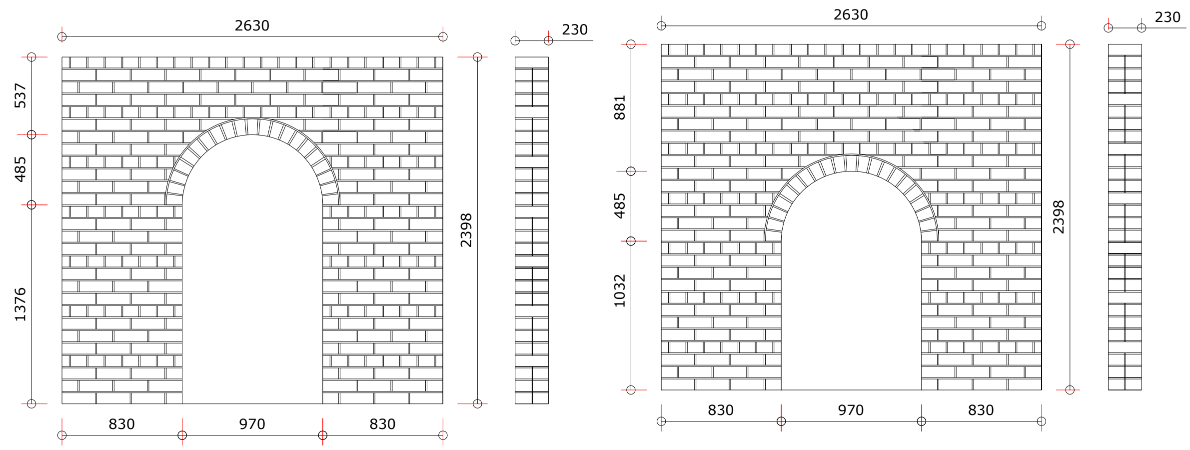
EXPERIMENTAL TESTING

This phase of the project aims to investigate the in-plane behaviour of URM wall typologies that were commonly encountered in the building characterisation discussed in the previous section. The following is an overview of the currently ongoing work.

In-plane shear tests on clay brick arched portals

Geometry and Materials

Testing of eight full-scale semi-circular arched portals under cyclic in-plane pseudo-static loads is underway at The University of Newcastle (Howlader et al, 2018). The geometries of two of the portals are shown in Figure 5, where spandrel depth was varied. The arched geometry is intended to replicate typical wall construction technique observed in heritage clay brick buildings such as those shown in Figure 6. The specimens each have two leaves (230 mm thick) engaged using the 'common' or 'American' bond pattern by placing the header bricks at every fourth course to connect tightly the two leaves of the wall. The specimens were made using dry pressed clay brick units of common available dimensions 230 mm x 110 mm x 76 mm, which prove the closest possible replication of heritage clay brick masonry (typically higher suction) rather than extruded units. Lime rich cement-lime mortar joints having 10 mm thickness was used in the testing program with mix proportions by volume of 1 cement: 2 lime (rock): 9 sand. This mortar falls into the AS3700 'M2' classification (Standard Australia, 2011) which is low in strength and can represent the weather deteriorated mortar of the heritage buildings. The resulting material properties were reported (Howlader et al 2018) to be E_m = 9570 MPa, f_{mt} = 0.25 MPa and f_{mc} = 8.5 MPa for Young's modulus, tension and compression strength, respectively.



(a) Shallow spandrel (b) Deep spandrel

Figure 5: Geometry of arched portal walls to be tested at The University of Newcastle (all dimensions are in mm).

Figure 6: Examples of arched openings encountered in Newcastle.

Test Set-up and Instrumentation

The test setup is shown in Figure 7. The walls were constructed by professional bricklayers with proper supervision. The footing beam consisted of a steel channel (300 PFC) with its web laid flat on the laboratory floor and with a reinforced concrete beam cast between the flanges of the PFC such that the upper surface of the beam is concrete. The footing beam was bolted to the laboratory strong floor. Vertical pre-compression load was applied at the centre of each pier by the vertically aligned hydraulic jack. The vertical load was equally distributed to the centre line of each pier through the spreader beam (200 UC 46.2) and was kept constant during the test. Cyclic lateral displacement (Figure 8) was applied at the mid-length of the loading beam (200 UC 46.2). Extra beam sections over the pier length were located below the spreader beam to uniformly distribute the vertical load from the jack to the top of the pier throughout its length. To allow the vertical deformation of the spandrel, a composite steel section (300 PFC with top plate and stiffener) was placed in between the loading beam and the wall along the length of each pier, hence leaving the upper edge of the spandrel free. This beam top was bolted to the loading beam and the bottom surface was attached to the top edge of the wall specimens by using high strength epoxy.

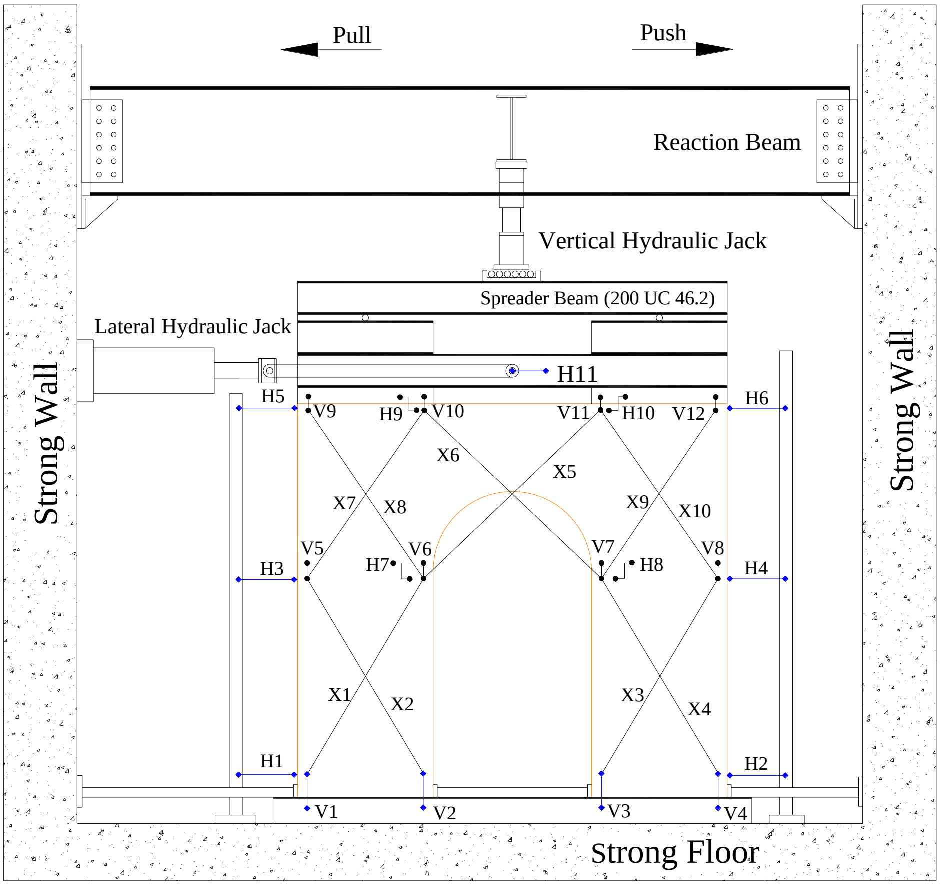


Figure 7: Test set-up and instrumentation (blue denotes absolute and black denotes relative displacement; H, V, X denotes horizontal, vertical and diagonal respectively).

Lateral force applied to the URM wall was measured using a load cell connected to the horizontal hydraulic actuator. On one side of the wall, linear variable differential transformers (LVDTs) attached at various locations were used to monitor displacements and deformations of the wall (Figure 7). On the other side, digital image correlation (DIC) was used to capture full-field deformation.

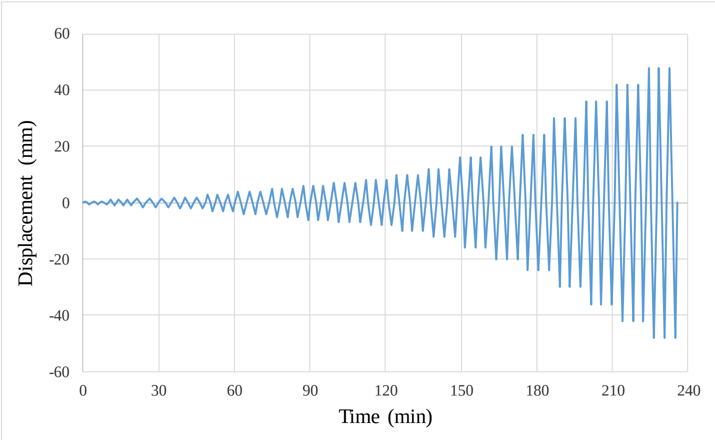
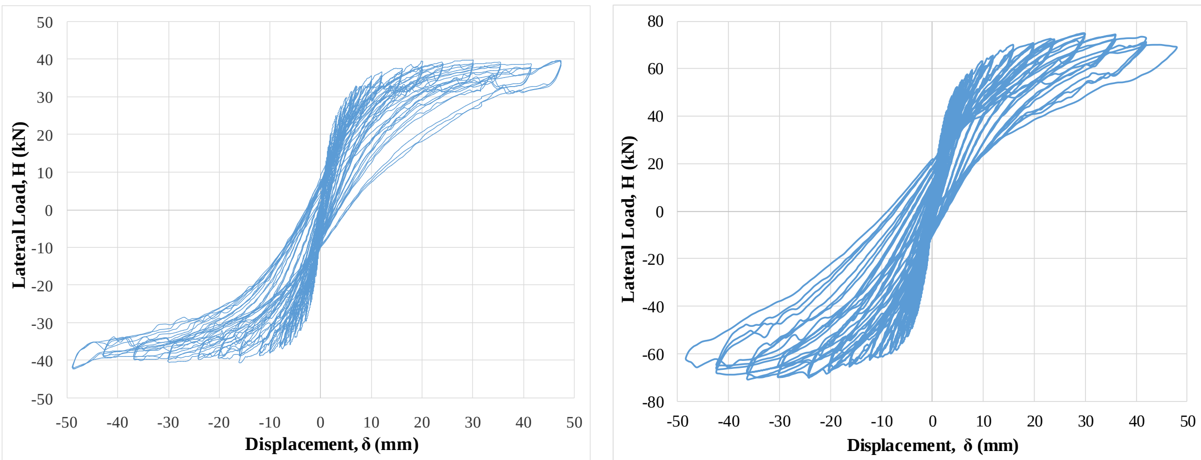


Figure 8: Quasi-static cyclic displacement time history for tests.

Test Result and Discussion

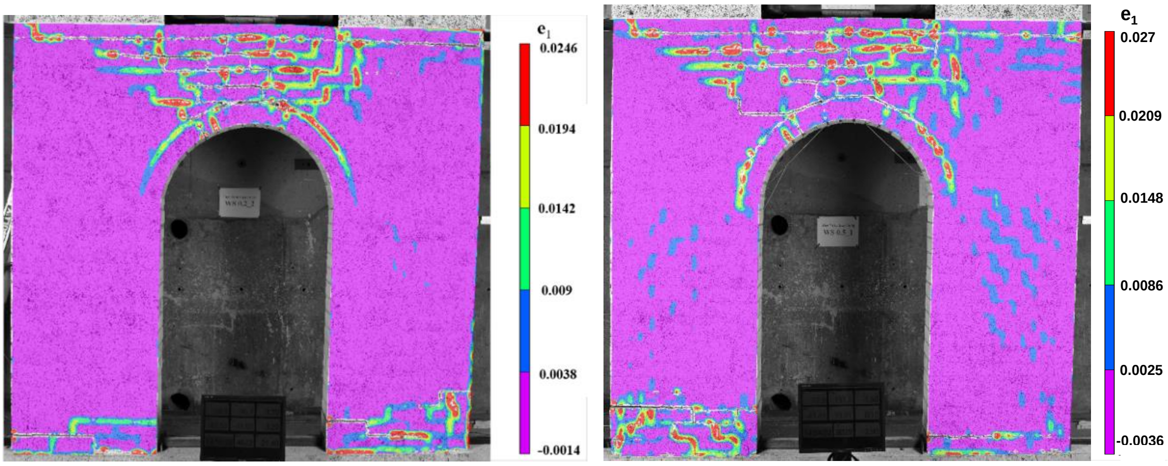
The experimental load displacement hysteretic loops for the shallow spandrel walls with low (0.2 MPa) and high (0.5 MPa) precompression stress are shown in Figure 9. The loops are nearly symmetric in push (+) and pull (-) cycle with narrow band in both precompression levels. The maximum lateral shear strength is 40 kN in positive (push) direction and 42 kN in negative (pull) direction for low precompression level. For high precompression level, the maximum shear strength value in positive and negative direction is 74 kN and 70 kN respectively. The narrow hysteretic loops and minimal decrease of the strength with the increased displacement indicate the rocking nature of the pier. The crack pattern (Figure 10) of the walls are presented by plotting the contour map of the major principal strain obtained by DIC. The spandrel showed mixed flexure and shear failure and the top brick course slid through the uppermost mortar joint in both cases. Compressive toe crushing of the pier was more prominent for 0.5 MPa precompression level (left pier) than for 0.2 MPa precompression level (right pier) and it started after 36 mm displacement.



(a) 0.2 MPa precompression

(b) 0.5 MPa precompression

Figure 9: Force-displacement behaviour of shallow spandrel wall (Figure 5a).



(a) 0.2 MPa (b) 0.5 MPa

Figure 10: Failure pattern of Shallow spandrel wall due to cyclic loading.

In-plane shear tests on square panels built with clay brick and stone

The University of Adelaide will soon begin testing a series of 1.2 x 1.2 m square panels under cyclic in-plane loading. The aim of the tests will be to investigate various types of masonry wall morphologies typically encountered in heritage construction in terms of their strength, stiffness and drift capacity. The results of these tests will subsequently be used to assess the applicability of existing design equations and analysis models toward this class of walls (e.g. Magenes and Calvi, 1997; Lagomarsino et al, 2013).

The tests will utilise approx. 100 year old sandstock clay bricks (compressive strength f_{uc} = 28 MPa) obtained as a by-product of demolition of old buildings in Adelaide. The stone used in the tests is sandstone (f_{uc} = 58 MPa) sourced locally from the Basket Range quarry. All masonry is constructed using a 1:3 (lime-sand) mortar representative of historical construction. A total of 10 specimens will be tested with two of each of the following:

- Single leaf clay brick with half-overlap stretcher bond;
- Single leaf stone ashlar with half-overlap stretcher bond;
- Double leaf wall comprising clay brick and stone leaves engaged together with through-bricks;
- Double leaf wall comprising clay brick and stone leaves with no engagement; and
- Stone random rubble (double leaf).

Construction of these panels is shown in Figure 11. The walls will be subjected to constant precompression and a fixed-fixed boundary condition to be generated by a stiff steel beam at the top of the wall as indicated in Figure 12. The intent of the applied boundary conditions is to generate shear failure in the wall as opposed to flexural modes of failure. The walls will be subjected to displacement-controlled cyclic loading at increasing levels of applied displacement until the walls reach their ultimate drift capacity.

These tests will be undertaken along with a range of material property characterisation tests in order to provide inputs for the associated mechanical models. This will include diagonal compression tests on similar panels, shear couplet tests, bond wrench tests, compression tests on stacks, as well as compressive and tensile strength tests on the brick and stone units.

Figure 11: Construction of brick and stone walls for cyclic in-plane testing.

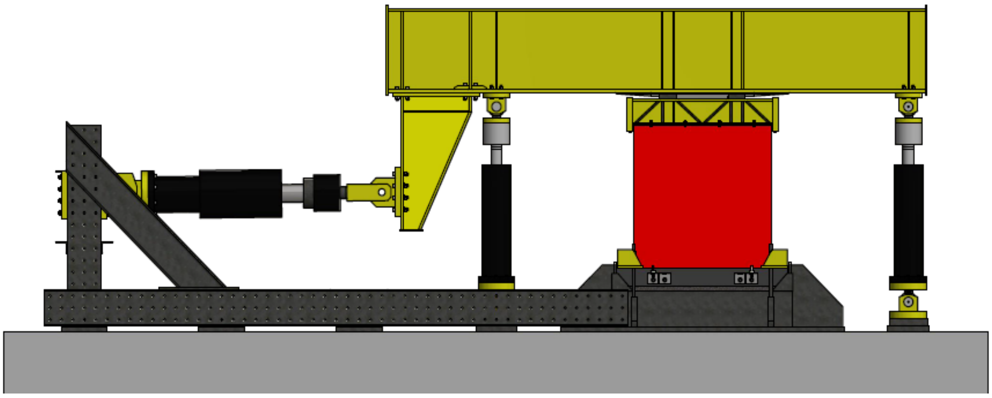


Figure 12. In-plane shear test rig (under construction) at Adelaide.

SUMMARY AND FUTURE WORK

This paper has provided an overview of the collaborative research currently underway between the Universities of Adelaide, Newcastle and Auckland into the seismic performance expectations of Australian heritage URM buildings. The work to date includes characterisation survey studies across NSW and parts of the Adelaide CBD, which have provided insight into the range of different aspects of heritage URM construction. Experimental test campaigns are presently underway to investigate the in-plane shear response of heritage URM-specific wall geometries and morphologies. The results of these tests will be used to obtain inputs for existing design equations and analytical procedures toward this class of URM structures so that the findings may be implemented in practical design.

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