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TYPOLOGICAL CHARACTERISATION OF VINTAGE UNREINFORCED MASONRY BUILDINGS OF QUEENSLAND, AUSTRALIA

Nouman Khattak[a,*], Hossein Derakhshan[a], David P Thambiratnam[a], Nimal Jayantha Perera[b]

[a] School of Civil and Environmental Engineering, Queensland University of Technology (QUT), Brisbane, Queensland 4001, Australia

[b] Kasina Consultants Pty Ltd, Queensland, Australia

*Corresponding Author

Email addresses:

nouman.khattak@hdr.qut.edu.au (N. Khattak), ORCID: https://orcid.org/0000-0002-0815-9062

hossein.derakhshan@qut.edu.au (H. Derakhshan), ORCID: http://orcid.org/0000-0003-1859-4700

d.thambiratnam@qut.edu.au (D. P Thambiratnam), ORCID: https://orcid.org/0000-0001-8486-5236

njp@kasinaconsultants.com (N. J. Perera)

Abstract

Characterisation of buildings is critical for the rapid assessment and seismic loss estimation of buildings after an earthquake event. This paper presents a literature review on the characterisation of unreinforced masonry (URM) buildings followed by a typological study of the building stock in Queensland, Australia. The literature review showed that characterisation studies are aimed at cataloguing and developing inventories of buildings for the purpose of seismic vulnerability and risk assessment, and behaviour-influencing parameters are often used as a basis for building classification. Guided by the literature review, a field study was conducted to document important features of vintage (pre-1940) URM buildings that can influence their behaviour during an earthquake. The surveyed aspects included the construction year, number of storeys, roof type, irregularities in plan, isolated or inter-connected buildings, overall dimensions of the buildings, size and shape of windows, façade opening ratio, presence of chimneys, and the style of parapets. Importantly, it was found that certain parapet typologies are prevalent, but that their seismic behaviour is currently unknown. A few such typologies were recommended for future seismic assessment studies. This study can serve as a basis for conducting seismic assessment risk and vulnerability studies in the future.

Keywords: unreinforced masonry (URM); characterisation; typology; parapets; seismic vulnerability

1. Introduction

Unreinforced masonry (URM), especially clay brick and stone masonry, is one of the ancient construction materials in the human history and is still a preferred choice in many parts of the world. The reason for its popularity is the availability of the raw materials and skilled labour and its demonstrated longevity. But over time engineers have observed poor performance of masonry buildings during earthquakes. This poor performance under ground shaking is due to the low tensile strength of masonry and the lack of proper connections between the wall and floor/roof structures.

URM building construction in Australia accelerated since European settlement in late 18th century (Page 2012) although almost all survived cases have been built from 1830 onwards. Century-old textbooks (e.g. Rivington 1891 and 1904, Burrell 1907) have provided construction details and methods, which suggest that the structures were designed for gravity and wind loadings without the consideration of earthquake loads. A schematic representing one such, existing, two-storey, URM building is shown in Figure 1 for the purpose of illustrating several building parts.

In Figure 1, the wall with openings is referred to, in this research, as the main building façade, which is the exterior wall facing a street. It is usually comprised of parapets and other ornamental features such as balustrades, cornices, pilasters, pediments and finials. Balustrades are a row of small column type pieces that are usually provided between two pilasters to increase the aesthetics of the parapet. Cornice is a horizontal decorative element, usually projected from the façade and provided either above or below the roof eave line. Pilasters are pillars made of masonry starting either from the ground or from the eaves line and continuing to the top of the parapets. Pilasters can improve stability of the façades/parapets due to their increased thickness. Pediment is a central part (often triangular, rectangular, arched or more complex shaped) of the parapet, mostly raised above the rest of the parapet and used to write the construction year or the name of the building. As pediments are usually higher than the parapets, they can pose a more serious falling hazard. Finials are decorated/ornamental pieces usually rounded with or without a spike type top placed over the pilasters for aesthetic purposes. These finials if not properly connected to pilasters can pose a serious falling hazard.

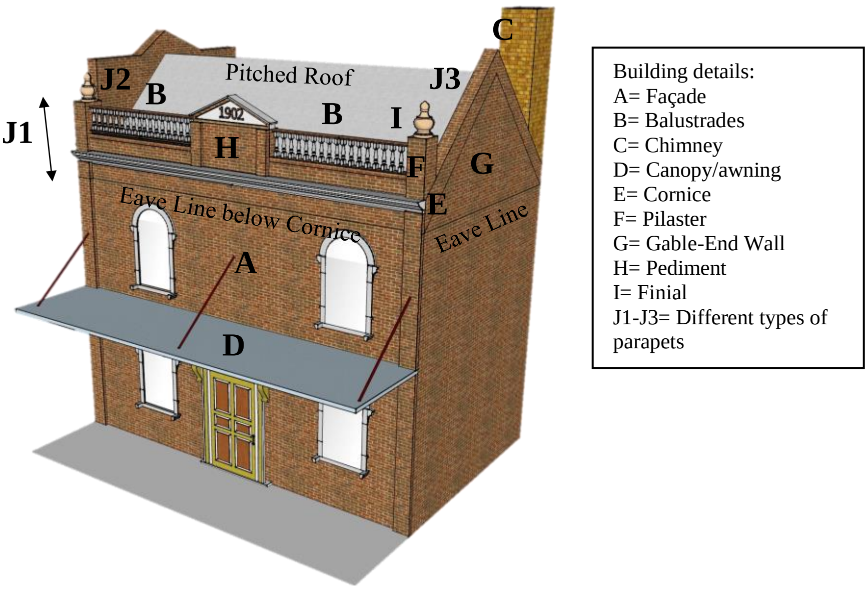


Figure 1. Schematic of a two-storey vintage (pre-1940) URM building

These building types are also common in New Zealand, which shares similar European settlement history with Australia (Russell and Ingham 2010, Griffith et al. 2017, Abeling et al. 2018). These buildings were found to be vulnerable to seismic actions during past New Zealand (Ingham & Griffith 2010, Moon et al. 2011) and Australian earthquakes (Griffith 1991, Edwards et al. 2010). The documented building damage included out-of-plane (OOP) wall failure, in-plane (IP) wall failure, and complete collapse of the buildings. The OOP wall failure included toppling of non-structural components (Derakhshan et al. 2020a) such as chimneys (Giaretton et al. 2018), gable-end walls (Ingham & Griffith 2010, Page 1991), parapets (Page 1991, Edwards et al. 2010, Giaretton 2016a), corner failures, and partial or complete overturning of façades (Ingham & Griffith 2010). Damage to canopies have also been reported (Galvez et al. 2019).

The poor performance of these buildings in Australia during the 1989 Newcastle earthquake led to the development of new Australian seismic loading code, AS1170.4 (AS 1993), and the Australian Masonry Standards, AS3700 (AS 1998), (Page 1996, Page 2012, Woodside & McCue, 2016). As a result of these new developments, the modern Australian masonry constructions (Page 1996, 2012) are relatively robust and often either reinforced or in the form of brick veneers in timber-framed houses. Occasionally, low-rise URM buildings are also constructed but they are engineered against seismic loads and mostly exclude the ornamental features shown in Figure 1. In addition, during the current field research it was found that all buildings that had the unique ornamental features schematically shown in Figure 1 were constructed prior to 1940 as discussed later. Therefore, in this paper the surveyed buildings are referred to as “pre-1940”, a posteriori.

To protect buildings from damage during future earthquakes, building inventories should be created that include information of buildings and classification according to their construction details and geometries (Polese et al. 2020, Vettore et al. 2020, Kelam et al. 2020, Altindal et al. 2021, Sanrı Karapınar et al. 2021, Ilic et al. 2020). There are several benefits for developing building inventories, however, great amount of time, human and economic resources are required for the development of a building inventory of a region (Masi et al. 2014). Therefore, data collection can be focused only on the most important and common classification level, which is to characterise the overall building configuration (Russell and Ingham 2010). The major parameters for this type of classification include the building dimensions, the size and location of structural and non-structural components, and the type of material. In addition, the use of digital tools to acquire building information such as the one used in this study (IkeGPS) can save time in data acquisition and minimise the errors in data collection.

A limited number of URM building characterisation studies have been previously performed in Australia. These studies were conducted in the State of New South Wales, NSW, (Howlader et al. 2016), the State of South Australia (SA; Adelaide city; Griffith et al. 2017 and Vaculik et al. 2018a) and the Western Australia (WA; York Town; Vaculik et al. 2018b and Wehner 2020). The State of Queensland has been excluded primarily due to the lack of sufficient survey resources.

The aim of this research was to create a database of vintage (pre-1940) unreinforced masonry buildings that are present in the central business district (CBD) of seven towns in Queensland. The focus of the survey was placed on CBD areas due to both the high concentration of URM buildings and the significance of these buildings in Queensland economy. It is highlighted that almost all CBD buildings have commercial usage and that the residential buildings are commonly located outside the CBD and made of timber-framed or other newer building systems. Therefore, non-CBD areas were excluded from the scope. The collected data was limited to building dimensions (including the façades dimensions), year of construction, whether the buildings are isolated or connected, visible roof construction details, and the architectural detailing of building ornamental façades including openings and parapets. This data was collected through field visits and subsequent desktop study of online resources including aerial images from Google maps, databases from Queensland Heritage Register (QHR, Davies 2014), and a few other sources as discussed later herein. A limitation of this study is that vulnerability parameters such as roof/floor stiffness or masonry material properties that cannot be measured using a brief external field survey are excluded.

The present paper includes a literature review on the criteria that are commonly used for building classification and factors affecting vulnerability of URM buildings. The Queensland seismicity and observed URM building damage in Australia are briefly discussed. The results from the field surveys are next presented followed by a statistical interpretation of the data, and classification of ornamental parapets based on their shape and boundary conditions.

2. Previous typology studies of URM buildings

Existing literature was studied to understand common criteria for building characterisation and to identify important vulnerability factors for URM buildings. The studies that had a focus on URM buildings are discussed in the following paragraphs, with a summary reported in Table 1. In particular, the intermediate rows in Table 1 detail the parameters that were used to assist characterisation, and the last row indicates whether a vulnerability (V) study was conducted as part of the research. Based on these studies it can be concluded that characterisation studies have been performed on URM buildings to inform seismic vulnerability studies.

2.1 New Zealand

Russell and Ingham (2008, 2010) categorised New Zealand URM buildings into seven typologies and studied the prevalence of each type. It was estimated that around 3750 URM buildings existed in New Zealand, the majority of which having one or two-storeys. Walsh et al. (2014) performed field inspections to document details of 206 URM buildings of Auckland, New Zealand. The details included geometric details such as wall heights and parapet heights, isolated vs row configuration, cavity vs solid walls, number of leaves and wall construction material e.g. brick or stone. Ismail et al. (2013) classified 226 URM buildings of Dunedin CBD, New Zealand according to construction year, number of storeys, footprint, isolated or row buildings and plan irregularities as given in Table 1. Giaretton et al. (2014) compiled an inventory of 668 unreinforced load-bearing stone masonry buildings of New Zealand.

New Zealand studies identified critical factors influencing the seismic performance of URM buildings such as building age, number of storeys, position of the building, roof type, building size, irregularities, in addition to presence of non-structural components such as, parapets canopies (Galvez et al. 2019) and chimneys. As New Zealand and Australia share a similar post-European settlement URM building construction history, these factors are also considered in the current study for Queensland buildings. However, it was identified that a relatively simple parapet typology has been assumed in various studies despite the URM buildings including parapets with a variety of geometries and boundary conditions. The assumed typology has been cantilevers with rectangular shapes supported horizontally at base (Giaretton et al. 2016b, 2018). The provisions in Section 8 of the New Zealand Society for Earthquake Engineering (NZSEE) Guidelines for Seismic Assessment of Existing Buildings (NZSEE 2017) suggest that the same typology can be used to assess cantilevers with irregular mass distribution. However, the typology does not accommodate parapets that are supported at locations other than their base.

Table 1. Summary of previous studies on characterisation of URM buildings

		(Russell and Ingham 2008, 2010)	Ismail et al. (2013)	Walsh et al. (2014)	Giaretton et al. (2014)	Howlader et al. 2016)	Griffith et al. (2017) and Vaculik et al. (2018a)	Vaculik et al. (2018b) and Wehner (2020)	Erberik (2008)	Masi et al. (2014)	Uva et al. (2016)	Chieffo et al. (2019)
Location		New Zealand	Dunedin, New Zealand	Auckland, New Zealand	New Zealand	NSW, Australia	Adelaide, Australia	York town, WA, Australia	Dinar & Zeytinburnu, Turkey	Val d'Agri, Italy	Italy	Muccia, Italy
Building Type/Use		All	All	Commercial	All	All	All	All	All	All	All	All
Construction Type		URM (Brick & Stone)	URM	URM	URM (Stone & Stone+Brick)	URM (Stone & Brick)	URM (Brick & Stone)	URM	URM	URM & others	URM & others	URM
Data/No. of Buildings		3750	226	206	668	1017	300	1463	209	17500	4519	50
Characterisation	Year of Construction	✓	✓	-	✓	✓	✓	-	-	✓	✓	-
	No. of Storeys	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	✓
	Footprint	✓	✓	-	✓	-	✓	✓	-	✓	-	✓
	Occupancy/Use	✓	-	-	✓	✓	✓	✓	-	✓	-	-
	Floor or Roof type	-	-	-	✓	✓	-	✓	-	✓	✓	✓
	Position (isolated connected or other)	✓	✓	✓	✓	-	✓	✓	-	✓	✓	✓
	Dimensions (either H, W, L)	✓	✓	✓	✓	-	-	✓	✓	✓	-	✓
	Irregularities (either plan or elevation)	-	✓	-	✓	-	-	-	✓	✓	✓	✓
	Material properties	-	-	-	-	-	-	-	-	-	-	-
Methodology adopted		Existing database +Field Survey	Existing database +Field Survey	Existing database +Field Survey	Existing database +Field Survey	Existing database	Existing database +Field Survey	Existing database +Field Survey	Existing database	Existing database +Field Survey	Existing database +Field Survey	Existing database +Field Survey
Followed by Vulnerability (V)		No	Yes	Yes	No	No	No	Yes	Yes	Yes	Yes	Yes

Table 1. Summary of previous studies on characterisation of URM buildings (Cont.)

		Pavić et al. (2019)	Santos et al. (2013)	Lovon et al. 2021	Athmani et al. (2015) and CTC (2010)	Jiménez et al. (2018)	F. Salazar, & Ferreira (2020)	Novelli et al. (2021)	Valluzzi et al. (2021)
Location		Osijek, Croatia	Seixal, Portugal	Portugal	Annaba, Algeria	Valparaíso, Chile	La Merced, Mexico	Malawi	Central Italy
Building Type/Use		All	All	Residential	All	All	Residential	Residential	All
Construction Type		URM & others	URM & others	URM (Stone)	URM & others	URM & others	All	URM	URM
Data/No. of Buildings		1075	504	200	380	111	166	323	2306
Characterisation	Year of Construction	✓	-	-	✓	-	-	-	-
	No. of Storeys	✓	✓	-	✓	✓	✓	✓	✓
	Footprint	✓	-	✓	-	-	✓	-	-
	Occupancy/Use	✓	-	-	✓	✓	-	-	-
	Floor or Roof type	✓	✓	-	✓	✓	-	✓	✓
	Position (isolated connected or other)	-	✓	-	✓	✓	✓	-	✓
	Dimensions (either H, W, L)	✓	✓	✓	-	✓	✓	✓	-
	Irregularities (either plan or elevation)	✓	✓	-	✓	✓	✓	-	-
	Material properties	-	-	✓	-	-	-	✓	-
Methodology adopted		Existing database +Field Survey	Field Survey	Existing database	Existing database	Field survey	Existing database +Field Survey	Field Survey	Field Survey+ Existing database
Followed by Vulnerability (V)		Yes	Yes	No	Yes	No	No	Yes	No

2.2 Australia

Using the NSW State Heritage Register, Howlader et al. (2016) studied the prevalence of URM building stock in that State. As detailed in Table 1, the characterisation parameters were the construction year, use, type of URM materials, number of storeys, roof shape, geographical location and the past and current functions of the buildings. Griffith et al. (2017) and Vaculik et al. (2018a) performed street surveys of more than 300 heritage-listed buildings in the Adelaide CBD, SA. The included data was detailed information on the masonry material, whether the buildings were isolated or interconnected with other buildings, type of gravity load-bearing system (frame or wall only), the presence of vulnerable features such as parapets, chimneys and gable-end walls, and noticeable past alterations or strengthening. Vaculik et al. (2018b) and Wehner (2020) conducted a survey to document and classify the URM buildings in the township of York, WA. About 1663 buildings were surveyed and 307 buildings were identified as URM buildings and then these buildings were classified into five typologies, i.e. one-storey isolated, one-storey row, two-storey isolated, two-storey row, and two-storey corner buildings. Risk posing components of URM buildings such as chimneys, façades, gable end walls and parapets were identified and evaluated. It was found that many residential buildings on the main street of York have high pitched roofs with gable-end walls. Experimental and numerical research on non-structural components (Lam et al.1995, Doherty et al. 2002) has included rectangular parapets connected to roof at their base in a similar way as that assumed in New Zealand studies (Giaretton et al. 2016b, 2018). This typology has a shortcoming that it does not represent parapets that are connected to pitched roofs.

The common observation from these studies is that vintage (pre-1940) Australian URM buildings are low-rise and have many vulnerable non-structural elements e.g. gable-end walls, chimneys and parapets. In addition, a need was identified to classify parapets with different boundary conditions into groups enabling a more accurate assessment of their lateral behaviour.

2.3 Europe

Erberik (2008) classified 209 Turkish URM buildings located in the region of Dinar (Afyon) and Zeytinburnu (Istanbul), based on number of storeys, irregularities in plan, wall construction material and size of walls and openings. In Italy, existing databases of buildings such as CARTIS (Caratterizzazione TIpologica Strutturale) developed by research groups of Italian Universities are commonly used to perform seismic assessment studies for a region (Nale et al. 2021, Brando et al. 2021). Masi et al. (2014) characterised 17500 dwellings including all types of buildings in 18 villages located in Val d'Agri area (Basilicata region, Southern Italy). Uva et al. (2016) surveyed 4519 Italian buildings of Foggia city, Vico del Gargano, Sant'Agata di Puglia, and Carlantino. Chieffo et al. (2019) characterised 50 URM buildings in Muccia, Italy. Valluzzi et al. (2021) inspected and analysed 2306 buildings/structural units of 20 villages in Central Italy after the 2016 Central Italy earthquake. The buildings were characterised based on position, number of floors, masonry units used, mortar used and types of floor and roof diaphragms. Furthermore, the influence of these parameters over the structural damage was also studied. Pavić et al. (2019) classified 1075 URM and other buildings located in Osijek, Croatia from existing database and field surveys, based on construction year, number of storeys, size, floor types and irregularities as given in Table 1. Santos et al. (2013) grouped buildings in old city centre of Seixal, Portugal, based on building age, size and materials. Lovon et al. (2021) characterised residential URM stone buildings of Portugal, based on building sizes.

For a certain European building construction form prevalent in Groningen region, Kallioras et al. (2018) & Tomassetti et al. (2019a, 2019b) identified gable end typologies and studied their lateral stability. As a result of these studies gable-end walls were pointed out as the most vulnerable non-structural component of European buildings. Many other studies from across Europe have considered parapet typologies that are fundamentally regular cantilevers supported at their base (Sorrentino et al. 2011, Godio & Beyer 2019, Degli et al. 2021).

The dimensions and other properties of the subject buildings in European studies are more detailed and in-depth when compared to those in New Zealand and Australia-based studies, because the former studies included vulnerability studies. In particular, an important dimension is the wall height, which is lacking in most of the Australian and New Zealand studies.

2.4 Other regions

Athmani et al. (2015) used an existing database (CTC 2010) and categorised 380 masonry buildings in Annaba, Algeria based on building age, size, number of storeys and roof/floor details and irregularities. Jiménez et al. (2018) used building survey forms to document 111 buildings located in Valparaíso, Chile. F. Salazar, & Ferreira (2020) identified 36 typologies from residential buildings stock located in La Merced, Mexico. Novelli et al. (2021) conducted field surveys to collect data and categorised 323 URM buildings of Malawi. Giordano et al. (2021) used this data for developing fragility curves. Aleman et al. (2015) conducted experimental research with a scope to study the seismic behaviour of regular parapets with rectangular shape and connected to a flexible diaphragm at base.

Similar to studies in Europe, studies in other parts of the world are also in great details compared to Australian and New Zealand based studies.

2.5 Summary of literature review

The above-mentioned literature assisted in the identification of two sets of parameters i.e., those related to building classification and those related to vulnerability/risk assessment. The building classification parameters included building age, number of storeys and floor/roof details. The vulnerability/risk assessment parameters included size of the buildings, openings in the walls, occupancy, position of the buildings and irregularities. How these parameters can affect the seismic performance of URM buildings have been discussed in the following paragraph.

The construction year indicates the quality and method of construction at that time. The older the URM buildings, the more vulnerable they are to seismic excitations as they would have been built, prior to the introduction of seismic codes and without seismic detailing (Russell and Ingham 2010). Number of storeys is used to reflect approximate building period and modal properties of buildings to estimate their seismic capacities. Information about floor/roof details can be very useful to assess building behaviour during earthquake (Valluzzi et al. 2021).

The size of the buildings can greatly influence the performance of buildings during earthquake especially the height of URM building façades/parapets. In addition, roof behind the façade/parapets (boundary condition) can influence the position of the hinge in the overturning of the façade/parapet. Façades usually fails by one-sided rocking mechanism when insufficient connections to floors/roofs and side walls are provided. Parapets, gable-end walls and chimneys failure corresponds to two-sided rocking (Vlachakis et al. 2021). The failure of these masonry elements can be limited by providing restraints (Giresini et al. 2018, Jaimes et al. 2021, Solarino et al. 2021, Giresini et al. 2022) and also by improving the in-plane stiffness of the flexible roof by providing a roof sheathing material (Giongo et al. 2014). The taller the URM building façades/parapets, the more vulnerable they are during seismic excitations because seismic excitations are amplified at the top of the building and the upper floor walls (Derakhshan et al. 2020b; 2020c), which are usually thinner than the lower storey walls (Russell and Ingham 2010), can fail in OOP direction. The roof behind the parapet has a significant influence on the OOP behavior of façades (Tomassetti et al. 2019a). The characterisation of shape and construction details such as boundary conditions of façades/parapets are important. The presence of a strong canopy in front of the façade can help protect pedestrians from the falling masonry debris (Galvez et al. 2019). The presence of openings in masonry walls can greatly influence their performance during earthquakes especially their in-plane behaviour (Parisi & Augenti 2013). Position of the building (connected or isolated) can help to determine the pounding risk during an earthquake (Cole et al. 2012). Plan irregularity produces torsion as well as regions of high-stress concentration during seismic excitations. A regular-shaped building performs better during earthquakes than those with irregular plans (Erberik 2008).

The literature review assisted with identification of parameters affecting the global building vulnerability, and the parameters were studied for the surveyed buildings as discussed in the next few sections. In addition, a special focus was placed on parapet characterisation based on shape and boundary conditions, which include roof type and configuration.

3. Queensland seismicity

This work will address seven towns from Queensland. Six of the seven surveyed towns fall in Zone 3 of the seismic zoning map developed by Queensland according to Queensland Fire and Emergency Services (QFES 2019) as shown in Figure 2. Zone 3 is accorded as Queensland's highest earthquake research priority area due to significant risks.

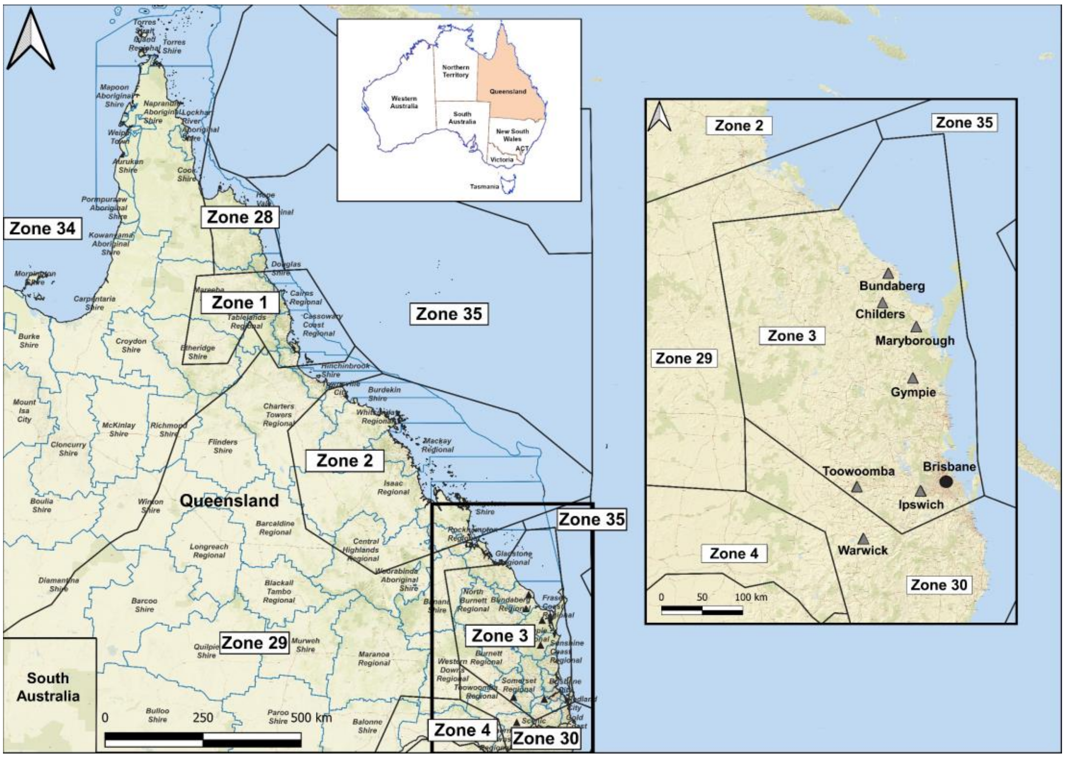


Figure 2. Seismic zoning map of Queensland (QFES 2019) and surveyed towns

Queensland has experienced 17 documented earthquakes of magnitude 5 and more in the past 140 years as shown in Figure 3. A summary of observations reported at the time of earthquakes are presented herein for the purpose of contextualising the survey work.

The oldest documented 5+ magnitude earthquake is 1883 Gayndah earthquake (Richter magnitude, M_L 5.9), which was followed by an aftershock of lesser intensity (M_L 5.2) on the same day. In Gayndah, several brick buildings were damaged including a courthouse, the School of Arts and a state school. The courthouse walls were split at several locations. This earthquake was also felt in towns such as Maryborough, Toowoomba, and Warwick, all of which were surveyed in this study. Cracks were also noticed in elevated areas of the brick walls of a Toowoomba Hospital building, located 230 km from the epicentre. In Maryborough region, cracks were developed (Rubenach et al. 2020) in walls of several buildings located on Kent Street, Childers, which is also a town that was surveyed as part of this study.

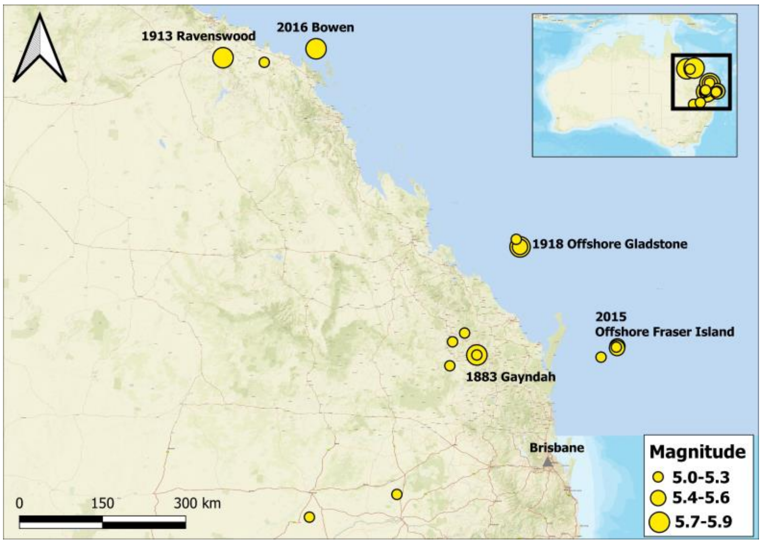


Figure 3. Known history of 5+ magnitude earthquakes in Queensland

An earthquake with M_L of 5.2 occurred in Mundubbera in 1910, with associated brick wall damage being reported in Bundaberg situated about 85 km away from the epicentre. A foreshock to this earthquake was reported in Childers, and a slight aftershock next day was also reported in Rockhampton, situated 205 km north of the epicentre (Rubenach et al. 2020).

An earthquake of magnitude (M_L) 5.7 occurred in Ravenswood in 1913. This region is located in Zone 2, and the earthquake was also felt in Mackay, Townsville, Ayr, Brandon, Charters Towers, and other locations north of Mackay. These areas are located in Zones 2 and 9, which are of a lower seismic research priority than Zone 3. There is no evidence of earthquake induced damage in the masonry buildings (Rubenach et al. 2020) in these regions.

An earthquake of magnitude (M_L) 5.7 occurred in 1918 in the ocean at about 130 km from Gladstone. The main shock was felt most intensely at Bundaberg, Rockhampton, and Yeppoon. This event was followed by many aftershocks, and building damage included plaster spalling, wall cracking, broken windows, and toppled chimneys. At Toowoomba, the tremor was considered severe, waking most of the town, shaking houses, and displacing furniture. This earthquake was considered to have a similar intensity to the 1883 Gayndah earthquake based on local residents' feedback (Rubenach et al. 2020).

A second Gayndah earthquake occurred in 1935 with a magnitude of (M_L) 5.2. It was felt over a wide area in Southeast Queensland, being reported from Rockhampton to Warwick. This event led to the installation of a permanent seismograph in South-East Queensland. The township of Monto, located 90 km from the epicentre, was strongly impacted with several cracks in brick walls and damage to cement buildings. Broken crockery was reported in Bundaberg, Gympie, Maryborough, and Rockhampton (Rubenach et al. 2020). Other significant earthquakes were the 1956 St George earthquake, 1965 Goondiwindi earthquake, 1978 Heron Island earthquake and 2016 Bowen earthquake, with no damage to URM buildings being recorded.

Pictorial evidence of damage to URM buildings or components located in the Queensland State during past Queensland earthquakes is unavailable. However, damage to URM buildings during Australian earthquakes has been documented for the 1989 Newcastle, NSW (M_L 5.6) and 2010 Kalgoorlie (M_L 5.0), WA earthquakes as shown in Figure 4. The damage is especially focused on facades and non-structural components such as gable-end walls and parapets (see Figure 1). Figure 4a shows complete collapse of full façade of a URM building during the 1989 Newcastle, NSW earthquake (M_L 5.6). Figure 4b shows collapse of parapet of URM building during the 2010 Kalgoorlie Boulder, WA earthquake (M_L 5.0). Figure 4c shows collapse of two gable end walls and a damaged chimney during the 1989 Newcastle, NSW earthquake (M_L 5.6). Due to this evidence of damage to non-structural components, a specific focus of this research was on classifying parapets.

a) Kent hotel after the 1989 Newcastle, NSW earthquake (M_L 5.6)

b) The commercial hotel after the 2010 Kalgoorlie Boulder, WA earthquake (M_L 5.0)

c) The Junction public school after the 1989 Newcastle, NSW earthquake (M_L 5.6)

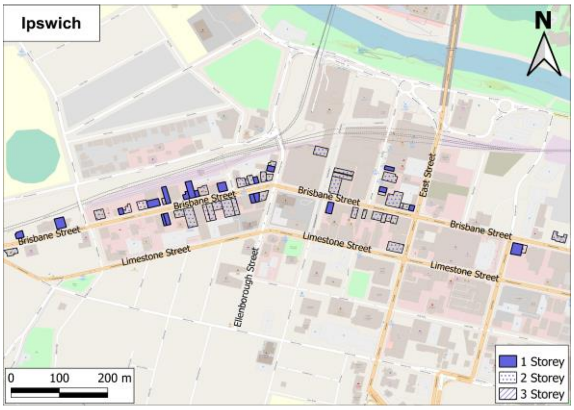
Figure 4. Performance of non-structural URM building components during past Australian Earthquakes.

4. URM buildings survey

Seven towns and cities of Queensland located to the West, North and South of Brisbane City were visited to document the details on URM buildings. A location map of these towns that included Ipswich, Warwick, Toowoomba, Gympie, Maryborough, Childers and Bundaberg is shown in Figure 2. In addition, Figure 5 shows the location and footprints of URM buildings within these towns. The maps of Figure 5 were created using QGIS, an open-sourced geographic information system. The building coordinates were obtained from Nearmap (2021). A total of 363 URM buildings were surveyed (Figure 6), including 77 in Maryborough, 76 in Toowoomba, 58 in Ipswich, 46 in Bundaberg, 45 in Warwick, and 13 in Childers. These towns were selected because of the seismicity of Queensland and many vintage (pre-1940) URM buildings in these towns were registered in the Queensland Heritage Register (QHR, Davies 2014). The protocol for the survey was to include commercial URM buildings and exclude Governmental buildings such as schools, post offices, town halls etc. Some buildings were located on the street corners, and as these buildings have two façades, the features of main façades were studied, with the main façade being assumed to be the building façade that included the main building entrance. A brief description of these towns is provided in the following paragraph.

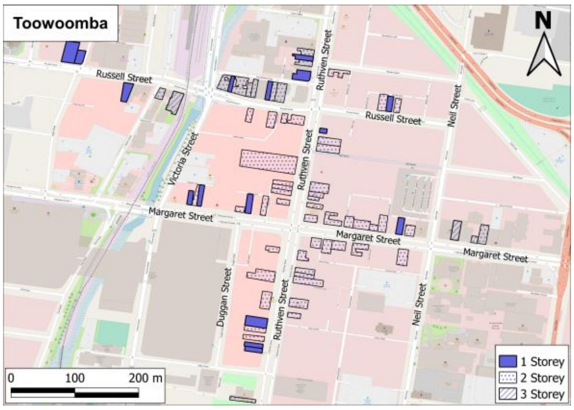
Ipswich is the CBD of the city of Ipswich, and most of the vintage (pre-1940) URM buildings of this area are located on the Brisbane Street (Figure 5a). Warwick is situated about 130 kilometres South-West of Brisbane, and most of the pre-1940 URM buildings of this town are located on the Palmerin Street (Figure 5b). Toowoomba is a regional city in the Toowoomba Region, Queensland, Australia. This town is 125 km away from Brisbane by road and is West of Brisbane. Pre-1940 URM buildings in Toowoomba are located on the Ruthven, Russell, and Margaret Streets (Figure 5c). Gympie is located in the Wide Bay-Burnett district, 170 kilometres north of Brisbane, and most of the pre-1940 URM buildings of this town are located on Mary Street (Figure 5d). Maryborough is a city and a suburb in the Fraser Coast Region, with most pre-1940 URM buildings being located on Adelaide and Kent Streets (Figure 5e). Childers is a rural town and locality in the Bundaberg Region with most of the pre-1940 URM buildings being situated in Churchill Street (Figure 5f). Finally, Bundaberg is situated about 385 kilometres north of Brisbane with pre-1940 URM buildings that are clustered on Bourbong Street (Figure 5g).

Parameters noted during the survey included buildings coordinates, address, façades dimensions (including opening ratio) acquired using laser-based measurement equipment (IkeGPS), construction year noted from the pediments and number of storeys via visual observations. Building lengths and footprints were acquired using Nearmap (2021). Other details e.g. window openings, roof shape (but not structure), presence of chimneys and canopies, parapet shapes and presence of ornamental features e.g. pilasters, pediments, balustrades were captured after the survey during desk study using online maps like Google maps. The surveyed buildings all were made of clay bricks although a detailed material characterisation was outside the scope as discussed earlier in the introduction.

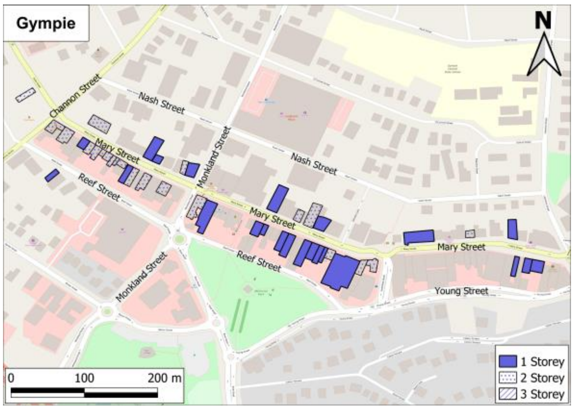


a) Ipswich

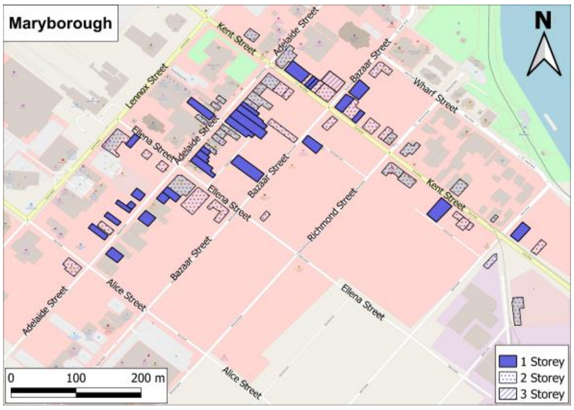
b) Warwick



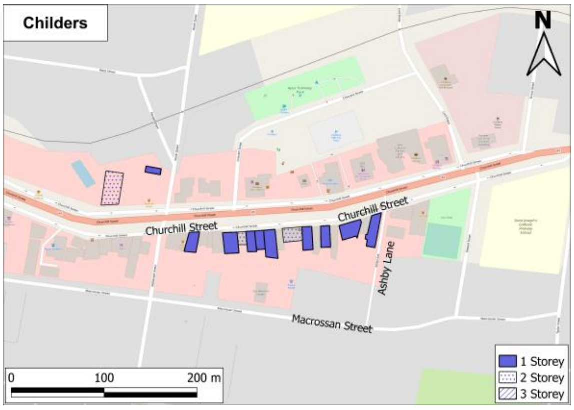
c) Toowoomba



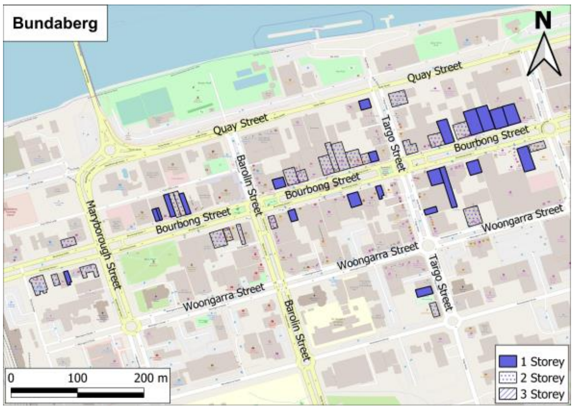
d) Gympie



e) Maryborough



f) Childers



g) Bundaberg

Figure 5. Areas where most of pre-1940 URM buildings are located

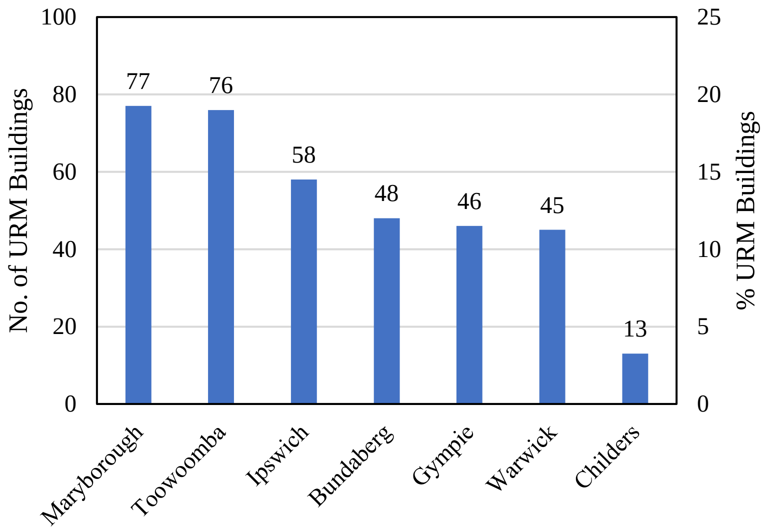


Figure 6. No. of vintage (pre-1940) URM buildings in each town

4.1 Construction Year

Before the survey, QHR was studied to identify the location and date of construction of URM buildings. For some buildings, the year of construction was noted from the pediments. Out of 363 buildings, the construction year of only 134 could be determined (about 37%) from the QHR and from the pediments. It was identified that the greatest proportion of existing URM buildings in these towns were constructed between 1881 and 1890 (see Figure 7). Overall, the data indicates that these buildings were constructed in a span of about 80 years prior to 1940, pre-dating the introduction of seismic codes. This short time period of construction provides an advantage in effective characterisation of the URM buildings in Australia as opposed to that in other regions, e.g. in Europe. The long history of masonry construction in the latter poses challenges in the building classification (Russell and Ingham 2010).

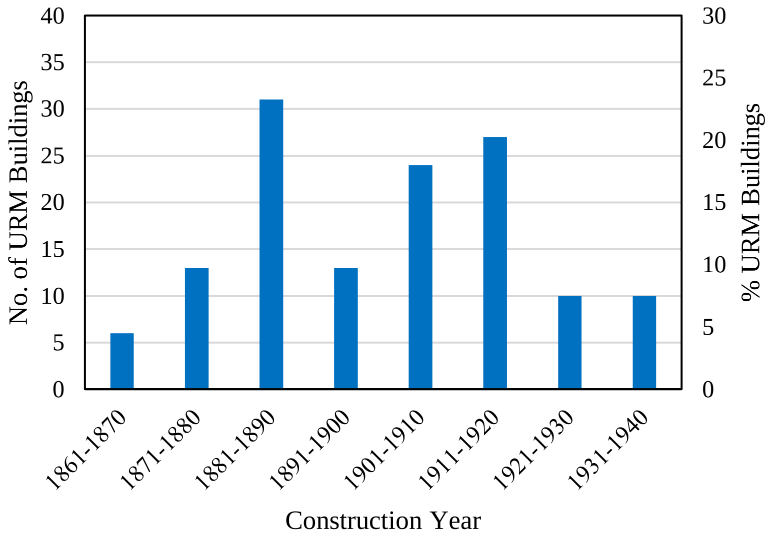


Figure 7. Known construction period of URM buildings

4.2 Isolated Vs interconnected buildings

About 91% of the buildings were interconnected, with no separation gaps between two adjacent buildings (see Figure 8). This condition is likely to result in pounding-related damage during an earthquake (Cole et al. 2012, Shrestha and Hao 2018), especially when floor levels are different as shown in Figure 8.

Figure 8. Inter-connected buildings in Gympie

4.3 Number of storeys

Only four of the total surveyed buildings had three storeys. For the rest of the surveyed buildings, it was found that two-storey construction was the most common (59%) followed by one-storey structures (40%). From Figure 9, it can be seen that several towns have almost equal numbers of one and two-storey building. In Maryborough, Toowoomba and Ipswich, two-storey buildings are more common than one-storey buildings, whereas the opposite is true for Childers.

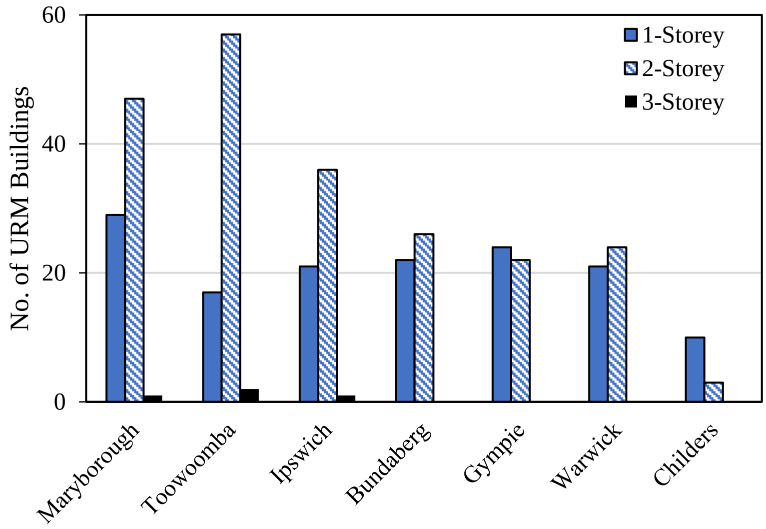


Figure 9. No. of storeys of pre-1940 URM buildings in each town.

4.4 Buildings Dimensions

Dimensions of the building façades were measured using Spike device manufactured by IkeGPS (2021). This device is handheld and is clamped to the back of a smartphone or tablet, which is used to record a picture of the building façade. The dimensions can be extracted during post-processing with good accuracy. The device contains a laser rangefinder, compass and Bluetooth. The device pairs with the phone or tablet via Bluetooth and is controlled through a mobile app to access the smartphone or tablet's camera, accelerometer, and Global Positioning System (GPS) information. The manufacturer specifies that the accuracy of the rangefinder is ±5 cm for objects located between 2 and 200 m away, and the accuracy of the photo measurements is ±1% of the object being measured (IkeGPS 2021). When using the Spike device, it was made sure that a clear line of sight to the buildings was established so that accurate dimensions could be acquired. In follow-up desktop studies, supplementary building plan dimensions were obtained using Nearmap (2021).

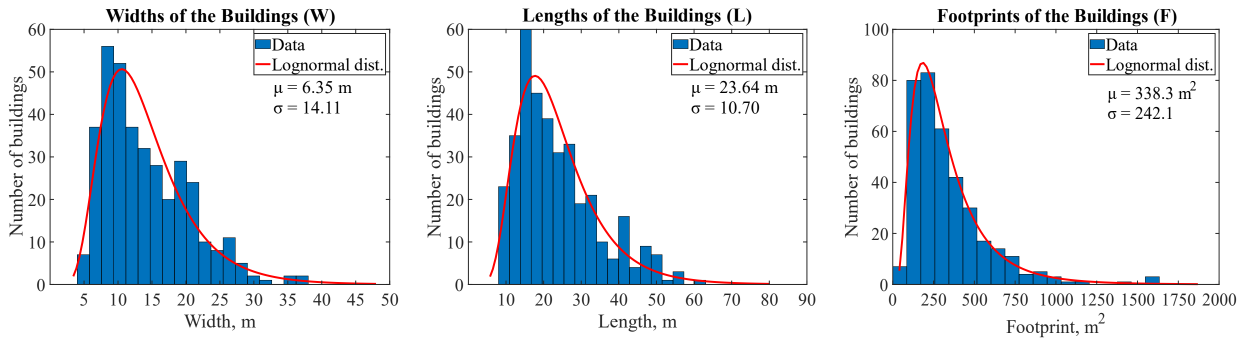
Critical dimension properties are reported herein including a statistical evaluation of the probability distributions. For statistical evaluation, Goodness of Fit tests were performed on Normal, Lognormal, Weibull and Gamma distribution functions. The best distribution was selected based on Anderson-Darling (AD) and P-value criteria, which include lowest AD-value and highest P-value.

During the survey, it was difficult to establish the thickness of the façade walls and whether façade walls had solid or cavity construction. But from visual observations, solid walls especially at the parapet level can be clearly seen from the side of the buildings, the thickness of which were either 230mm or 350mm i.e. one brick and one and half brick thick, respectively.

4.4.1 Plan

The distribution of the overall widths (W) and lengths (L) of the buildings are shown in Figure 10a and Figure 10b, respectively. Building widths in the range of 6-13m are the most common, with greater widths being appropriate for row buildings. The mean width of the buildings is 14.11m.

For irregular buildings, the longer side is taken as total length of the buildings considered in the data. Lengths of 11-23m are the most common. The mean value for length of the buildings is 23.64m. Moreover, from the plan view it was found that 19% of the buildings are irregular. The plan area (footprints) of the buildings is reported in Figure 10c. Footprints (F) of 110-350 m^2 are the most common. The mean for footprint of the buildings is 338.32 m^2.



a) Widths of the buildings b) Lengths of the buildings c) Footprints of the buildings

Figure 10. Distribution of building floor dimensions.

4.4.2 Building Elevation

Figure 11 shows a typical URM building façade including parameters, W (building width), H1 (height from ground level to the side of the parapet), H2 (total height), h1 (ground-storey height), h2 (first-storey height), P1 (parapet corner height from roof line), P2 (parapet center height from roof line), x (window width), y (window height) and finally C (height from roof line to cornice).

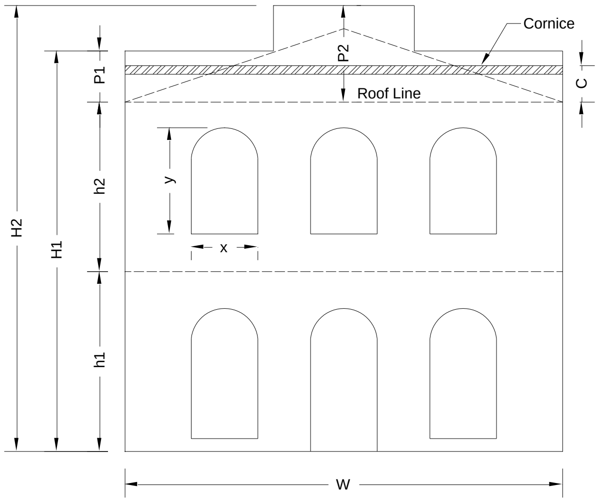
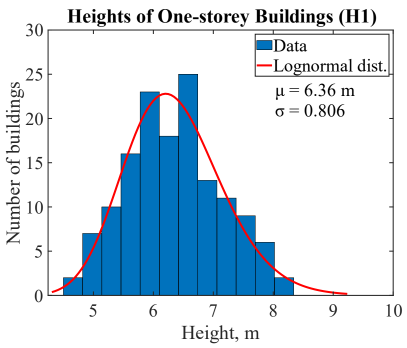


Figure 11. Typical representation of different dimensions of the buildings.

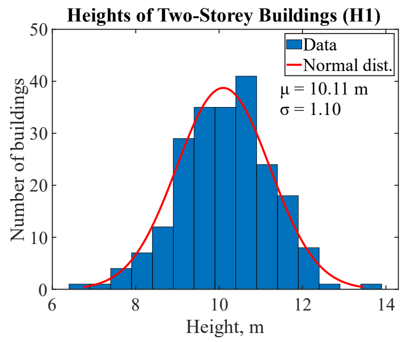
Only four of the total surveyed buildings had three storeys. Their average total heights H1 and H2, are 13.9m and 16.3m, respectively. The average ground-storey heights (h1), first-storey heights (h2) and the second-storey heights are 4.75m, 4.05m and 3.65m, respectively.

The distribution and fitted probability functions are presented in Figure 12 for heights H1 and H2, plotted for one and two-storey buildings. Similar data are presented in Figures 13 and 14 for storey heights and parapet heights in these buildings.

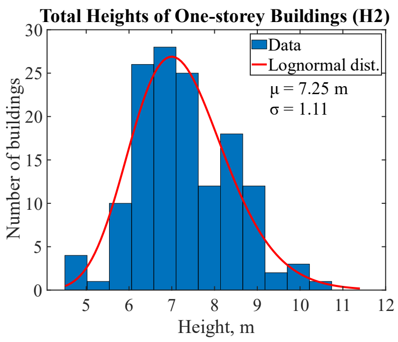
The mean for heights H1 and H2 in one-storey buildings were, respectively, 6.35m and 7.25m, and these parameters were, respectively, 10.09m, and 10.93m for two-storey buildings.



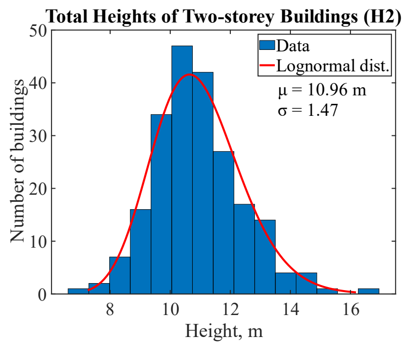
a) Heights (H1) of one-storey buildings



b) Heights (H1) of two-storey buildings



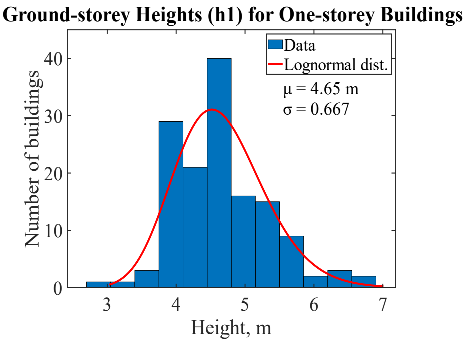
c) Heights (H2) of one-storey buildings



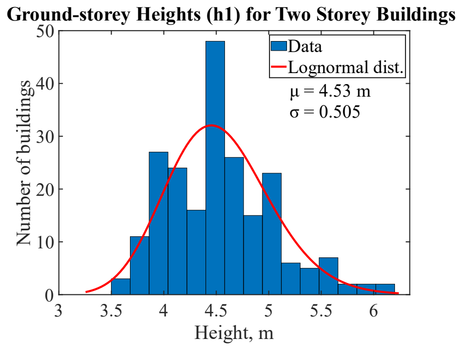
d) Heights (H2) of two-storey buildings

Figure 12. Building heights distributions.

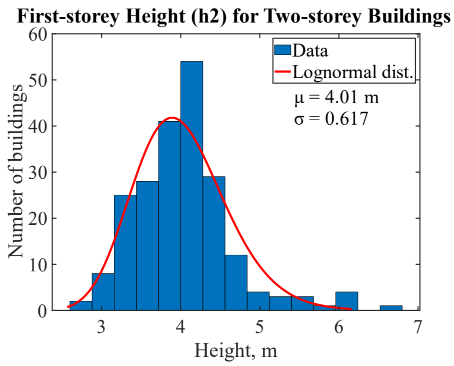
The mean storey height was between 4.0 m and 4.65 m, with mean h1 being 4.65 m and 4.53 m, respectively, for one-storey and two-storey buildings. The mean h2 in two-storey buildings was found to be 4.01m.



a) Ground-storey heights (h1) for one-storey buildings



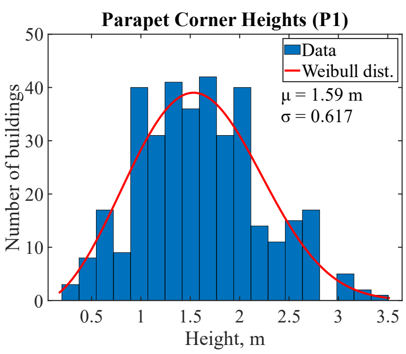
b) Ground-storey heights (h1) for two-storey buildings



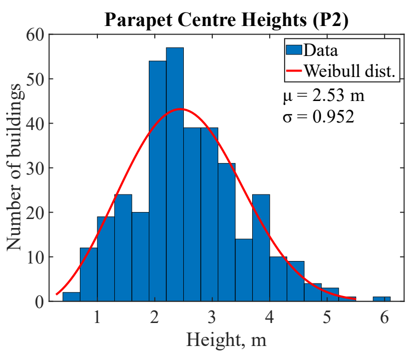
c) First-storey height (h2) for two-storey buildings

Figure 13**.** Storey heights distributions.

Parapet heights (P1 and P2) were measured from the roof line/eaves and are reported in Figure 14. The mean parapet corner height, P1, and parapet centre height, P2, were, respectively, 1.59m and 2.53m.



a) Parapet corner heights (P1)



b) Parapet centre heights (P2)

Figure 14. Distribution for parapet heights.

A common perception in visual building observations is that the roof line is situated along the cornice, which is a projected portion seen at the top of the façades (see Figure 16). It was found during the survey that the roof line is situated within a mean distance C of 1.018 m (see distribution in Figure 15) below the cornice. This type of construction results in a relatively tall cantilever masonry parapet.

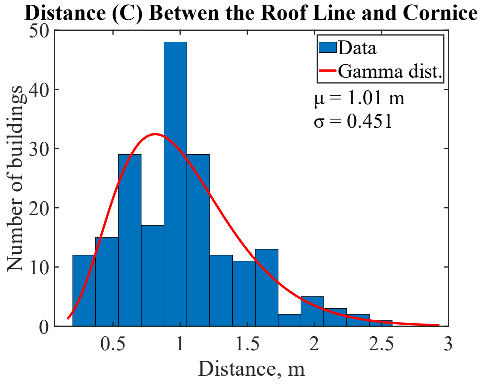


Figure 15. Distance (C) between the roof line and cornice.

Figure 16. Positioning of the roof line with respect to cornice.

4.5 Roof types

The percentages roof types were pitched (50%), hipped (28%), skillion (11%), flat (2%), and multi-pitched (16%) as shown in Figure 17. These roofs were mostly covered with corrugated iron/steel sheets. About 9% of the buildings had irregular roofs, for example a building with hipped roof but having some walls connected to a pitched roof. Similarly, some buildings had pitched or hipped roof sections but also had significant skillion roof sections. The information presented in Table 2 is consistent with findings of Howlader et al. (2016) who concluded that gabled (pitched) roofs are the most common roof type in NSW (40%) followed by hipped roofs (36%). Table 2 and Figure 18 are based on roofs connected with the main façade of the URM building that were encountered during the survey.

For some buildings, several hipped and pitched roof sections were connected to a single façade. The number of these occurrences is reported in Table 2 and shown in Figure 18, where for example 3P refers to a façade being connected to 3 pitched section of a roof. In some instances, the pitched roof was off-centre of the parapet as shown in Figure 19. In addition, the roof pitch angle was determined using façade measurements. It was found that the pitch angle of the pitched roof for the majority of the URM buildings was between 20^{o} and 30^{o} as shown in Figure 20, with the mean value of 24.94^{o}.

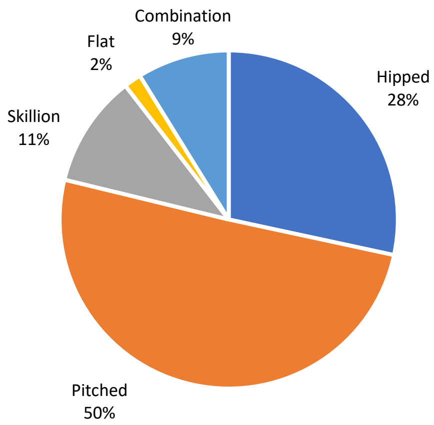


Figure 17. Distribution of type of roofs in URM Buildings.

Table 2. Number of roof types in URM Buildings

Location	**Roof Types**															**Total**
	1-H	**2-H**	**3-H**	**4-H**	**1-P**	**2-P**	**3-P**	**4-P**	**5-P**	**S**	**Flat**	**IP**	**C1**	**C2**	**C3**	
Maryborough	19	2	0	0	24	5	4	1	2	13	0	0	2	4	1	77
Toowoomba	13	3	0	1	35	6	4	0	0	5	0	0	4	4	1	76
Ipswich	20	4	2	0	17	6	3	1	0	3	1	0	0	1	0	58
Bundaberg	8	1	2	0	17	4	3	0	0	4	0	0	1	5	3	48
Gympie	10	0	0	0	17	4	2	0	0	8	0	2	1	1	1	46
Warwick	14	1	2	0	11	5	1	1	0	4	5	0	1	0	0	45
Childers	1	0	0	0	4	2	1	1	0	2	0	0	0	2	0	13
Total	**85**	**11**	**6**	**1**	**125**	**32**	**18**	**4**	**2**	**39**	**6**	**2**	**9**	**17**	**6**	**363**
Prevalence (%)	23	3	2	0	34	9	5	1	1	11	2	1	2	5	2	100

Where: H= Hipped; P= Pitched; #H= number of hipped roofs in a row; #P= number of pitched roofs in a row; S= Skillion; IP= Inverted Pitched (butterfly roof); C1= Combination of hipped and pitched roofs; C2= Combination of pitched and skillion roofs; C3= Combination of hipped and skillion roofs

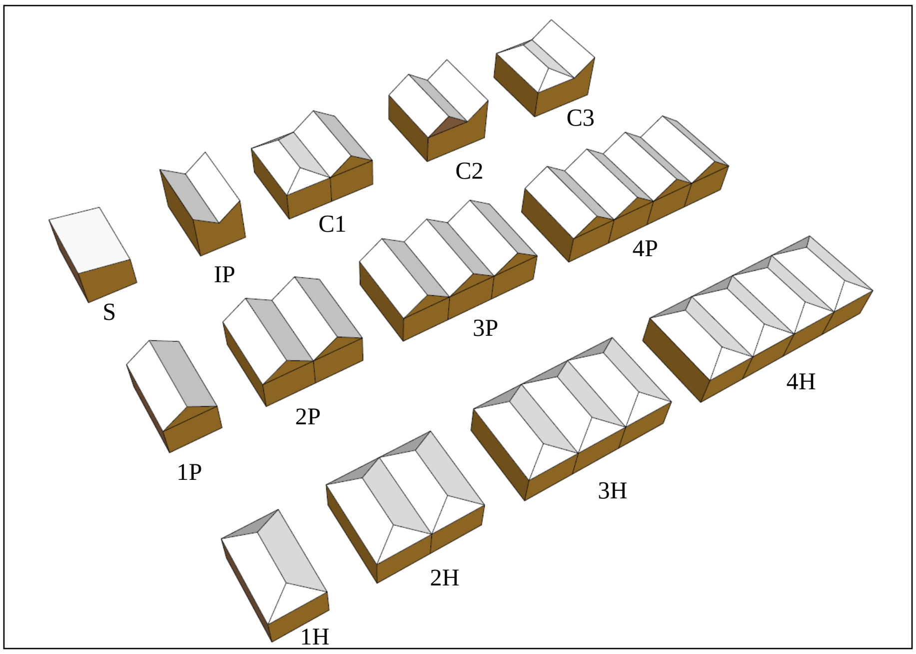


Figure 18. Examples of roof types in URM Buildings (Parapets are not shown).

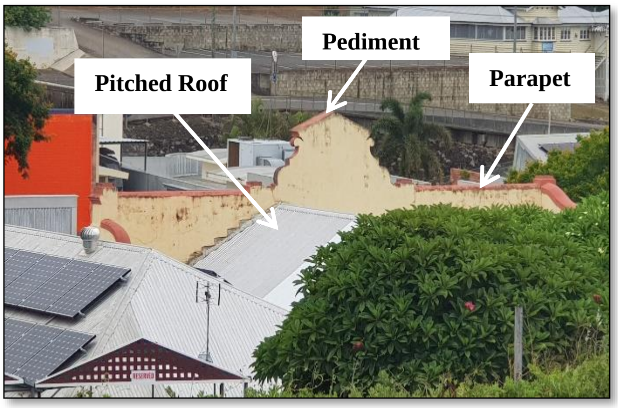


Figure 19. Off-centred pitched roof in Gympie.

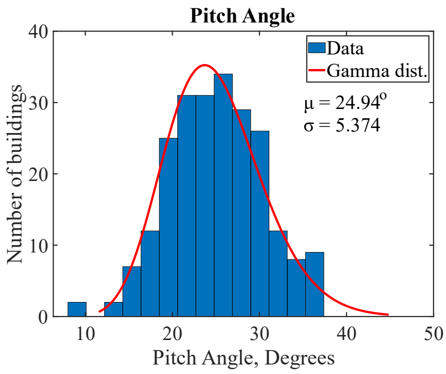


Figure 20. Pitch angle distributions.

4.6 Parapet Typology

Parapets have been constructed in different styles ranging from simple straight parapets to more complex shaped parapets. Their construction also depends upon which roof type is constructed behind the parapets. They are mainly constructed for aesthetic purposes, to hide the roof structure behind it and to act as a fire barrier to protect the combustible roof material from fire that can emerge from inside of the building and propagate to the roof through windows (Burrell 1907). The minimum height of parapet above the gutter should be at least 300mm and the thickness should be approximately 210mm (Burrell 1907). Since there were many different types of parapets encountered during the survey, it was necessary to categorise them based on roof types and construction details. The building parapets were categorised into seven groups, some with further sub-divisions.

It is highlighted that the parapets encountered during the survey are mainly of four types but some of them have different boundary condition (i.e. roof). Although the overall geometry of the prevalent parapets is well contained within the typologies reported below, it is acknowledged that realistic dimensions of prototype parapets are required in order to conduct further seismic assessments. In particular, it is noted that the previously-reported median parapet corner and centre heights (P1 and P2 in Figure 11 and Figure 14) may not be directly usable in structural models as they are median values of the aggregate of data. A similar problem has been reported in Russell and Ingham (2010), which outlines only the median and distribution of various building dimensions. To alleviate this shortcoming in conducting a quantitative vulnerability study, it is recommended that the detailed database of actual parapet geometries (Derakhshan et al. 2022) that accompanies this work be used in conjunction with the current interpretive paper.

4.6.1 Type I

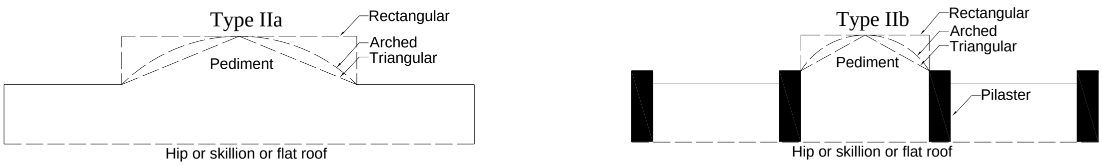
This type includes a solid straight rectangular parapet connected to either a hipped, skillion or flat roof behind. This type is further divided into two subtypes ie. Subtype Ia and Subtype Ib depending on the presence of pilasters as shown in Figure 21. These pilasters that can be found at certain intervals have the potential to increase the parapet stability.

a) Subtype Ia   b) Subtype Ib – with pilasters

Figure 21. Type I - Solid parapet with hipped, skillion or flat roof.

4.6.2 Type II

This type is a solid parapet with central pediment constructed in front of either a hipped or skillion or flat roof. The pediment is typically taller than the normal parapet wall. The pediment can be rectangular, arched or triangular in shape, and the parapet type is sub-divided into two subtypes i.e. Subtype IIa and Subtype IIb depending on the presence of pilasters as shown in Figure 22.

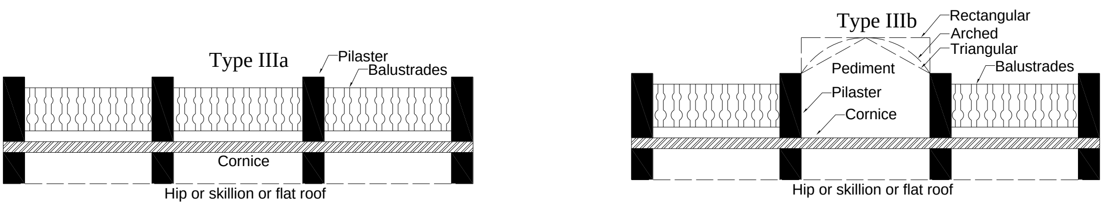


a) Subtype IIa   b) Subtype IIb – with pilasters

Figure 22. Type II - Solid parapet with hipped, skillion or flat roof having central raised portion.

4.6.3 Type III

This type of parapet has ornamental features such as balustrades, finials, pilasters, cornices, and pediments with either hip, skillion or flat roof. This type has lower heights and has pilasters which can provide extra stability to parapets and hence are considered as comparatively less risk posing during an earthquake. This parapet type is sub-divided into two subtypes i.e. Subtype IIIa and Subtype IIIb as shown in Figure 23. Figure 1 shows an example of parapet subtype IIIb.



a) Subtype IIIa   b) Subtype IIIb – raised centre

Figure 23. Type III - Parapet with hipped, skillion or flat roof having balustrades and pilasters.

4.6.4 Type IV

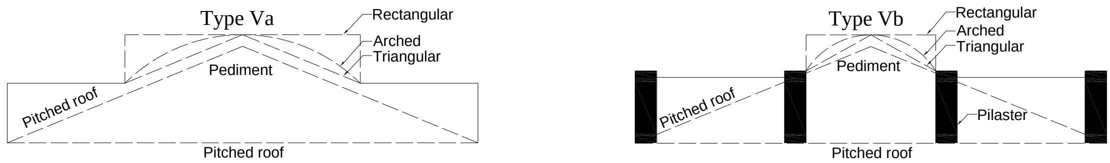
This parapet type is similar to Type I except that the roof behind is pitched resulting in relatively tall cantilever portions at the corners when compared to Type I. This type is sub-divided into two subtypes i.e. Subtype IVa and Subtype IVb depending on the presence of pilasters as shown in Figure 24.

a) Subtype IVa b) Subtype IVb – with pilaster

Figure 24. Type IV - Solid parapet with pitched roof.

4.6.5 Type V

This parapet type is similar to Type II except that the roof behind is pitched. It has a solid parapet with central pediment. The pediment can be rectangular, arched or triangular shape. This type is further sub-divided into two subtypes i.e Subtype Va and Subtype Vb depending on the presence of pilasters as shown in Figure 25. Figure 1 and Figure 19 is an example of parapet subtype Va.



a) Subtype Va b) Subtype Vb – with pilaster

Figure 25. Type V - Solid parapet with pitched roof having central raised portion.

4.6.6 Type VI

This parapet type is similar in construction to Subtype IIIb except that the roof behind is pitched as shown in Figure 26. Figure 16 also shows this type of parapet.

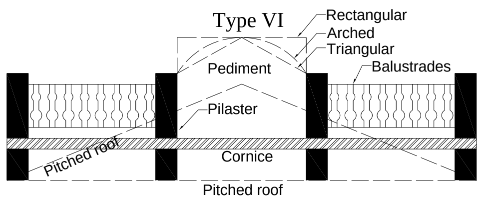


Figure 26. Type VI.

4.6.7 Type VII

This parapet type is also called gable type wall and the parapeted gable is as shown in Figure 27. It has a pitched roof with raised straight parapet running along the rafters of the roof. Figure 1 also shows this type of parapet.

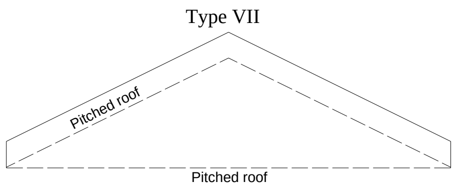


Figure 27. Type VII.

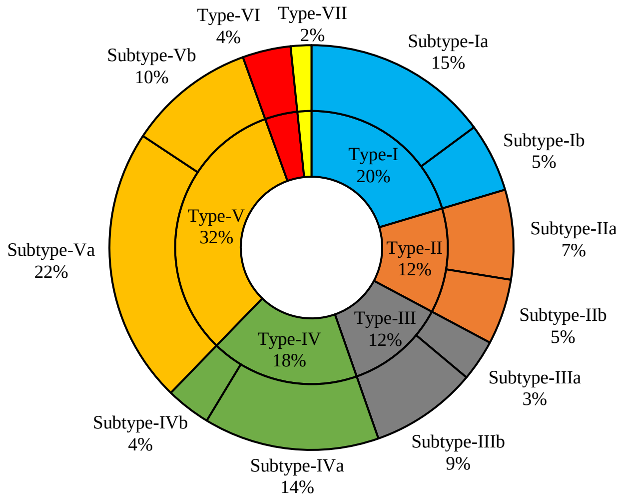


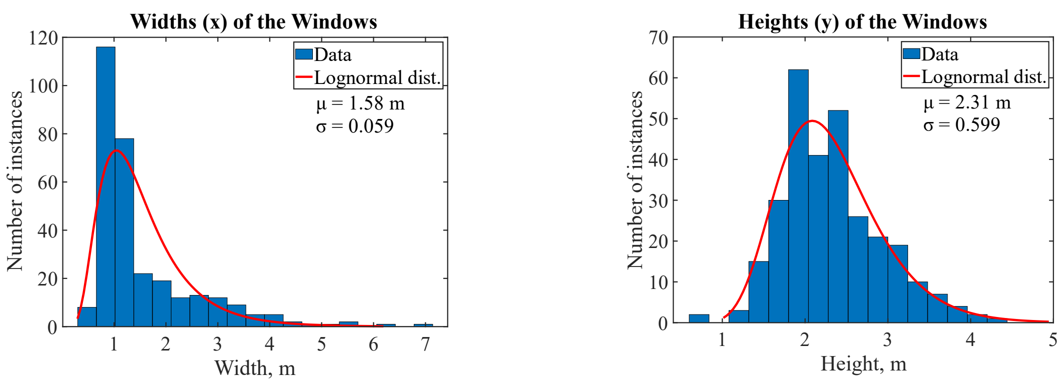
Figure 28. Parapet types and subtypes.

Figure 28 shows the distribution of main types of parapets and subtypes. It was found that Type V is the most common parapet type (32%), followed by Type I (20%). In Subtype Va, 9.1% of the parapets were triangular, 7.2% were rectangular, and 5.8% were arched. In Subtype Vb, 3.6% were triangular, 1.7% were rectangular, and 5.0% were arched.

4.7 Other Details

4.7.1 Window openings

From the surveyed photographs, it was found that 67% of the buildings had regular window openings but that the rest of the buildings (33%) had a large shop-front opening. The window openings are either rectangular/square (46% of buildings), arched (15% of the buildings) or a mix of both forms (6% of the buildings). Window dimensions were measured, with a summary reported in Figure 29. The mean window width (x in Figure 11) and height (y in Figure 11) are 1.58m and 2.31m, respectively. Figure 30 shows the façade opening ratio that was calculated from measurements, with the mean value being 0.336.



a) Widths (x) of the windows

b) Heights (y) of the windows

Figure 29. Distribution of windows dimensions.

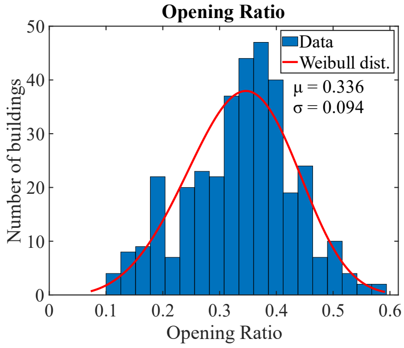


Figure 30. Distribution of façade opening ratio.

4.7.2 Chimneys

It was found that chimneys were present in 13% (47) of the buildings, with Toowoomba having the highest number of buildings with chimneys (15) followed by Warwick (10).

4.7.3 Presence of canopies

Details of canopies were obtained from the survey photographs, and it was found that 90% of the buildings have a shop-front canopy. Out of these, 60% of the buildings have suspended canopies, meaning that the canopy's end is supported through rods connected to the façades. In 27% of the buildings, canopies were cantilever, meaning that they are not supported through rods. In 13% of the cases, canopies are supported on the ground through either steel or timber posts/columns at their end.

4.7.4 Pilasters, pediments, balustrades, and finials

From this study it was found that 74% of the surveyed buildings included pilasters, 17.6% included balustrades, 40% included pediments, and finally 19.3% included finials. Examples of these elements are shown in Figure 1 and 15.

5. Identification of research gaps for seismic assessment

As evident from Figure 28, parapet subtypes Ia, IVa and Va are common in Queensland. Parapet subtype Ia have been extensively investigated as discussed in the introduction. Despite the abundance of studies on parapet subtype Ia and some studies on parapeted gables (type VII), no documented studies could be found in the literature on parapet subtype IVa and Va. Therefore, the applicability of the above studies to Australian URM buildings may be limited. To address this research gap, the following parapet types (see Figure 31) are recommended to be investigated for seismic behaviour.

a) Subtype IVa- Solid parapet with pitched roof

b) Subtype Va- Solid parapet with pitched roof having central raised portion

Figure 31. Recommended parapet types for further study.

6. Conclusions

This research included an investigation of the typologies of vintage (pre-1940) URM buildings prevalent in seven towns of Queensland, Australia through a field survey of 363 buildings. As a first step, a compilation of previous studies on the characterisation of masonry buildings around the world was presented assisting in understanding the building behaviour-influencing factors. A need for more work on Australian buildings was subsequently identified. Statistical survey data was presented on the building age, number and height of storeys, presence of non-structural components, roof types, and parapet types and dimensions. In addition, statistical data on some of vulnerability factors such as the building and especially the façades sizes that could be determined using brief external survey have been presented. The presented vulnerability factors are limited to externally visible building features and hence excluded parameters such as roof/floor stiffness and masonry material properties.

From the survey it was found that most of the buildings were constructed prior to 1940. The surveyed URM buildings were low-rise i.e. up to two-storeys and were made of brick masonry material. Different roof types were encountered during the survey, with about 50% of all roofs being of pitched type. The roof covering was mostly corrugated iron/steel, and the pitch angle was mostly between 20^{o} to 30^{o}. Parapets are relatively tall and often with a raised centre. The mean parapet height was 1.59m at the corner of the building and 2.53m at the centre. Most of the buildings (91%) were inter-connected (non-isolated), and about 19% of the buildings had plan irregularities. The parapets that were encountered in the survey were classified into seven typologies, some with further sub-divisions. Several prevalent typologies were recommended for further seismic assessment studies.

The raw data collected during this study is separately being published in a data archival journal (Derakhshan et al. 2022) and can be used to conduct a seismic vulnerability study of URM buildings in Australia. It can be concluded that none of the existing studies were focused on material properties of old Australian URM buildings, and this area is a significant research gap and hence recommended for exploration. Other areas of recommended further research include a comparative study of the ranges and distribution of factors influencing building vulnerability as identified from this research and those from international research, in particular from regions with available empirical URM building vulnerability data.

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