Australian Earthquake Engineering Society 2016 Conference, Nov 25-27, Melbourne, Vic

Characterisation of Heritage Masonry Construction in NSW - State Heritage Register

Milon Howlader, Mark Masia, Michael Griffith, Jason Ingham, Bill Jordan

Abstract: *Numerous low to moderate magnitude earthquakes have been recorded across the state of New South Wales (NSW) since European settlement in 1788. Of these, significant damage was caused by the moderate M5.6 Newcastle earthquake in December 1989, causing the deaths of 13 people and extensive damage to unreinforced masonry (URM) buildings. The majority of the building structures listed by the Heritage Council of NSW on the State Heritage Register were constructed using URM before the development of earthquake design standard guidelines. Therefore, to help protect and preserve these invaluable historical assets, characterisation of the building typologies and materials adopted in their construction is needed in order to better understand their seismic performance and inform strategies for strengthening, where required, in a cost-effective way. This paper presents the results of an analysis of NSW heritage URM building stock listed on the State Heritage Register by the Heritage Council of NSW. The most significant parameters considered for characterisation are the URM materials, the number of stories, roof type (shapes and materials), construction year, geographic location and the past and current use for the buildings. Religious URM buildings are also classified according to their use and construction materials.*

Keywords: masonry, characterisation, heritage, religious

1. INTRODUCTION

The Australian insurance industry (ICA, 1990) has reported that the economic risk posed by a moderate earthquake in any of the capital cities in Australia is of the order of billions of dollars. For example, a “design magnitude” earthquake in Sydney is predicted to cause over $10 billion damage to domestic construction, most of it unreinforced masonry (URM), and more than 5,000 deaths (Blong, 1993). The damage bill for the entire built environment (including business interruption costs) could easily be an order of magnitude greater. The vast majority of culturally significant heritage buildings in Australia are constructed of unreinforced stone or clay brickwork, with all of these buildings erected many decades before seismic design guidelines or requirements existed. Hence, the risk posed by earthquakes to these important buildings is significant. This risk was further highlighted by the M6.3 Christchurch earthquake in 2011 where both major cathedrals in the city were heavily damaged (Griffith et al., 2013; Ingham & Griffith, 2011). In terms of risk (i.e., probability times exposure), the lower seismic hazard in Australia compared to NZ is more than offset by the higher population and greater proportion of unreinforced masonry construction in Australian towns and cities. URM construction in Australia is also less likely to have been retrofitted, further increasing its vulnerability to earthquake loading. However, before these heritage buildings can be cost-effectively strengthened, their seismic capacity (or weaknesses) must be determined. The challenge in assessing the safety of such buildings is complicated by the fact that today’s design codes do not cater for the construction materials and building geometries that our heritage buildings possess. For example, when assessing and designing the repair and strengthening strategy for the Christ Church Cathedral in Newcastle following the 1989 earthquake, Collins & Jordan (1997) highlighted that the lack of guidance for such a building resulted in cost estimates for the work varying by A$12.6M and even once the preferred strategy was chosen, the cost estimates varied by A$1.6M depending on the choices made for the seismic design factors adopted in the assessment. Therefore, a need exists to develop a more accurate yet practical approach for the seismic assessment of heritage URM buildings that accounts for the material properties, limited ductility, and atypical structural layouts used in heritage buildings. A precursor to achieving this overall aim is the characterisation of Australian unreinforced masonry (URM) construction with respect to building geometries, construction details and material properties. The research reported in this paper represents just one step in this process of characterisation. The aim of this study is to give a systematic, reliable and comprehensive overview of the heritage buildings in NSW which are registered in the State Heritage Register list. The conservation of these buildings is important, because they represent the culture, and enrich the understanding of the history and identity of NSW.

2. STATE HERITAGE REGISTER NSW

The State Register of Heritage represents a list of buildings, structures, works, gardens, relics, cemeteries, memorials, landscapes, moveable objects or precinct and archaeological sites, which contain significant value for the State of New South Wales in relation to the historical, scientific, cultural, social, archaeological, architectural, natural or aesthetic value of the item. To conduct investigations, to research and to maintain a database inventory of items of state and local heritage significance, an organisation named the Heritage Council of New South Wales is constituted under the NSW Government agency. To identify significant heritage places and objects, the Heritage Council works with the community, local councils, and State government agencies to ensure that the community has the opportunity to provide consent to the proposed item being listed.

To recommend an item on the State Heritage Register, the Heritage Council must consult with the owner or occupier in the case of structures and objects and for a prescient the notice should be published in at least one metropolitan newspaper and one local newspaper. Finally, with the agreement of the Minister to the council, the item is listed on the State Heritage Register (Heritage Act, 1977)

3. LITERATURE REVIEW

The characterisation of URM buildings means the grouping of buildings to some general parameters and features according to formal qualities, context or function, to which properties defining their behaviour can be assigned. Classification of buildings into different typologies is mostly used for a large scale of building stock at a particular location which may not be valid to another place. The purpose of the building typology is to get an overview of the buildings of a city, town or community instead of looking at individual buildings as isolated cases.

Extensive previous research has been carried out for the characterisation of building stock in villages, cities or regions in the field of structural engineering for the purpose of seismic assessment in earthquake active zones. This classification helps us to analyse the seismic vulnerability of structures, and most importantly the heritage/historic buildings which are constructed using unreinforced masonry. The concept of characterising buildings into different typologies which are used by researchers worldwide is described below.

After the earthquake of magnitude M_L 5.2 on March 1993 in Pyrgos, a town which is one of the most seismic prone areas in Greece (Karantoni & Bouckovalas, 1997), a vulnerability analysis was carried out considering a large statistical study of URM building samples. In this analysis, Karantoni & Bouckovalas (1997) classified buildings according to the material of construction (adobe, stone, and brick), the number of stories (1, 2 and 3), the age of the buildings (1800-1850, 1850-1900, 1900-1940 and 1940-today) and soil conditions. The effect of the above parameters were presented corresponding to the degree of damage (D.D.) Old adobe masonry structures (mostly constructed between 1800-1850) exhibited heavy damage when compared to more recently constructed stone and brick masonry buildings. In addition, the seismic performance was better for lower storied buildings and damage increased with the number of storeys. The date of construction of the building was found to have a great effect not only on the material properties but also the structural form of the buildings. There was also a notable correlation between soil profiles which resulted in increased ground accelerations and an increased degree of damage observed. It was noted by Karantoni & Bouckovalas (1997) that Pyrgos is a typical city in Greece, so the seismic behaviour of the buildings in other Greek towns was expected to be similar when subjected to the action of near-field earthquakes. Hence the results obtained from their research were thought to be relevant also for planning seismic scenarios throughout the country and for further research work.

D'Ayala & Speranza (2003) carried out a seismic vulnerability analysis of the four historic towns of the Marche region in Italy by studying the construction of masonry and the layout of buildings to assess the seismic behaviour of the external walls and the damage behaviour. At first, the basic typologies were analysed and compared to the four case study towns and found that while there were some dissimilarities in geometric dimensions, the number of stories, and the foundations, similarities could be seen in the case of horizontal structures and masonry characteristics. The outcome of the analysis was presented in four vulnerability classes (low, medium, high and extreme) in relation to the seismic damage caused by the 1997 Umbria-Marche earthquake.

Nollet et al. (2005) proposed a seismic vulnerability evaluation method based on the structural characterization of a group of buildings in the historic Old Montreal district in Quebec. Eighty-nine buildings were identified for the purpose of characterisation, being those constructed before 1929. These buildings were classified into different typologies based on year of construction, construction materials, the number of storeys, functions, and structural types. After the analysis of the inventory, it was observed that notable distinctions exist between the structural characteristics of those buildings and the North American typology described in the report ATC-21 (ATC, 1996). This observation confirmed the need for an approach to evaluate the seismic capacity of historic areas in Quebec (where 44% of the building are URM) by developing vulnerability curves from analytical models adapted to the structural and material characteristics of the buildings.

Binda (2005) performed a comprehensive investigation after the 1997 Umbria-Marche earthquake in the Umbria region of Italy to identify the most appropriate vulnerability analysis method. Direct and indirect survey techniques were carried out to gather knowledge about the formation process, masonry sections and texture, material characteristics, etc. Initially, the number of stories, exposure, type of facade, material, and structural elements were the more common factors for the building topologies of a city centre, while the change of the function of the building over the time has a significant effect on the seismic capacity. She (Binda, 2005) pointed out that a building born as isolated could be converted to a row or complex building over time. It was stated that, for the seismic vulnerability analysis of the complex building, the geometric survey possibly not sufficient, therefore its structural evolution should be known as much as possible. Also for the identification of various materials used and their physical and mechanical properties in masonry structures, a minimal investigation is useful by getting information from a sample building which symbolizes the whole. This approach can also be useful to select appropriate materials and techniques for retrofitting of the representative buildings.

Valluzzi et al. (2005) performed vulnerability analyses of the historical centres of Vittorio Veneto, Italy for the structural improvement in seismic areas. The buildings were classified according to dimensions (palaces, buildings, large complexes, and annexes), the presence of contiguous constructions (isolated or row) and the presence of colonnades at the ground level. From the macro-modelling analysis, it was observed that the isolated buildings are less vulnerable to seismic actions than row buildings. Also, the palaces and large complexes are more vulnerable in a seismic zone and sometimes it is not possible to use the common structural assessment procedures which are applied in the case of regular structures (Valluzzi et al., 2005).

Magenes (2006) stated that plan irregularity results in increased seismic vulnerability due to the resulting torsional effects and stress concentration. The seismic vulnerability also increased due to irregularity in elevation which can lead to insufficient load paths and stress concentration. Plan and elevation irregularities also reflect in a variation of OSR (over strength ratio). The OSR is determined from the inelastic cyclic deformation and energy dissipation capacity of the structure. Other geometric configurations, such as lack of wall to wall and wall to horizontal structure connection, and very slender walls also lead to buildings which are more vulnerable to earthquake induced damage.

According to Tomaževič & Lutman (2007) the characteristics of heritage buildings vary from region to region and from rural to urban areas. The construction materials generally used to construct URM buildings in Slovenia are locally available limestone and slate except in some parts where the use of clay brick is dominant. Stone masonry buildings which are located in urban areas are three to four stories high while two stories are common in rural areas. Also, in the city centres and towns the mix of stone, brick, and mortar is more compact with no distinct discontinuation between the individual layers of the walls. The wall is uniformly distributed along orthogonal directions and the load bearing walls and cross walls are so thick that sometimes the wall/floor ratio exceeds 10%. From their observation, the authors (Tomaževič & Lutman, 2007) stated two main causes of masonry building damage which were the lack of structural integrity and inadequate structural resistance. Sometimes inadequate structural layout was the consequence of partial and or total collapse of the buildings.

Russell & Ingham (2010) classified New Zealand URM buildings according to their overall configurations from building surveys undertaken throughout the country. Buildings were classified into seven categories based on the storey height and building footprint (either isolated, /stand-alone or row). Religious, institutional and industrial buildings which did not be easily fit into any other category due to their plan and elevation irregularities were grouped separately. The building typologies were also divided into importance level according to AS/NZS 1170.0, with all buildings falling into the range of ordinary to high consequence for the loss of human life and economy, with importance level 2 or more. In the case of prevalence, one storey row buildings were the most common. Russell & Ingham (2010) contended that this classification was important as isolated square buildings behave differently to long row type buildings during an earthquake. Also, the row type buildings which are common residential buildings in New Zealand are more prone to pounding effects, particularly when the floor or roof diaphragms are constructed of concrete or have different alignment with respect to an adjacent lot within the row. Due to the high seismic vulnerability across New Zealand, Giaretton et al. (2014) compiled a building characterisation according to the age of the buildings, their function, architectural configuration (regularity and irregularity in plan and elevation, number of stories, the area of the foot-print and whether isolated or connected). Buildings were also classified on the basis of the constituent stone types and the source of location; wall cross section and surface texture. The authors (Giaretton et al., 2014) declared that this classification would help in the conservation and retrofitting of heritage URM building in New Zealand and assist in ensuring personal safety.

Marotta et al. (2015) prepared a database of 297 URM churches located across New Zealand which included general information, architectural features and structural characteristics, and any architectural and structural alteration that had been made. The churches were classified according to history (construction period, church denomination and use), geography (location, seismic hazard factor (Z)), topology (plan and spatial features such as box type behaviour), architectural features (foot-print area, height and length of the wall with respect to thickness, regularity in plan). In addition, features such as the masonry type used in construction (stone, brick), the cross section of the wall, nave cover, and type of roof support were accounted for in the characterization.

4. HERITAGE UNREINFORCED MASONRY (URM) BUILDINGS IN NEW SOUTH WALES

The data from the State Heritage Register listed by the Heritage Council of NSW under the NSW Heritage Act at section 136 (Heritage Act, 1977) were analysed for the purpose of characterising the URM building stock in the NSW region. For some cases, Google street view was used to enrich the missing information in the documentation available in the State Heritage Register. According to the register, there are 1676 items listed containing buildings, places, and objects owned by both private and public entities. Of them, a major proportion (76%) are building structures, including residential, public, commercial, religious, and railway stations. The material used to construct these structures are mainly brick, stone, steel, concrete and timber according to its availability and the development of technology. Within the building structures, 1017 (approximately 80%) can be classified as load bearing unreinforced masonry structures, highlighting the need to characterise these structures in terms of earthquake performance, given the vulnerability of this form of construction to earthquake loading.

5. BUILDING CHARACTERISATION

URM buildings can perform in different ways during earthquake induced shaking depending on attributes such as building geometry, construction details and material properties. The characterisation plays an important role to assess the seismic capacity of the URM buildings and to choose an appropriate solution of retrofitting.

5.1. Construction Year

The URM buildings listed on the State Heritage Register are classified according to their construction period. The number and percentage of buildings constructed in each 20-year period are shown in bar chart (Figure 1). It can be seen that most of the URM heritage buildings were constructed between 1821 and 1900, with this period containing more than 70% of the total building stock. The construction date of 83 buildings, representing 8.2% of the total buildings are unknown.

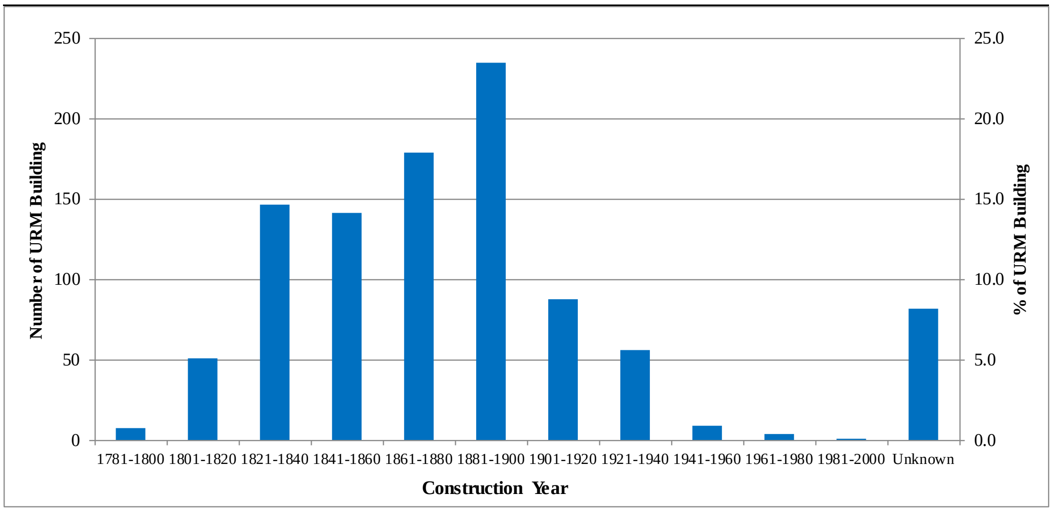
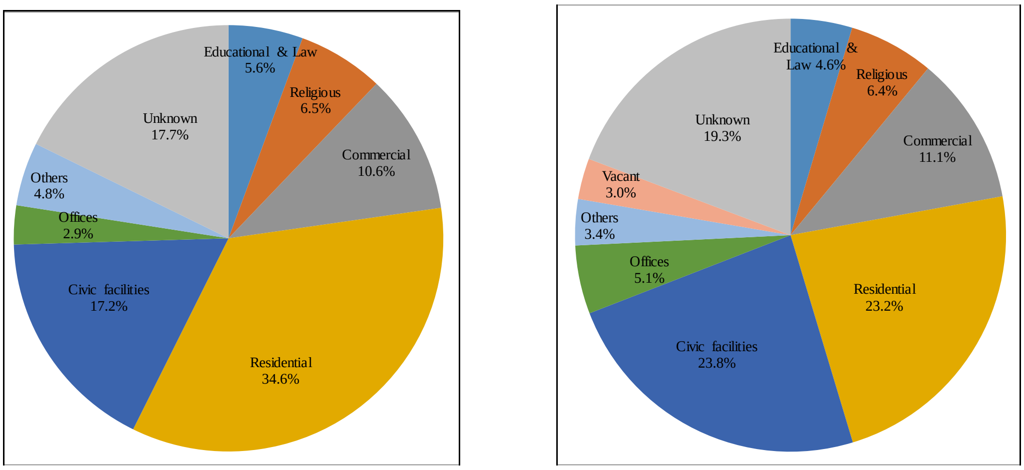


Figure 1: Construction period of URM heritage building stock in NSW

Earthquake loading has not conventionally been considered as part of structural design for the construction of buildings in Australia, before the 1968 (M_L=6.9) Meckering earthquake. After the occurrence of this seismic activity, Australian Standard for The Design of Earthquake Resistant Buildings (AS2121,1979) was proposed by the Standards Association of Australia, but not followed in all locations of Australia. The heritage buildings record (represented in Figure 1) shows that almost all of the buildings listed were constructed before the introduction of seismic loading to the design process.

5.2. Function or Use

The URM stock are grouped into categories according to their use, both at the time of their construction and their current use. Of them, Educational and Law includes schools, colleges, universities, courthouse, prisons, police station, and correctional centres. Religious buildings are churches, chapels, cathedrals, and temples. Shops, pubs, cafes, hotels, motels, bars etc. fall into the commercial categories.



(a) Former use

(b) Current use

Figure 2: Statistics of URM building function or use

The civic facilities represent cinemas, theatres, libraries, museums, banks, post offices, railway stations etc., which are needed for entertainment, finance, and communication. Also, in the other categories are included; lighthouse, precent, farm, power station, pump station etc. The function or use of a building will impact the level of imposed loads to be considered in its structural assessment and will define its importance level. When a building is listed on a heritage register, this in itself may imply that a higher importance level be considered when assessing the structural safety of the building. Moreover, for retrofitting or strengthening an earthquake-prone building to reach its required level of % NBS (New Building Standard), the materials and methods required depend on the type of building and also the aesthetic requirement to preserve the uniqueness.

The most significant differences in former and current use are shown in categories of residential and civic facilities buildings (see Figure 2), where the percentage of residential buildings decreases and the civic facilities buildings increases. As currently some buildings are vacant/unused (3%) and some buildings are converted to museums to keep its history and culture, it is more reasonable to change the function of the building. To change the function of a building, sometimes it is necessary to alter the original configurations of the structures such as the removal of load bearing walls, facades, the modification/adding of floors, roof, or other parts to adjust the internal spaces and passage ways. This alteration can result in the modification of the seismic performance of the building, which was observed from previous earthquake damage.

5.3. Number of Stories

The URM buildings listed on the State Heritage Register are classified according to the number of stories in Figure 3. A small, low-rise square building will behave differently compared to a long, rectangular and high-rise building when subjected to the same induced seismic force (Robinson and Bowman, 2000). Also, they (Robinson and Bowman, 2000) have quoted that, buildings of three stories or less can endure a reasonable amount of earthquake shaking. However, buildings higher than three stories with open plan frame type geometries are much more susceptible to damage during earthquake shaking.

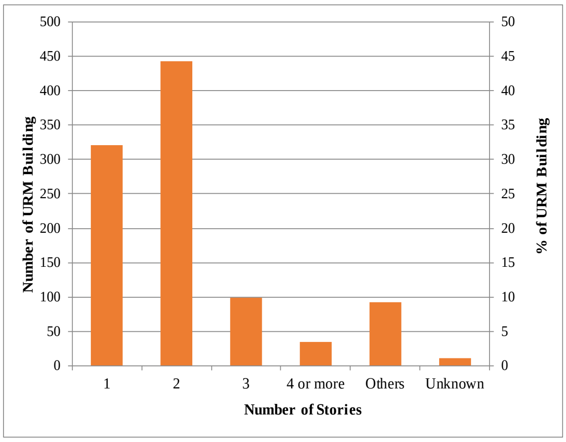


Figure 3: Number of URM Buildings according to storey height.

The ground floor wall behaviour under lateral load is influenced by increasing storey height causing different failure modes due to the increasing axial forces. In a multi-storied building, the ground floor walls are generally thicker than the upper stories, and also much wider than for a single storey building (Russell, 2010). Russell also performed an economic analysis of the buildings with respect to the number of stories and observed that the buildings of four or less stories have a linear relationship with their financial value (average value increases with the increase of the number of stories) but beyond four stories the average value in fact decreased.

The majority of heritage URM buildings in NSW are one or two stories with two storey buildings making up 44% of the total, followed by one storey buildings at 32% as shown in Figure 3. The buildings of three or more stories comprise only 13%.

Here, the categories of the others, contains the religious buildings, such as churches, chapels, cathedral etc. which because of their structural shape and irregularities do not have clearly defined numbers of stories. These buildings are more vulnerable to seismic action due to their large wall height to thickness and length to thickness ratios, more open plan and also the presence of thrusting horizontal structures (vaults and roof) and the decoration assets which are more susceptible to cracking (D'Ayala, 2000).

Excluding the others and unknown categories, it appears that the NSW heritage URM building stock are mainly low rise buildings, where the combination of one and two storey buildings represents 85% of the entire building stock.

5.4. Constituent Materials

A major percentage (60%) of the heritage URM building walls (load bearing) are constructed by using brick, with 20% of the buildings being stone and the remaining 20% of buildings being made with brick and or stone, see Figure 4. The stone masonry is constructed mostly by using sedimentary rocks, such as sandstone (historically known as Yellow block), due to its availability in the NSW region. For the brick masonry buildings, there is no clear indication about the type of brick, whether it is mud, burnt clay, concrete etc. Sometimes in the Heritage database it is written only as masonry, and these buildings are included in the Brick/Stone categories.

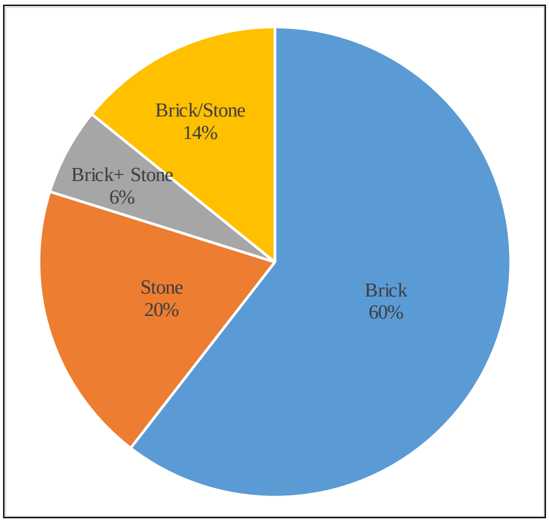
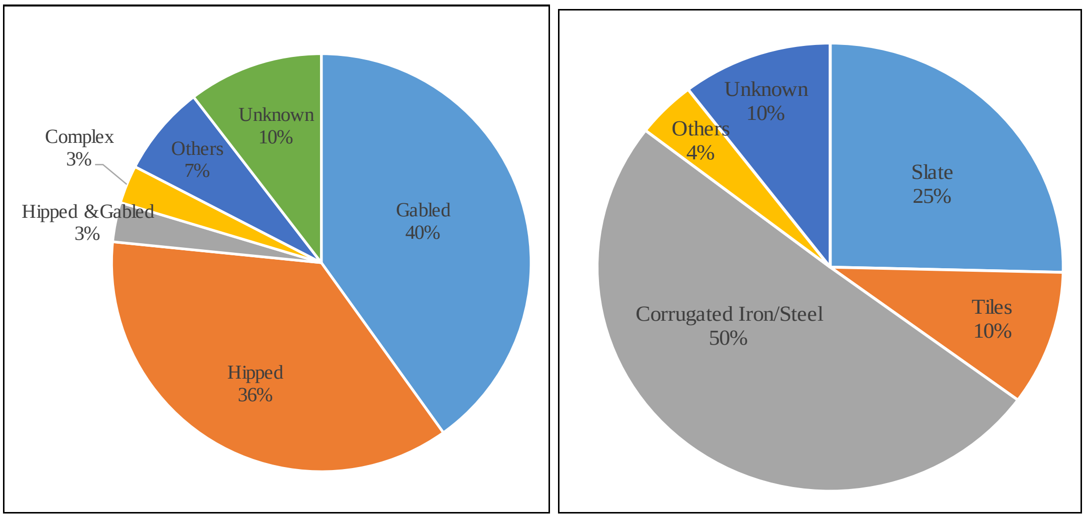


Figure 4: Material used in URM buildings

5.5. Roof Type

The characteristics of a roof are dependent on the building function that it covers, the availability of local roofing materials, traditions and legislation of construction and in a broader concept of architectural design and practice. The shape of the roof varies from region to region according to the climate and the available materials for the roof structure and its cover. Gabled roof structures are less stable than hipped roofs due to the triangular cantilever of masonry extending from the wall to meet the gable roof, which shows poor seismic performance as it easily collapses laterally under out of plane seismic shaking (Arya, 2000). From the Figure 5 below, it is shown that the gabled shape is the most prominent (40%) shape of the roof, which is due to its easier and cheaper construction and more space and ventilation. The complex shape contains the domed, pyramid, mansard, multi gabled, multi hipped roof types.

The material characterisation shows that, half (50%) of the URM building roofs are covered with corrugated galvanised iron or steel sheeting. Its light weight, ease of transportation, waterproofing, low cost and easy application make it a more common roofing material than the others. Although slate and terra cotta tiles were used for the original roof construction in many cases, when it came time to replace or repair roof systems, galvanised corrugated iron frequently took its place as a more economical alternative.



(a) Shape (b) Material

Figure 5: Roof characterisation according to shape and material.

5.6. Regional Distribution

For this study URM building stock are distributed geographically according to districts, where NSW is divided into seventeen (17) districts by The Australian Bureau of Meteorology (see Table 1).

Table 1: Regional distribution of heritage URM stock in NSW

District	URM (Nos.)	URM (%)	Zone Coefficient (Z)
Northern Rivers	4	0.4	0.05
Mid North Coast	17	1.7	0.05-0.09
Hunter	87	8.6	0.09-0.11
Northern Tablelands	27	2.7	0.06-0.07
Sydney Metropolitan	596	58.6	0.08
Illawarra	56	5.5	0.09
South Coast	5	0.5	0.09
Central Tablelands	117	11.5	0.08-0.10
Southern Tablelands	23	2.3	0.09-0.10
Snowy Mountains	3	0.3	0.08
North West Slopes & Plains	8	0.8	0.07-0.08
Central West Slopes & Plains	12	1.2	0.06-0.08
South West Slopes	4	0.4	0.05-0.09
Riverina	38	3.7	0.08-0.10
Lower Western	10	1.0	0.03-0.05
Upper Western	5	0.5	0.04
Australian Capital Territory	5	0.5	0.09

A major portion (58.6%) of the heritage building stock is located in the Sydney Metropolitan district. The Central Tablelands, Hunter, Illawarra districts, which surround the Sydney Metropolitan, have 11.5%, 8.6%, and 5.5% of buildings respectively. This distribution of the URM buildings is also presented based on their seismic hazard coefficient (Z) with the help of seismic hazard maps of NSW (AS

1170.4, 2007). It is seen that the highest seismic factor is 0.11 in the Hunter zone (particularly Newcastle, Lake Macquarie and Cessnock), and most of the buildings are located in the region of Z = 0.08, which is responsible for causing low to moderate earthquakes in NSW.

5.7. Religious Buildings

A total of 104 religious buildings are listed in the NSW State Heritage Register. Of these, 94 (90%) are of URM construction (see Figure 6). The buildings are also classified according to their use in Table 2, where 81% of the buildings are used as a church, cathedral, church hall or chapel. Generally, the religious buildings have irregularities in plan and elevation and they contain more ornamental elements which are more vulnerable to seismic action. Therefore, more emphasis should be given for the purpose of understanding the nature and scale of the seismic action and their importance in the communities to which they belong.

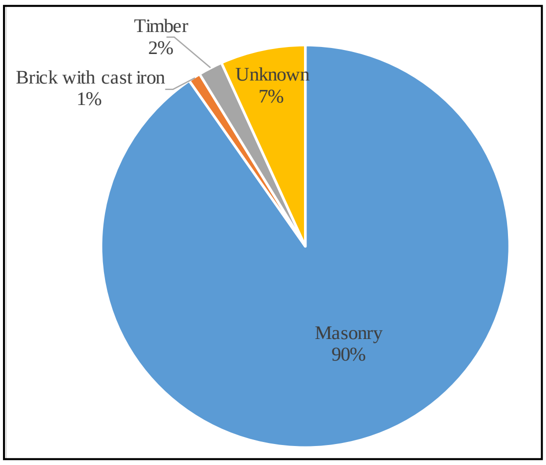


Figure 6: Classification of Religious building according to material.

Table 2: Current use of religious building in NSW

Function	Number	Percentage (%)
Church, Cathedral, Church Hall, Chapel	84	81
Buddhist temple	1	1
Convent/Nunnery	3	3
Mosque	1	1
Other - Religion	2	2
Presbytery/Rectory/ Vicarage/Manse	8	8
Shrine	2	2
Synagogue	3	3
Total	**104**	**100**

6. CONCLUSIONS

The unsatisfactory seismic performance of many older URM buildings in NSW is highlighted by the 1989 Newcastle earthquake. Severe damage was observed in Christ Church Cathedral, and many of the buildings in Beaumont Street, Hamilton and elsewhere in the Newcastle region. The Newcastle experience serves as a reminder that assessment and mitigation of risk associated with the heritage URM buildings in NSW, and Australia more broadly, is of prominent importance for the safety of people and to preserve the buildings for their heritage importance. In order to gather knowledge about the traditional construction methods of heritage URM buildings throughout NSW, and to choose appropriate methods of assessment and suitable intervention techniques, a total 1017 URM buildings listed under the NSW State Heritage Register are characterised.

The following observations can be made:

- Most of the heritage URM buildings were constructed between 1821 and 1900.
- Approximately half of the heritage URM stock are used as residential and civic facilities, both in terms of their former and current use.
- A large proportion of the buildings are low rise containing one storey (32%) and two stories (44%) and 60% of buildings use load bearing brick walls.

- In cases where stone masonry URM walls are used, Sandstone is the most common material.
- Gabled roofs are slightly more common than hipped roofs and the corrugated galvanised iron/steel is the most common (50%) material used as the roof outer cover.
- More than half (58.6%) of the heritage URM in NSW is located in the Sydney Metropolitan district, where the seismic hazard factor Z=0.08.
- For the religious buildings, 90% of the buildings are of URM construction and are mostly used for Church, Cathedral, Church Hall and Chapel.

Due to the lack of available data contained within the State Heritage Register, it is not possible to aggregate information about the brick type used in the construction. The next step of the project is to select a prototype heritage URM building in Newcastle and to characterise the constituent materials through visual inspection and on-site and laboratory tests. This will help to understand the present situation of the building and help inform appropriate methodologies for assessment and selection of suitable retrofit techniques and materials to conserve and protect the heritage URM in Australia.

REFERENCES

Arya, A. S. (2000) Non-engineered construction in developing countries-an approach toward earthquake risk prediction, Bulletin of the New Zealand Society for Earthquake Engineering, 33(3), pp 187-208.

ATC (1996) ATC-21: Rapid Visual Screening of Buildings for Potential Seismic Hazards Training Manual, Applied Technology Council, Redwood City, California.

Binda, L. (2005) Methodologies for the vulnerability analysis of historic centres in Italy, Advances in Architecture Series, 20, pp 279–290

Blong, R.W. (1993) Hazard microzonation of Melbourne. Proceedings of the Earthquake Engineering and Disaster Reduction Seminar, Australian Earthquake Engineering Society, Melbourne, pp. 107-117.

Collins, B. B. and Jordan, J. B. (1997) Earthquake Damage Repair and Strengthening of Christ Church Cathedral, Newcastle NSW, 7th International Conference on Structural Faults and Repair, Edinburgh, Scotland.

D’Ayala, D. (2000) Establishing correlation between vulnerability and damage survey for churches, 12th World Conference on Earthquake Engineering.

D'Ayala, D. and Speranza, E. (2003) Definition of collapse mechanisms and seismic vulnerability of historic masonry buildings. Earthquake Spectra, 19(3), pp 479-509.

Giaretton, M., Dizhur, D., da Porto, F. and Ingham, J. M. (2014) An inventory of unreinforced load-bearing stone masonry buildings in New Zealand, Bulletin of the New Zealand Society for Earthquake Engineering, 47(2), pp 57-74.

Griffith, M., Moon, L., Ingham, J. and Derakhshan, H. (2013) Implications of the Canterbury earthquake sequence for Adelaide, South Australia, 12th Canadian Masonry Symposium.

Heritage Act (1977) No. 136, State's environmental heritage by the Minister administering the Act, Heritage Council of New South Wales, Australia.

Ingham, J. and Griffith, M. (2011) The performance of earthquake strengthened URM buildings in the Christchurch CBD in the 22 February 2011 earthquake, Addendum Report to the Royal Commission of Inquiry.

Insurance Council of Australia (1990) Newcastle earthquake-our worst natural disaster, ICA Bulletin Special Issue.

Karantoni, F. V. and Bouckovalas, G. (1997) Description and analysis of building damage due to Pyrgos, Greece earthquake, Soil Dynamics and Earthquake Engineering, 16(2), pp 141-150.

Magenes, G. (2006) Masonry building design in seismic areas: recent experiences and prospects from a European standpoint, 1st European conference on earthquake engineering and seismology, pp 1-22.

Marotta, A., Goded, T., Giovinazzi, S., Lagomarsino, S., Liberatore, D., Sorrentino, L. and Ingham, J. M. (2015) An inventory of unreinforced masonry churches in New Zealand, Bulletin of the New Zealand Society for Earthquake Engineering, 48(3), pp 171-190.

Nollet, M.-J., Chaallal, O. and Lefebvre, K. (2005) Seismic vulnerability study of historical buildings in Old Montreal: Overview and perspectives, WIT Transactions on The Built Environment, 83, pp 227-236.

Robinson, L., Bowman, I. and Bowron, G. (2000) Guidelines for earthquake strengthening: New Zealand Historic Places Trust.

Russell, A. P. (2010) Characterisation and seismic assessment of Unreinforced Masonry Buildings, PhD thesis, The University of Auckland, New Zealand.

Russell, A. P. and Ingham, J. M. (2010) Prevalence of New Zealand's unreinforced masonry buildings. Bulletin of the New Zealand Society for Earthquake Engineering, 43(3), pp182-201.

Standards Australia (1979) AS2121-The Design of Earthquake Resistant Buildings, Australia.

Standards Australia (2007) AS1170.4 -Structural design actions Part 4: Earthquake actions in Australia, Australia.

Standards New Zealand (2002) AS/NZS 1170.0- Structural Design Actions Part 0: General Principles. Standards New Zealand, Wellington, New Zealand.

Tomaževič, M. and Lutman, M. (2007) Heritage masonry buildings in urban settlements and the requirements of Eurocodes: Experience of Slovenia. International Journal of Architectural Heritage, 1(1), pp 108-130.

Valluzzi, M., Bernardini, A. and Modena, C. (2005) Seismic vulnerability assessment and structural improvement proposals for the building typologies of the historic centers of Vittorio Veneto (Italy). WIT Transactions on The Built Environment, 83, pp 323-332.

Valluzzi, M., Cardani, G., Saisi, A., Binda, L. and Modena, C. (2005) Study of the seismic vulnerability of complex masonry buildings, WIT Transactions on The Built Environment, 83, pp 301-310.