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Bolted Connection Design Recommendation of *Nyatoh* Hardwood for Retrofitting the Unreinforced Masonry Buildings

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Bolted Connection Design Recommendation of *Nyatoh* Hardwood for Retrofitting the Unreinforced Masonry Buildings

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A thesis submitted

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DECLARATION

I declare that the work in this thesis was carried out in accordance with the regulations of Universiti Malaysia Sarawak. Except where due acknowledgements have been made, the work is that of the author alone. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

………………………………

Signature

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ABSTRACT

Referring to the design code of the Malaysian Timber Standard of MS544: Part 5: 2001, the design of timber bolted connections only considers the ductile failure mode. This is opposed to the agreed principle set by the international timber engineering community of timber design standards. The principle states that the design code should be able to identify both ductile and brittle failures in order to determine the capacity of bolted connection strength. Therefore, there is a need to validate the existing Malaysian Timber Code in order to produce an optimised retrofit design of the wall-diaphragm connections for an unreinforced masonry building in Malaysia, especially the bolted connection on the floor joists or roof rafters. The occurrence of local earthquakes in Malaysia has increased in recent years, thus it is essential to provide sufficient lateral resistance to the unreinforced masonry building due to the absence of connections between the masonry brick walls and timber floor / roof diaphragms in the building as-built constructions. There are many unreinforced masonry buildings in Malaysia, of which, if subjected to earthquake, can cause major devastation and fatality, as most of these buildings are situated in main towns and business district. Because of the lack of bolted connection experimental data on wood species that commonly used to construct roof or floor diaphragms of unreinforced masonry buildings, a series of bolted connection test was conducted. By using the results obtained from this study, the effectiveness of the current timber code was validated and the accuracy of the other design equations such as the European Yield Model (EYM) and the Row Shear Model (RSM) was evaluated. From this experimental study, a calibration factor specifically for *Nyatoh* hardwood was identified to optimize the bolted connection design using the RSM for the brittle failure mode. To optimize the bolted timber connection design using the EYM for the ductile failure mode, a specific embedding strength value for *Nyatoh* hardwood was also provided. It was found that the design capacity given by the MS544-5 was too conservative when compared to the EYM and RSM for ductile and brittle failure modes, respectively. From the analyses of results, the 5th percentile bolted connection strength prediction of MS544-5 against the 5th percentile experimental results yielded a percentage accuracy of 27% - 39% for the connections that fail in the ductile mode. A percentage accuracy of 75% - 107% was determined using EYM for the ductile failure mode. In the brittle failure mode, the RSM yielded a percentage accuracy of 50% - 82%, while the MS544-5 generated 32% - 63%.

Keywords: Retrofit design, bolted connection, European Yield Model (EYM), Row Shear Model (RSM), Malaysian Standard (MS544)

Cadangan Rekabentuk Sambungan Bolt ke Kayu Nyatoh untuk Mengukuhkan Bangunan Batu yang Tidak Diperkukuh

ABSTRAK

Merujuk kepada kod rekabentuk Piawaian Kayu Malaysia MS544: Bahagian 5, rekabentuk sambungan bolt kayu hanya mengambil kira mod kegagalan mulur. Ini bertentangan dengan prinsip yang dipersetujui dan ditetapkan oleh komuniti kejuruteraan kayu antarabangsa bagi piawaian rekabentuk kayu. Prinsipnya menyatakan bahawa kod rekabentuk harus dapat mengenal pasti kedua-dua kegagalan mulur dan rapuh untuk menentukan kapasiti kekuatan sambungan bolt. Oleh itu, terdapat keperluan untuk mengesahkan Kod Kayu Malaysia sedia ada bagi menghasilkan rekabentuk pengubahsuaian yang optimum bagi sambungan dinding-diafragma untuk bangunan batu tidak bertetulang di Malaysia, terutamanya sambungan bolt pada gelegar lantai atau kasau bumbung. Kejadian gempa bumi di Malaysia telah meningkat dalam beberapa tahun kebelakangan ini, maka adalah penting untuk menyediakan rintangan sisi yang mencukupi kepada bangunan batu yang tidak bertetulang kerana ketiadaan sambungan antara dinding batu bata dan diafragma lantai kayu / bumbung dalam binaan asal bangunan. Terdapat banyak bangunan batu yang tidak bertetulang di Malaysia, yang mana jika terkena gempa bumi, boleh menyebabkan kemusnahan besar dan kematian, kerana kebanyakan bangunan ini terletak di bandar utama dan daerah perniagaan. Oleh kerana kekurangan data eksperimen sambungan bolt pada spesies kayu yang biasa digunakan untuk membina diafragma bumbung atau lantai bangunan batu tidak bertetulang, satu siri ujian sambungan bolt telah dijalankan. Dengan menggunakan keputusan yang diperolehi daripada kajian ini, keberkesanan kod kayu semasa telah disahkan dan ketepatan persamaan rekabentuk lain seperti European Yield Model (EYM) dan Row Shear Model (RSM) dinilai. Daripada kajian eksperimen ini, faktor *penentukuran khusus untuk kayu keras Nyatoh telah dikenalpasti untuk mengoptimumkan rekabentuk sambungan bolt menggunakan RSM untuk mod kegagalan rapuh. Untuk mengoptimumkan rekabentuk sambungan bolt kayu menggunakan EYM untuk mod kegagalan mulur, nilai kekuatan benam khusus untuk kayu keras Nyatoh turut disediakan. Didapati bahawa kapasiti rekabentuk yang diberikan oleh MS544-5 adalah terlalu konservatif jika dibandingkan dengan EYM dan RSM untuk mod kegagalan mulur dan rapuh. Daripada analisis keputusan, ramalan kekuatan sambungan bolt persentil ke-5 MS544-5 terhadap keputusan eksperimen persentil ke-5 menghasilkan ketepatan peratusan 27% - 39% untuk sambungan yang gagal dalam mod mulur. Peratusan ketepatan 75% - 107% ditentukan menggunakan EYM untuk mod kegagalan mulur. Dalam mod kegagalan rapuh, RSM menghasilkan ketepatan peratusan 50% - 82%, manakala MS544-5 menjana 32% - 63%.*

Kata kunci: *Rekabentuk retrofit, sambungan bolt, European Yield Model (EYM), Row Shear Model (RSM) dan Malaysia Standard (MS544)*

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CHAPTER 1

INTRODUCTION

1.1 Background

Unreinforced masonry (URM) buildings can be found throughout the world. It is often defined as historic buildings in the general public's eye because this building system was constructed prior to the late 1800s. They were so popular and widely used before the reinforced concrete and steel structures building systems taking place in the late 1800s or early 1900s. Due to the unique nature of the masonry buildings, many relevant authorities are keen to preserve it due to its aesthetic look, for examples the famous A Famosa remnants in Malacca and The Old Courthouse in Kuching, Sarawak. From 1992 to 1993, the Heritage Trust of Malaysia, in collaborations with the National Museum and Local Government Ministry and Faculty of Built Environment, Universiti Teknologi Malaysia, conducted a study on the heritage buildings and have estimated that there are around 39,000 of historic buildings are worth of preservations and protections (Idid, 1995).

Barrantes (2012) stated that in hundreds of years leading up to the modern days, URM buildings were constructed as it possessed the nature of high durability, fire resistance and isolation properties. This further explains the reason why most URM buildings still stand majestically like URM buildings in Kuching, Sarawak, albeit it has undergone through many harsh weather conditions that mother nature has to offer. This URM building will continue to stand tall, provided they are not subjected to lateral or horizontal external forces. According to the Federal Emergency Management Agency (FEMA, 2009), the URM building is typically comprised of masonry brick walls with no steel reinforcement bars to act as the vertical structural component, and roof / floor diaphragms that made from wood to serve the building as the horizontal structural element. Figure 1.1 shows the example of unreinforced masonry buildings that can be found in the Kuching City Centre. Typically, in their as built, the buildings provide no connections between the vertical and horizontal structural components, whereas the roof / floor diaphragms are found to be seated on the building perimeter walls. This significantly causes the buildings to be very vulnerable in resisting the lateral or horizontal external forces, which is predominantly induced by earthquakes. Nowadays, some of the buildings found to have wall-diaphragm connections that are found to be part of the strengthening efforts prior to lessons learned from the major earthquake events. According to Abdul Karim (2012), the major parts of the wall-diaphragm connections are divided into: (i) wall anchorages, either a through-bolt rod connected with an external wall plate, or a dowel rod drilled into the wall; and (ii) diaphragm connections, bolted connections to the timber floor joist or to the timber roof rafters.

Figure 1.1: The Old Courthouse in Kuching

The terminology of the URM buildings (FEMA, 2009) is mainly referring to the lack of extra reinforcement systems that are commonly used in modern construction practice like the reinforced concrete design. Pineda et al. (2011) stated that an ancient URM building is likely to suffer structural failures, which could result in global or local collapse mechanisms if these buildings are situated in a seismically active area. New Zealand Society for Earthquake Engineering (NZSEE, 2006) mentioned about the susceptibility of the construction of URM buildings to earthquake shaking due to its enormous mass, lacking in integrity between elements and cannot be easily deformed. The URM building weakest point is often referred to the inadequate restraint at the building storey-heights, which is the absence of wall-diaphragm connections. Major failures involving the inadequacy of the connections are the tearing out failure of timber floor or roof joists, the out-of-plane failure of masonry brick walls, and the global collapse of the floor diaphragms (Bausabah and Bruneau, 1992). Figure 1.2 shows the example of typical failure of roof joists off their wall supports in Santa Cruz, whereas Figure 1.3 shows the example of out-of-plane failure of URM walls. The tear-out failure of the timber joists directly signals a warning that the bolted connection design provides insufficient resistance, which is the main concern of the present study.

Figure 1.2: Typical Failure of Slipped Roof Joists Off Their Wall Supports (Bruneau, 1994)

Figure 1.3: Out-Of-Plane Failure of URM Top-Storey Wall at San Francisco, Loma Prieta Earthquake (Bruneau, 1994)

Russell (2010) stated that, the masonry walls that are loaded in perpendicular direction to the wall surface is termed as out-of-plane walls. In the case of out-of-plane failures, the masonry walls can collapse either by falling outward or inward from the building perimeter. Both walls collapse can significantly claim the lives of the building occupants and even the nearby pedestrians. The greater the height of the wall, the greater the flexural stress (Bruneau, 1994). As shown in Figure 1.4, the masonry walls act as a tall cantilever wall if there are no connections between the brick walls and the timber floor diaphragms when subjected to lateral loadings (Abdul Karim, 2012). From this observation, a retrofitting of the buildings by implementing the wall-diaphragm connections are very crucial to ensure the wall to be restrained at every building floor level in order to reduce the flexural stress to the walls. Thus, this present study was primarily initiated to provide an optimised design that focuses on the diaphragm connections, which is the bolted joint to the timber diaphragm structural members such as roof rafters and floor joists.

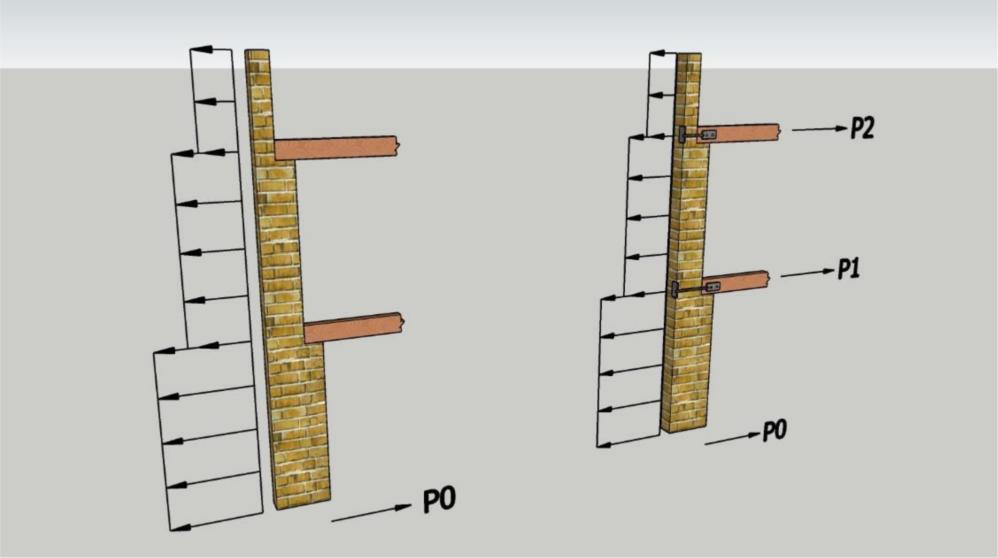

Figure 1.4: Behaviour of URM Walls Without Connections (left) and With Connections (right) (Abdul Karim, 2012)

In Malaysia, to design the timber bolted connection part, the MS544-5 (2001) can be used as a reference by the designers. The timber standard is developed based on the ductile failure mode when estimating the bolted connection strength. The brittle mode of failure is only considered with the use of k_{17} factor less than 1 for bolted connection that comprise of multiple bolts not less than 4 bolts per connection end as tabulated in Table 15 of MS544-5 (2001). Many published works (Abdul Karim et al., 2012; Abdul Karim et al., 2013; Abdul Karim et al., 2018; Abdul Karim et al., 2021; Abdul Karim et al., 2022) have identified that the geometrical parameters of the end distance, e, and spacing between bolts, s_b, govern the failure mode of the bolted connections as shown in Figure 1.5. From the studies by Abdul Karim et al. (2018), it was found out that the design strength provided by the existing Malaysian timber code was far too conservative when compared to the actual connection strength gathered from the laboratory data. The effectiveness of the design strength provided by the Malaysian timber standard was evaluated on the local hardwood of *Meraka*. The study disclosed a comparison between the MS544-5 code and the European Yield Model (EYM) versus the experimental results in order to assess their strength prediction accuracy. The EYM provides a better strength prediction with an average of 81% accuracy, while the MS544-5 only shows 38% efficacy. Thus, the study recommends that the design of bolted connection using EYM is more suitable for the retrofitting work on the URM buildings. Another study on brittle failure by Abdul Karim et al. (2021), also on *Meraka* hardwood, shows the same flaws on MS544-5, where the average accuracy of 79% was obtained via Row Shear Model (RSM) equation against 41% of MS544 standard. Thus, this present study was initiated to investigate the effectiveness of existing design equations on the *Nyatoh* hardwood due to the unavailable experimental data on the bolted connection of the selected local hardwood.

Figure 1.5: Illustration of Timber Bolted Connection Configuration Indicating The End Distance (e), and Bolt Spacing (s_b)

1.2 Issues with Unreinforced Masonry (URM) Buildings

An unreinforced masonry building is without a doubt recognized as the type of construction that is most vulnerable to earthquake strikes (Bruneau, 1994). It is termed ‘unreinforced’ due to the bricks, or the walls, do not have any support or anything to hold the building structure firmer. If subjected to lateral force such as the earthquake load, the URM buildings are prone to disconnect from other building components and collapse, which then potentially harming the nearby pedestrians in the process. Poor connections between masonry walls and the wood diaphragms are also one of the main causes of walls overturning and collapsed of floors during an earthquake (Moreira et al., 2014). Other characteristics of URM buildings defined by other sources are given below.

i. URM common types of construction were solid cavity walls (NZSEE, 2017). Industrial buildings and buildings on the outskirts of town mainly used solid walls besides partition walls and walls, either not visible or in the lower storeys. Cavity wall meanwhile, were used as control moisture ingress in a building. New Zealand Society for Earthquake Engineering, NZSEE (2017), stated that URM buildings have a seismic capacity that is difficult to quantify and may result in margins against a collapse that are small for the following reasons:

    a. URM buildings may have limitations of non-linear deformation capability which are directly depending on their configurations, material characteristics, vertical stress, and potential failure modes.

    b. Relying on friction and overburden pressure from load carried and wall weights.

    c. Varieties of material properties.

    d. Degradation of strength and stiffness with every additional cycle of greater displacements of inelastic response to shaking.

ii. A report by Senaldi et al. (2012) portrayed the URM buildings as a rigid structure with a low capacity to flex when subjected to high accelerations of lateral force causes by an earthquake. These buildings were originally designed only to resist gravity and wind loads. It was also reported that most of this building consists of one, two or three storey brick buildings that were built for commercial purposes. Stone also accounts as major materials used to construct URM buildings besides brick and is called stone masonry buildings. In such building, there are other materials being incorporated as essential building components, such as timber, lime mortar and metal. However, such materials are subjected to deterioration due to aging. Most of the time, these structural elements are poorly interconnected in every other element of the buildings and may easily detach.

iii. Russell and Ingham (2010) reported that most of the New Zealand's URM buildings were built between the 1870s and 1940s, which support the claims that URM buildings were mostly built prior to mid-20th centuries.

iv. Russell (2010) described URM buildings are characterized based on the number of floors and typically reach three storeys high in New Zealand. In general, URM buildings have regular plan shapes, and the external walls may act as the bracing to the lateral force applied other than earthquakes.

v. According to the Federal Emergency Management Agency, FEMA (2009), an URM building is a masonry building that does not have a grid of steel reinforcing bars embedded within the walls and only constructed using only masonry materials. In the United States, this building is normally constructed using brick walls and wood-frame for floors and roof. The exterior of the building shows that the windows have short span, and the walls are thick. The masonry walls of the building are known as bearing walls since it supports loading from the floor and/or roof frames. Bearing walls also have great performance in resisting gravity and provides stability for the building. However, it has consistently performed very poorly when subjected to earthquake. The most common failure in most URM buildings is an outward collapse of the exterior walls caused by the loss of lateral supports due to separation of the walls from the floor / roof diaphragms. Figure 1.6 shows the detail of the structural elements in URM buildings.

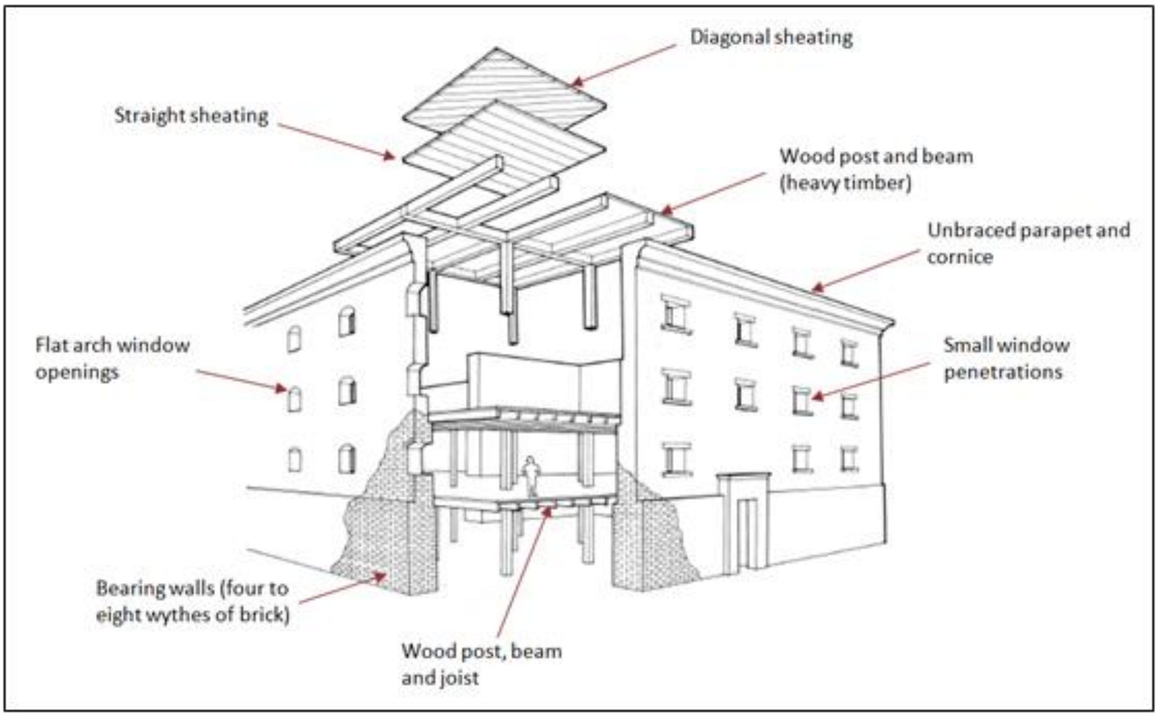

Figure 1.6: Unreinforced Masonry Buildings (FEMA, 2015)

vi. Page (1996) stated that traditional masonry structures relied on their massiveness of construction to achieve stability and were evenly proportioned to avoid forming tensile stress. URM buildings have very poor seismic performance, as they are very heavy with its materials having brittleness in nature and low tensile strength. Having brittleness properties coupled with low tensile strength leads to having no to little ductility. In terms of seismic design, the freestanding elements must have a support to resist it from failing laterally.

vii. Boussabah and Bruneau (1992) described URM buildings as a non-ductile type of constructions, most vulnerable to earthquakes, putting these old buildings to be at greater seismic risk compared to modern day buildings.

1.3 Problem Statement

Due to the fact that the load-bearing masonry walls of URM buildings do not have a lateral restrained mechanism, this makes them very vulnerable to total collapse when subjected to lateral forces induced by earthquakes (NZSEE, 1995; FEMA, 2006). The buildings become unsafe for both occupants and pedestrians as well as the surrounding public properties. Retrofit measures are obviously required by means of introducing the wall-diaphragm connections to restrain the masonry walls to the timber diaphragms at each floor level of the building (NZSEE, 1995; FEMA, 2006).

With reference to MS544-5 (2001), the timber code is not considering the brittle failure mode of bolted connections. Previous studies (Abdul Karim et al., 2018; Abdul Karim et al., 2021; Abdul Karim et al., 2022) have proven that the timber standard is too conservative in predicting the design strength when compared with other design equations such as the EYM and the RSM. In regard to this, further assessments on the timber standard for other local hardwoods are of vital importance.

Due to the lack of data for validating the design on bolted connections of local hardwoods that commonly used in the construction of timber diaphragm of URM buildings, it motivates this present experimental study to be initiated for the *Nyatoh* hardwood. The data obtained from this present study not only can be utilised to assess the accuracy of the existing design equation for the *Nyatoh* hardwood, but also can significantly support the development of a hardwood database. Consequently, the database can be adopted for the