STRUCTURAL BEHAVIOUR OF ASYMMETRICALLY DESIGNED TIMBER-CONCRETE HYBRID BUILDINGS WITH DIFFERENT ROOF MATERIALS SUBJECTED TO EL CENTRO EARTHQUAKE EXCITATIONS

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SCHOOL OF CIVIL ENGINEERING
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ABSTRAK

Bangunan berisiko tinggi mengalami kerosakan semasa bencana gempa bumi jika beban seismik tidak diambil kira dalam reka bentuk bangunan. Bangunan tidak sekata telah terbukti mengalami kerosakan lebih teruk semasa kejadian gempa bumi. Oleh sebab kurang penyelidikan tentang pengaruh beban gempa bumi terhadap bangunan hibrid kayu-konkrit tak simetri, sebuah model bangunan jenis tersebut yang berskala $^1/_4$ saiz asal telah diuji secara seismik menggunakan meja goncang ekaarah. Enam frekuensi struktur model yang diubah menggunakan rembat kayu pepenjuru dan kabel keluli telah dikaji, iaitu pada 5.88 Hz, 4.55 Hz, 3.85 Hz, 3.33 Hz, 2.70 Hz, 2.50 Hz. Dua bahan bumbung yang berlainan iaitu bumbung logam berat dan jubin bumbung tanah liat telah dipertimbangkan untuk model bangunan pada frekuensi 3.85 Hz dan 2.70 Hz. Ujaan gerakan bumi El Centro yang diskalakan kepada 0.08 g, 0.16 g, 0.24 g, 0.32 g bersamaan 25%, 50%, 75% dan 100% kekuatan gerakan tanah telah dijalankan ke atas model tersebut. Tujuh LVDT dan sembilan meter pecut digunakan untuk mengukur anjakan dan pecutan hasil gerak balas seismik model semasa ujian meja goncang. Jenis bahan bumbung menunjukkan kesan yang jelas terhadap gerak balas seismik dari segi pecutan dan anjakan nisbi bumbung. Bahan bumbung yang lebih berat menunjukkan amplitud yang lebih besar merentasi sejarah masa anjakan maksimum, tetapi terdapat penurunan yang ketara dalam gerak balas pecutan untuk aras bumbung berbanding dengan bahan bumbung yang lebih ringan. Faktor ubah bentuk global dan penguatan pecutan telah diperoleh dan dinilai. Hubungan antara anjakan bumbung maksimum dan PGA serta anjakan bumbung maksimum dan frekuensi bangunan telah dikenal pasti. Anjakan maksimum model adalah tertinggi apabila frekuensi bangunan tabii adalah berhampiran dengan frekuensi utama gerakan bumi El Centro. Seterusnya, persamaan ramalan untuk

anjakan bumbung maksimum yang berhubungkait dengan gerakan tanah maksimum dan frekuensi bangunan telah dicadangkan.

ABSTRACT

Buildings are susceptible to earthquake disaster if the seismic loading is not considered in the design. Irregular buildings have been proven to perform badly during earthquake events. Due to lack of investigation on asymmetrical timber-concrete hybrid building under earthquake loading, a $^{1}/_{4}$ scale of this type of building model was tested seismically using a unidirectional shake table. Six structural model frequencies varied by using diagonal wooden braces and steel cables were examined, which are 5.88 Hz, 4.55 Hz, 3.85 Hz, 3.33 Hz, 2.70 Hz, 2.50 Hz. Two different roof materials namely heavy metal roof and clay roof tile were considered for the building models with frequencies 3.85 Hz and 2.70 Hz. The model was subjected to El Centro ground motion excitation scaled to 0.08 g, 0.16 g, 0.24 g, 0.32 g resembling 25%, 50%, 75%, and 100% of the ground motion strength, respectively. Seven LVDTs and nine accelerometers were used to measure the seismic response of the model during the shake table test for displacement and acceleration, respectively. The change of roof material shows a clear effect on the seismic responses in terms of acceleration and relative displacement. Heavier roof material shows larger amplitudes across the maximum displacement time history, but a clear decrease in acceleration response for the roof level as compared with lighter roof material. Global deformation and acceleration amplification factors were obtained and evaluated. The relationships between the maximum roof displacement and PGA, and the maximum roof displacement and building frequency were established. The maximum displacement of the model is the highest when the natural building frequency is close to the predominant frequency of El Centro ground motion. A prediction equation for the maximum roof displacement relating the peak ground displacement and building frequency was then proposed.

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LVDT	Linear Variable Differential Transducer
M_w	Moment magnitude
PGA	Peak Ground Acceleration
PGD	Peak Ground Displacement

CHAPTER 1

INTRODUCTION

1.1 General

Seismic design is very essential to be considered for all buildings designed and constructed in earthquake prone areas like China, Japan and Indonesia. Otherwise, the resistance of these buildings to earthquake excitations might not be sufficient and does not meet the safety requirements. Non-structural damages, structural collapses, and follow-on disasters are the three main causes of death during an earthquake disaster, while structural collapses are responsible for 75% of the total fatalities (Coburn et al., 1992).

The latest strong earthquake of magnitude of 6.2 M_w took place on 25th of February 2022 in Sumatra, Indonesia. Sumatra earthquake caused massive destruction for both the infrastructure and structural buildings, which resulted in buildings collapse, 425 injuries, 14 fatalities and four missing victims. The event demonstrates that buildings in Sumatra, Indonesia are not seismic resilient to withstand a strong earthquake excitation without suffering major damages.

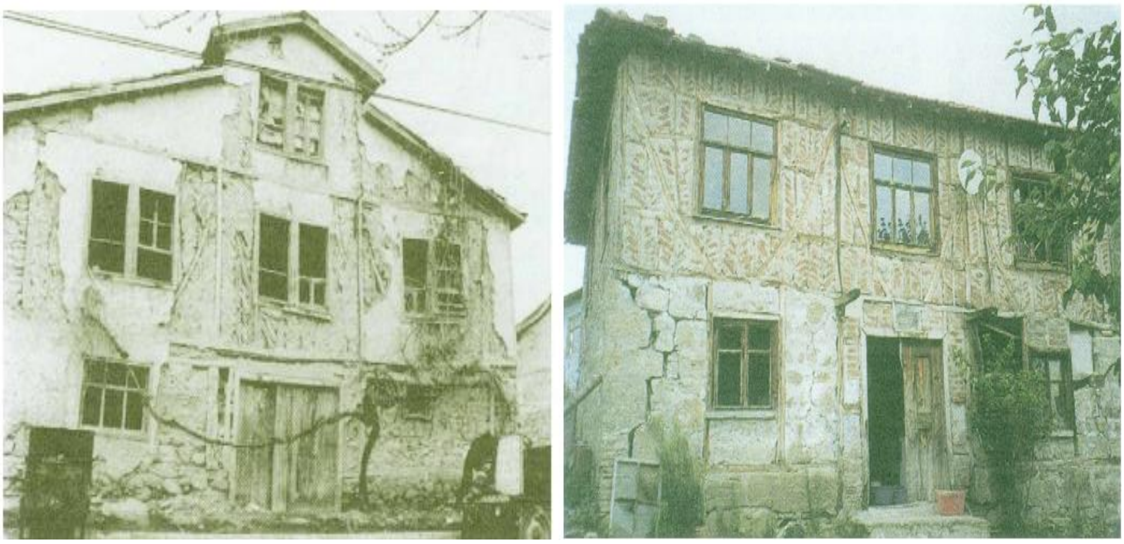
The seismic response of buildings during earthquake excitations depends on the nature of foundation soil, size, material, mode of construction and duration of ground motion. Other issues that contribute to wall separation and damage include a lack of bond beams, shoddy wall-to-roof connections, and large unsupported wall lengths. Because of said causes, significant portions of the wall fail during an earthquake, leading to partial or total collapse.

The violent ground motion pushes the building rapidly forcing it to sway from one direction to another, casing damages to the superstructures unable to balance its load due to inertial effects. Several methods were developed over the years to evaluate the seismic resistance of building including numerical analysis and laboratory experiments. Numerical analysis consists of modelling the building using software, where the seismic analysis considering various ground motions and peak ground accelerations could take place. The most common laboratory experiment to test for the earthquake resistance of building is shake table test, where a prototype model needs to be constructed and tested on the shake table.

Wood is one of the oldest structural materials making timber buildings commonly used in construction. Timber structures are usually hybrid with other structural material such as reinforced concrete or masonry for resistance enhancement. Therefore, a study was conducted to discuss different types of damages to masonry-timber structures, concluding the most common ones being horizontal and vertical cracks, falling of plaster, failure of mortar, loosening or failing of connections, large lateral displacements, dislodgement of the masonry infill, loosening or failing of connections and failure of connections to foundations as shown in Figure 1.1 (Doğangün et al., 2006).

A study conducted by Saatcioglu et al. (2005) concluded that low-rise timber frame structures suffered serious damage during December 26, 2004 Sumatra earthquake and tsunami. The timber structures were constructed of timber columns and beams, supporting timber joist floor system. Figure 1.2 illustrates the damage occurred to timber frame structures.

This study mainly focuses on testing a non-seismically designed timber-concrete hybrid building against peak ground accelerations using a shake table test. Various modifications are considered including varying the building frequency and roof material to examine the effect of these changes on the structural response during shake table test.



(a) **(b)**

Figure 1.1 Post earthquake effect on hybrid-timber structures showing (a) cracks and fallen plasters (b) failure of lime mortar (Doğangün et al., 2006)

Figure 1.2 Damage to timber frame buildings in Phi Phi Island, Thailand (Saatcioglu et al., 2005)

1.2 Problem statement

The asymmetrical timber-concrete hybrid building which is commonly constructed in many countries in low to moderate seismicity region may susceptible to earthquake excitation. Many damages of timber building have been demonstrated in past earthquakes especially for irregular buildings. Hence, the seismic response of these types of building must be investigated. Limited physical tests have been conducted on the asymmetrical timber-concrete hybrid building particularly in this region. An initial shake table test was conducted on a downscaled asymmetrical timber-concrete hybrid building under low to moderate earthquake excitations up to Peak Ground Accelerations (PGA) of 0.16 g. However, the behaviour of the structure under higher PGA up to 0.32 g is still unknown.

Different types of materials used for lateral force resisting elements and different connections used in constructing a building will change the dynamic characteristics of a building. In addition, different roof systems and materials have a direct effect on the seismic performance of the entire building structure, which could be concluded from previous post-earthquake observations. Due to the lack of studies considered these aspects in the past and the absence of any prediction equation for the maximum response, it is vital to investigate the seismic response for a wider range of this asymmetrical timber-concrete hybrid building covering various building frequencies and roof materials and propose a prediction equation for engineers.

1.3 Objectives

The objectives of this project are:

i. To evaluate the performance of an asymmetrical timber-concrete hybrid building with different natural frequencies subjected to El Centro earthquake ground motion with peak ground accelerations from 0.08 g to 0.32 g using shake table.

ii. To determine the effect of different weights of roof material on an asymmetrical timber-concrete hybrid building structure exposed to ground accelerations using shake table.

iii. To propose a prediction equation for estimating the maximum roof displacement for an asymmetrical timber-concrete hybrid building subjected to earthquake ground motion.

1.4 Scope of work

This research focuses on a timber-concrete hybrid building behaviour under low up to strong earthquake excitations. The timber-concrete hybrid building is downscaled to ¼ the original size of a commonly constructed building in low to moderate seismicity region, because of the limitations in workspace and shake table facility. The connections are not the focus of the study but they are varied and represented by different building frequencies of the model. The non-structural members such as timber floor and brick wall are neglected, while structural members such as main frame are considered. The earthquake ground motion used in this experiment is El Centro ground motion recorded in 1940. The ground motion is then scaled to 0.08 g, 0.16 g, 0.24 g, 0.32 g, which resembles 25%, 50%, 75% and 100% of the actual ground motion excitation’s strength, respectively. The ground accelerations chosen resemble low, moderate and high earthquake excitations as aimed for. The test is conducted in this experiment by a uni-axial shake table for earthquake simulation purposes. The measurements recorded at selected locations are the acceleration and displacement using accelerometers and Linear Variable Differential Transducers (LVDT), respectively. Two different masses are placed at the roof of the structure to resemble different roof materials, which are heavy metal roof and clay roof tile.

1.5 Structure of dissertation

This dissertation consists of five chapters in total as follows:

Chapter 1 mainly consists of a general introduction related to this study as well as the problem statement, which highlights the main issues and limitations of previous studies. This chapter gives a clear overview for the objectives of this project and scope of work.

Chapter 2 highlights the related past studies conducted using numerical simulations, finite element modelling and shake table tests on building structures, mainly timber and timber hybrid structures. The effect of structure's connections and wall frame used based on previous studies as well as the considerations used and output results.

The research methodology is discussed in Chapter 3, where it covers the methods used to fulfil the objectives of this project. Experimental analysis using shake table tests and all three different variables, PGAs, building frequency and roof materials are discussed. The validation and verification process for natural building frequencies. The structural building layout, equipment used, test cases and data analysis are also demonstrated in Chapter 3.

Chapter 4 presents the analysis and discussion for the seismic response for the timber-concrete hybrid model. The maximum displacements for each scaled PGA and building frequency, the global deformation of the model as well as the amplification between the floor and roof accelerations are critically discussed. The relationships between maximum displacement response against PGA and maximum displacement against building frequency are then developed. The response of different roof materials is compared the results are evaluated.

Chapter 5 depicts conclusion and recommendations for this study. This chapter highlights the important findings and concluded relationships observed from the analysis comparison. Recommendations for future studies are proposed.

1.6 Significance of this study

This study aims to evaluate the performance of existing commonly built timber-concrete hybrid building in low to moderate seismicity region subjected to peak ground accelerations ranging from 0.08 g to 0.32 g. Different roof materials are also included in the study to determine the effect of using different types of roofing systems on the seismic response. The findings of the study provide useful information for estimating the building response under targeted earthquake excitation. The results of the study could be applied in the seismic design of new buildings or retrofitting of existing ones.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Earthquake is a natural disaster that occurs in many regions, but with different severity. Some earthquakes with magnitudes up to 6.0 M_w may cause slight damage to buildings and other structures, while earthquakes with magnitude of 6.1 M_w and above could lead to serious damage and disasters (Michigan Technological University, 2022). Currently, structural buildings in seismic prone areas consider the design of structure for earthquake resistance. However, before practicing the structural codes for earthquake resistant structures, the structural buildings were designed by neglecting the seismic safety. The factor of safety and seismic resistance of these structural buildings must be checked to determine its suitability and whether retrofitting is required. The structural response is terms of acceleration, total displacement and storey drift are very important parameters to be determined to predict the failure modes of the structure as well as the capacity of the structure under seismic loads.

Several researches and studies were conducted using numerical simulations and laboratory experiments in the past decades to further enhance the structural resistance approaches as discussed in Sections 2.2 and 2.3. Numerical simulations require setting up a full-scale structural model with same dimensions and connections as in real condition to test against various peak ground accelerations. Experimental analysis requires constructing a full or down-scaled structural building to evaluate its seismic response using shake table test. Both experimental and numerical analyses are adopted for seismic performance analysis of structures. For numerical analysis, the results from experimental analysis are desired to verify the numerical analysis outputs. Combination of experimental and numerical simulations has been adopted in recent years as the economical approach for seismic analysis.

2.2 Shake table tests

Shake table tests have been conducted by many researchers in the past to investigate the dynamics characteristics and structural performance of full scale and down-scaled building structures. The following sections review the shake table tests carried out on concrete structures and timber structures.

2.2.1 Concrete structures

Gavridou et al. (2017) conducted shake table test on a full-scale four-storey precast concrete building to examine the effect of utilized unbounded posttensioned (UPT) walls and bonded posttensioned concrete frames on the structural seismic resistance. The structural model was subjected to scaled Kobe (25%, 50% & 100%) and Takatori (40% & 60%) ground motions to evaluate the seismic response such as spectral acceleration, spectral displacement, and lateral displacement for each storey. The study concluded UPT enhances the seismic resistance of the precast concrete building, due to the exhibition of little damage and no major deformation occurring after subjected to strong ground motions.

Non-compliant SMRF-reinforced concrete frame down-scaled to $^{1}/_{3}$ its size was seismically test using shake table subjected to various ascendingly scaled Northridge earthquake ground motions by Ahmad et al. (2019). Beams, columns and beam-column joints are designed and detailed to withstand flexural, axial, and shearing actions developed during ground motion excitations. The SMRF-reinforced concrete frame was checked after every shake table test for possible damages and global deformation was plotted. The ground motion was scaled to 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90% and 100% of Northridge earthquake ground motion. The model complied with the building code of Pakistan for code specified drift limit up to 70% of Northbridge ground motion. The results showed that the minimum column depth specified in the code will not prevent joint damageability in case of low-strength concrete and joints lacking enhanced ties.

Five-storey reinforced concrete (RC) building structure down-scaled to $^{1}/_{5}$ its size subjected to mainshock (MS) and aftershock (AS) sequences were tested by Qiao et al. (2020) using shake table tests to examine the unfavourable effect of ASs of structural seismic performance. The ground motion of one MS and three ASs for Wenchuan earthquake were selected from the database records. Series of peak ground acceleration (PGA) intensity levels were considered to scale the seismic sequence completely for simulation of sequential excitations. The structural model showed local and global deformations during the shake table tests due to the high after shock influence ratio (AIR) up to 85.2%. The highest seismic response of the reinforced concrete building structure was recorded during the second AS, showing that aftershocks could have higher seismic effect than mainshocks.

Shake table test was carried on full-scale two-storey reinforced concrete structural model subjected to 39 tests to evaluate the seismic resistance suitability of post-tensioned (PT) rocking walls by Henry et al. (2021). Lateral load resistance is provided from the PT rocking wall and the frame utilized the beam connections. The model was subjected to 39 bidirectional scaled ground motions, some of full intensity. The reinforced concrete model with PT rocking wall performed well against the seismic excitations as only minor damage was exhibited and repairing of damage could be done with minimal disruption.

Two 3D reinforced concrete frame structure specimens, crumble rubber concrete (CRC) and normal reinforced concrete (NC) were fabricated to $^{1}/_{3}$ its original size and seismically evaluated through shake table test by Khan et al. (2021). The CRC specimen contained 15% of rubber crumb replacing fine aggregate by volume, resulting in changed characteristics such as durability and natural frequency of the building. The specimens were subjected to multiple base excitations of Northridge ground motion to examine their seismic response. The acceleration response of NC frame and CRC frame subjected to 100% Northridge earthquake excitation resulted in peak seismic response of 1.47 g and 1.17 g, respectively as demonstrated in Figure 2.1. CRC frame shows 20.40% reduction in peak seismic acceleration response compared to NC, showing more impact resistance, ductility and toughness.

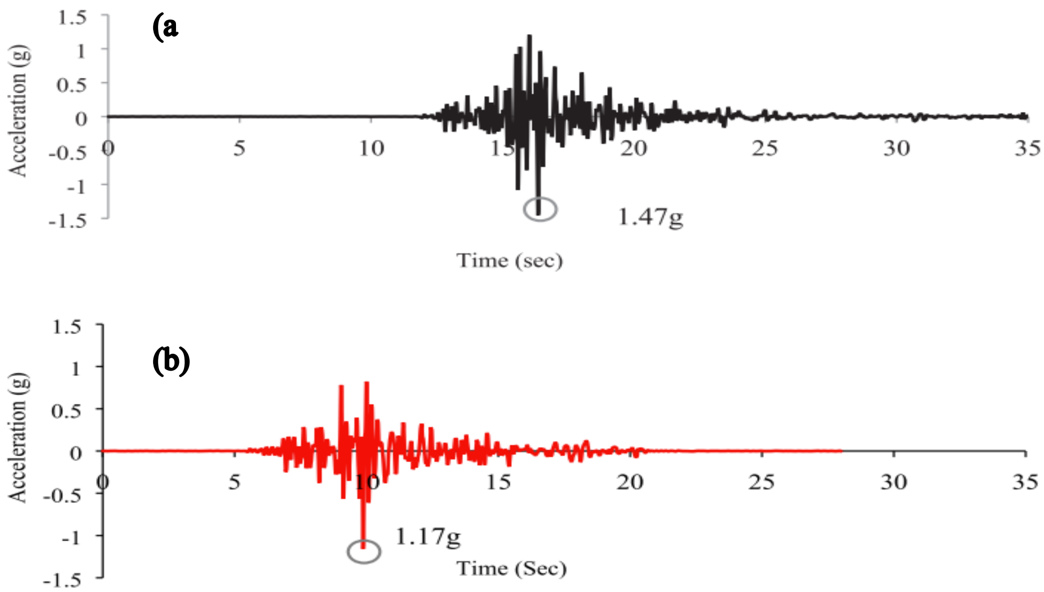


Figure 2.1 Acceleration response for (a) NC (b) CRC (Khan et al., 2021)

Sun et al. (2022) tested precast concrete structural building with concrete-steel hybrid columns through shake table test. Columns were reinforced by steel bars and fibre reinforced polymer bars to examine its effectiveness as compared with ordinary reinforced concrete column for seismic resistance subjected to El Centro earthquake excitations. Seven acceleration sensors and seven strain gauges bounded on one longitudinal bar were placed on the model to measure the seismic response in terms of accelerations and strain development of longitudinal reinforcement, respectively. The results show smaller residual deformation for columns with hybrid steel and FRP bars reinforcement as compared with ordinary reinforced concrete columns. The study suggests that the concrete-steel hybrid column could be used under severe environments due to its excellent anti-corrosion performance.

2.2.2 Timber structures

Timber structures are widely used and commonly constructed in rural and sub-urban areas without considering earthquake resistant design. Several experimental and numerical tests were carried out to evaluate the effect of parameters such as connections, shear walls, roof materials and building frequencies against various ground motion events with different PGAs. The results of these studies are then used to enhance the resistance of vulnerable structural buildings to seismic events by retrofitting existing structures and designing new structures. The development of engineered materials such as timber and improved techniques for construction along with shift to performance-based design has renewed interest in timber construction systems due to its high effectiveness. However, the main limitation is building codes for timber structures are not as developed as those of masonry, steel and concrete (Branco et al., 2017).

The seismic analysis studies conducted by Ladjinovic & Folic (2008) concluded that structural buildings symmetricity contributes to the structural resistance as asymmetrical structures are more vulnerable to seismic failure than symmetric structures. This is mainly because stiffness and strength in plan undergo coupled lateral and torsional motions during earthquakes. The bigger the distance between the centre of mass of the building and centre of stiffness, the greater the torsional effects. Therefore, for minimized torsional effect, the distance between centre of mass and centre of stiffness should be reduced.

2.2.2(a) Connections

A well-constructed timber model with accordance to seismic design should withstand moderate earthquake excitations without completely collapsing as concluded in the study by Haijiang et al. (2008). Two-storey light weight timber frame full size model with dimensions of 6 m × 6 m × 6.3 m as demonstrated in Figure 2.2 was constructed to test for symmetrical configurations with three types opening size and asymmetrical configurations. Five different phases and 67 tests were run for the full-size model with PGAs up to 0.55g. The results showed that several nails were pulled out, fatigue failure occurred on the nail joints and serious damage at joints part. However, the structural model survived a complete collapse.

Figure 2.2 Full size two-storey timber model and main floor plan dimensions (Haijiang et al., 2008)

Branco et al. (2013) examined the seismic performance of a two-storey log house subjected to bidirectional Montenegro ground motions scaled to 0.07 g, 0.28 g and 0.5 g. The test aims to evaluate the behaviour of the structural model as well as the behaviour of the connections between still logs and foundation. Figure 2.3 shows the connections using M16 bolts of class 8.8 placement in the model. After shake table tests, the connections suffer damages and fracture along the grains at connections between orthogonal walls. This damage caused a decrease in the building natural frequency from 5.389 Hz to 5.109 Hz.

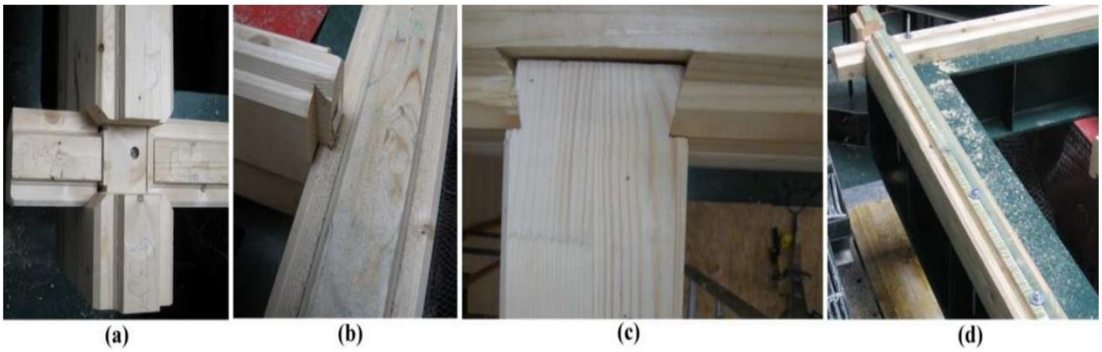


Figure 2.3 Connections used for the log structural model (Branco et al., 2013)

Two experimental two-storey laminated timber frames were constructed to undergo shake table tests and be evaluated seismically by Kasal et al. (2004). The two experimental models had different connections consideration. The first model had no reinforcement at joint areas while the second model had new frame design with densified material in the joint area along with enhanced reinforcement by glass-fibre composite material. The results demonstrated a well-designed connection can undergo several cycles and strong excitations without losing design capacity. However, ultimate capacity will decrease due to strength degradation. The seismic performance of a rigid three-dimensional beam to column connections was then studied for heavy laminated timber frames in Kasal et al. (2014). The connections had self-tapping screws and hardwood blocks to support the beams. Seismic test was carried out to determine the moment-rotation characteristics of connections. The yielding of connections is essential to prevent the brittle failure of timber structure members during strong earthquake excitations.

Several factors directly affect the seismic resistance of structural buildings such as connections. Common connections for timber structures are nails, screws, rivets and bolts. Hashemi et al. (2017) tested the conventional timber framed buildings with these connections for nine different ground motions using a shake table to determine the seismic resistance. The results showed the damages occurring in the connections could be either elastic or non-elastic both of which might be hard to repair economically due to high accessibility issues to the damaged connections. The strength and stiffness of the damaged structural buildings would significantly decrease due to the plastic deformation of connections, leaving the structural building more vulnerable. The damage could be mitigated using load resisting members such as Laminated Veneer Lumber (LVL) and Resilient Slip Friction (RSF) joins to hold down connectors at the base as shown in Figure 2.4.

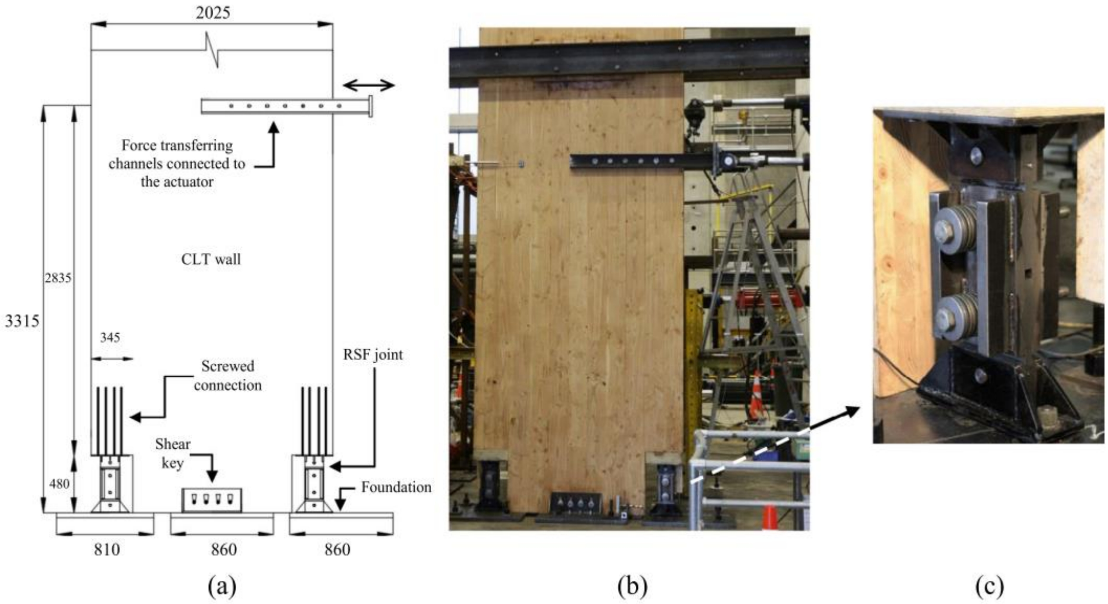


Figure 2.4 (a) General arrangement of RSF (b) Image of the test setup (c) RSF join as a hold-down connector (Hashemi et al., 2017)

2.2.2(b) Wall frame structures

A study conducted by Christovasilis et al. (2008) on two-storey full scale model with living space of 170 m^2 to study the behaviour of wooden structure with five different structural wall materials in cooperated together along five different phases. Phase 1 used shear wall alone, phase 2 used structural walls incorporating with fluid dampers, phase 3 used gypsum wall, phase 4 used gypsum wall board installed in interior and finally phase 5 used installation of stucco as exterior wall on to the timber structure. The displacement of the roof was recorded and it showed a significant decrease from phase 1 to phase 5 due to the increase in the overall stiffness. The absolute maximum displacement response for test phase 1, test phase 3, test phase 4 and test phase 5 are 42.1 mm, 24.6 mm, 23.6 mm and 14.1 mm, respectively as shown in Figure 2.5.

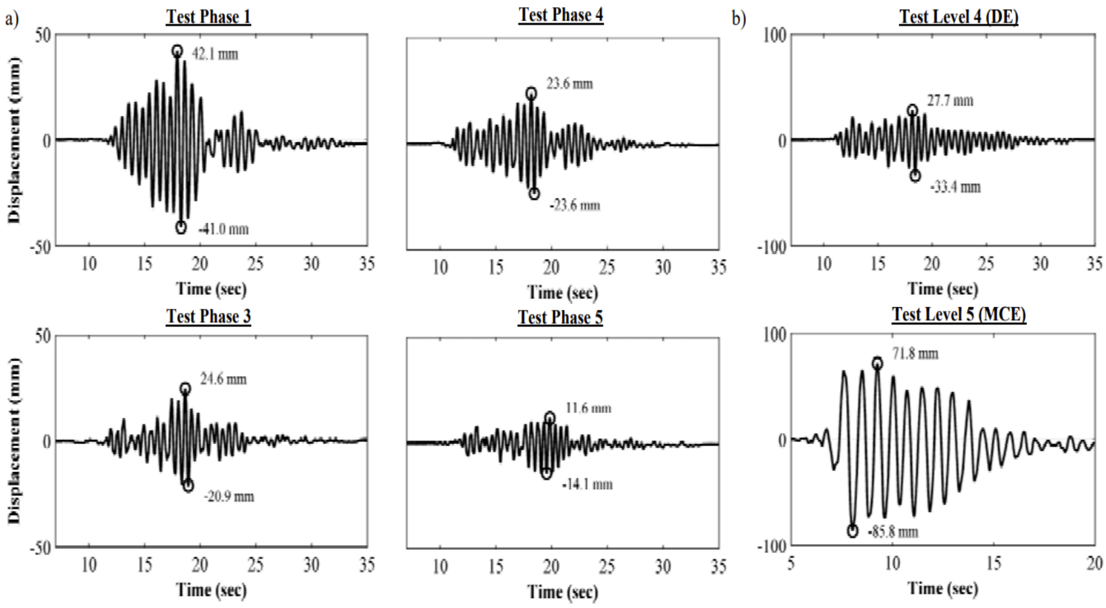


Figure 2.5 Displacement response for different phases and structural wall materials (Christovasilis et al., 2008)

Full-scale light frame timber building including and excluding gypsum wallboard and exterior stucco was examined seismically through shake table tests by Filiatrault et al. (2010). The results show the installations of gypsum wall to the interior surfaces of structural wood enhanced the seismic resistance. The seismic resistance was further enhanced with the addition of exterior stucco.

Structures with stone and earth infill were tested using shake table to determine its seismic performance and dynamic behaviour by Vieux-Champagne et al. (2017). The walls were infilled with stones and earth to adapt the design of Haitian building culture and seismically examine it. The openings in the shear walls affected the natural frequency of the structural model when tested using white noise excitation and measuring three axis acceleration responses. Similar study was conducted to determine the seismic resistance of timber-framed structures with zero opening walls. Figure 2.6 demonstrates the process of building a seismic resilient masonry shear wall from a joint, to elementary cell, to elementary wall, to shear wall.

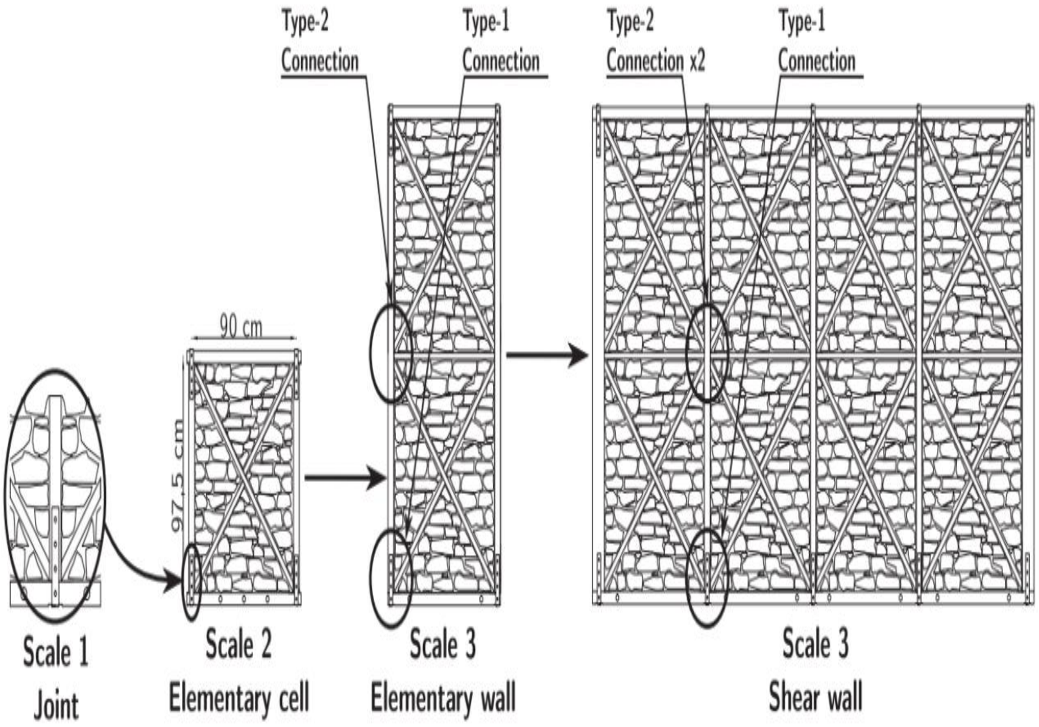


Figure 2.6 Three scales of experimental studies for shear wall (Vieux-Champagne et al., 2014)

Pei et al. (2018) tested two-storey full-scale mass timber building using shake table test to determine if resistance performance can be achieved in an open floor timber structure with the use of post tensioned Cross Laminated Timber (CLT) rocking wall. The study concluded CLT rocking walls can be designed to match with heavy timber gravity frames to provide an open floor building able to survive maximum considered earthquakes intensities with no visible damage.

Blomgren et al. (2019) conducted shake table testing on a full-scale of cross laminated timber rocking shear walls subjected to four different ground motions, Superstition Hills, Imperial Valley, Northbridge, Loma Prieta scaled to service level earthquake (SLE), design basis earthquake (DBE) and maximum considered earthquake (MCE) each to evaluate its seismic resistance. The MCE resulted in the highest roof drift of 3.85%. The results showed that cross laminated timber rocking shear walls performed well against maximum earthquake excitations for being repairable by replacing the damaged energy absorbing components.

2.2.2(c) Roof materials

Timber is a very common material and is used extensively in building structures for supporting roofs and floors. Timber roof structures were either enhanced by the addition of interventions including industrial fabricated products or removed and substituted. The increase of mass and stiffness by the addition of prefabricated elements may lead to lower seismic resistance of the whole structure; due to incompatibility with the old and weak masonry walls. The study carried by Parisi & Piazza (2015) concluded that timber roof structures should be preserved, enhancing their seismic resistance with no contribution of massive interventions.

It has been noted that the flexibility of light timber roof systems has a considerable impact on the overall seismic performance of the structure. A shake table test was conducted by Correia et al. (2018) on a full-scale unreinforced masonry model until collapse. The research concluded that the URM gable walls are particularly vulnerable to the formation of overturning processes due to out-of-plane excitations and in-plane timber diaphragm deformability. The same model used by Correia et al. (2018) is then modified and examined in Tomassetti et al. (2019). The model’s timber roof is a simple structure with one ridge beam, two timber plates on top of the longitudinal outer leaves of the walls, and two girders per side between the ridge beam and the timber plates, with a distance of around 1.13 m. The roof was then completed after the clay roof tiles installation before running the shake table test. Two-way bending out-of-plane and collapse of a load-bearing wall was observed.

Well-constructed timber structures are generally known for their high efficiency as aseismic structures. Especially with the addition of roof with increased mass to further enhance the stability of the entire structure. This was concluded Xie et al. (2019) after testing a traditional timber structure model down-scaled to $^{1}/_{6}$ its original size and subjected to 4 horizontal waves of different intensity to test for damage patterns, dynamic characteristics and responses.

2.3 Combination of experimental and numerical simulation

Shake table tests and numerical simulations of a $^{2}/_{3}$ down-scaled four-storey timber-steel hybrid structure subjected to PGAs scaled to 0.14 g, 0.40 g, and 0.80 g were conducted by He et al. (2018). The study aims to evaluate the seismic response of the structural model in terms of inter-storey drift, acceleration, loading sharing between the steel frames and infill walls and roof displacements. Numerical model and experiment test showed very similar responses under four different ground motions, Wenchuan, Canterbury, El Centro and Kobe as shown in Figure 2.7. The structural model withstood severe earthquake excitations without completely collapsing and showing minor damage. After validating the numerical model using shake table tests, more numerical simulations with minor changes to the structural building were performed to enhance the seismic resistance of the model economically.

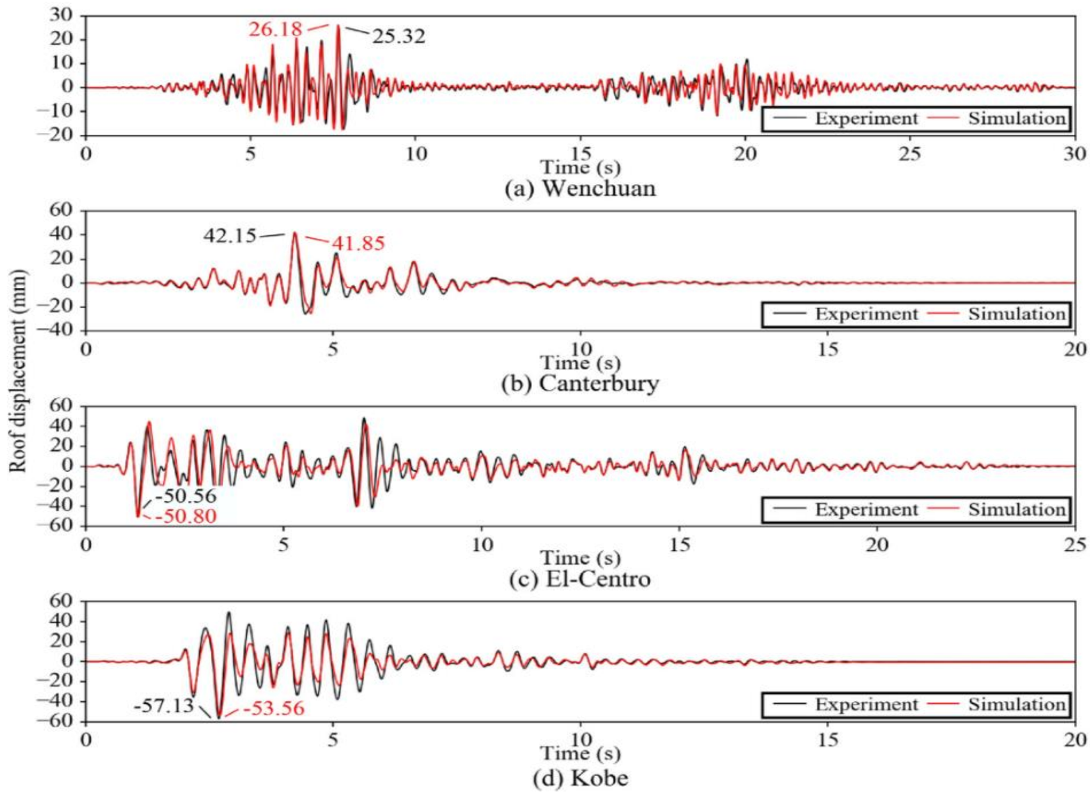


Figure 2.7 Time history of roof displacements for experiment and simulation (He et al., 2018)

Avcı & Alemdar (2019) conducted a study on a 3D three-storey steel frame system. The building was down-scaled to 1/4 of its original size and examined using shake table test and finite element analysis to evaluate the structural response under dynamic effects. Finite element model was modelled using ABAQUS to determine the base shear-displacement curves and top floor horizontal displacement of the steel frame structure subjected to Northridge earthquake scaled to 50% and 100%. The results from the finite element model matches the shake table tests up to 99%. The study concluded the high effectiveness for beam to column and column to foundation connections for general structural behaviour subjected seismic load. Figure 2.8 illustrates the deformation of connections for the steel frame system under 50% and 100% Northridge earthquake using finite element analysis.

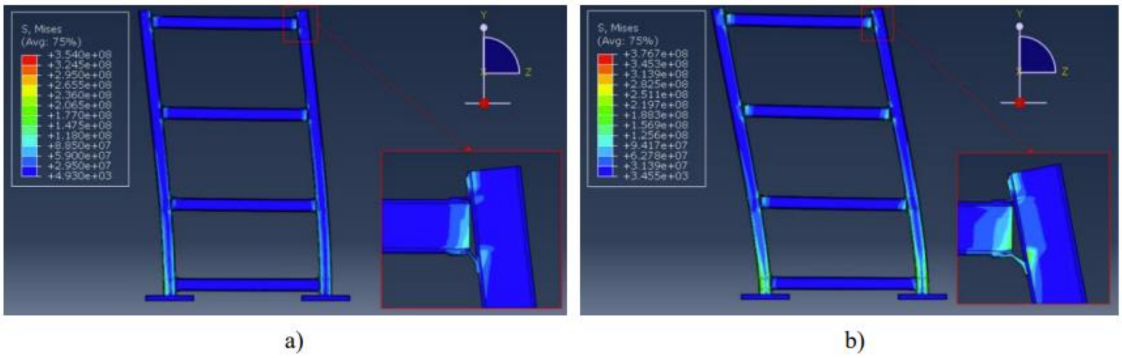


Figure 2.8 Joint deformation for steel frame system under (a) 50% and (b) 100% northridge earthquake (Avcı & Alemdar, 2019)

Eddy current turned mass damper (ECTMD) on structural consideration soil-structure interaction equipped in six-storey steel frame model with 1.56 Hz natural frequency and 1500 kg total mass subjected to seismic load using shake table and numerical simulation was carried out by Liu et al. (2020). In this study, the usage of ECTMD reduced the maximum displacement response of the steel frame structure. The mitigation in the maximum displacement response was shown from the shake table tests and three-dimensional finite element model. Analysis procedures such as equivalent linear model and bounding surface plasticity model were utilized in the numerical model to simulate the nonlinear soil behaviour and accurately estimate the structure response under earthquake excitations.

Xie et al. (2020) performed shake table test and numerical simulations on a vulnerable Chinese ancient masonry tower. The tower was down-scaled to $^{1}/_{8}$ of its original size to evaluate the seismic performance and dynamic characteristics. The structural model was subjected to four scaled ground motions, Taft, Lanzhou, Wenchuan and El Centro in two directions. A nonlinear finite element model was modelled to further study its seismic response. The numerical simulation results were compared and validated by shake table tests, showing similar damage propagations and seismic performance. Figure 2.9 shows the seismic response in terms of displacement for experimental tests and numerical simulations subjected to Wenchuan ground motion.

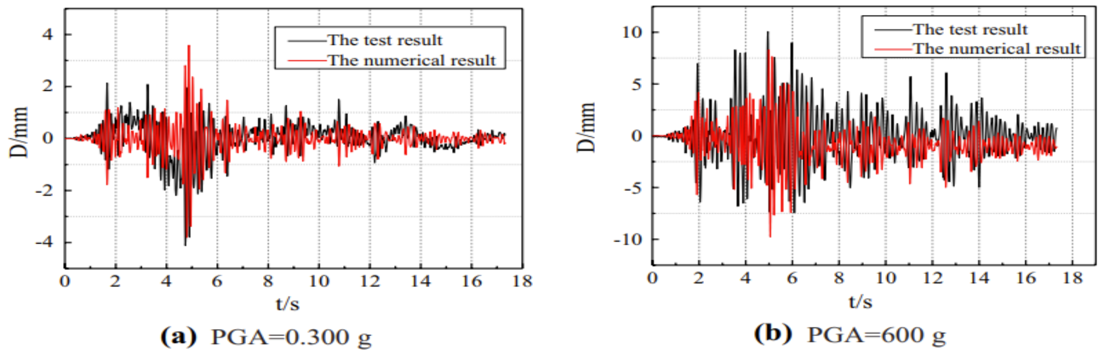


Figure 2.9 Comparison between experimental and numerical tests (Xie et al., 2020)

Shake table test was conducted on an asymmetrical timber-concrete hybrid structure to examine its seismic performance under down-scaled Ranau earthquake excitations to 0.08 g by Ng (2020). The results obtained were used to verify a numerical model in ETABS and simulate the predicted earthquake of 0.16 g PGA. The experiment concluded that under moderate earthquake excitations, the highest relative displacement recorded is at the roof of the structure compared to other locations.

2.4 Summary

Building models subjected to various ground motion excitations during shake table tests react differently and demonstrate different seismic response. El Centro ground motion excitation is commonly used in shake table tests and numerical simulations due to high intensity and strength.

Based on the discussed studies, asymmetrical buildings were concluded to be seismically more vulnerable as compared with symmetrical buildings (Ladjinovic & Folic, 2008). Several shake table tests were conducted on reinforced concrete models, timber models and hybrid timber-masonry models. However, lack of studies on hybrid timber-concrete building using shake table is observed. The hybrid timber-concrete building model tested in Ng (2020) on was limited to small earthquake excitations up to 0.16 g PGA. The same model was tested in this study under stronger earthquake excitations, different roof materials and various building frequencies. Demonstrated studies did not develop relationships between maximum roof displacement and PGA, maximum roof displacement and building frequency due to past studies being mainly focused on certain type of buildings. Therefore, no prediction equation was proposed to estimate the maximum roof displacement during PGA excitations.

CHAPTER 3

METHODOLOGY

3.1 Overview

The sequence of the work for this study is highlighted in this chapter, where it is mainly separated into three stages. These stages are data collection, where it vividly demonstrates the layout of the structural model and its scale factors as well as the three variables (ground motion, roof material and building frequency) considered for this study.

The second stage is the shake table test, which highlights the main instruments used and placement of the instrument along with their locations on the downscaled structural model along with modifications to connections due to nail size limitations. This stage also presents the validation and verification process for structural model building frequencies along with the test cases considered in this study.

The third stage is the data analysis conducted for all natural building frequencies of 5.88 Hz, 4.55 Hz, 3.85 Hz, 3.33 Hz, 2.70 Hz and 2.50 Hz. The model was subjected El Centro ground motion with PGAs 0.08 g, 0.16 g, 0.24 g and 0.32 g resembling 25%, 50%, 75% and 100% of the actual ground motion strength, respectively. The relative displacement, global deformation of the building and amplification of accelerations were determined in the data analysis.

The flow of this study, variables to be considered and experiments are illustrated in the flow chart of the research methodology as shown in Figure 3.1.