PERFORMANCE OF LOAD-BEARING PRECAST CONCRETE WALL WITH BASE ISOLATION SUBJECTED TO SEISMIC LOADINGS

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
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This humble piece of work is dedicated to my parents, my brother Philip, JMC and MWY who have always been supportive for every decision made and also not forgetting my relatives and friends whose companion is what makes this study possible

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ABSTRACT

The government of Malaysia has been strongly encouraging local construction industry to utilize Industrialized Building System (IBS) to reduce dependence on foreign workers and improve site safety and construction duration. This study investigated the seismic performance of a locally developed precast concrete wall system by local system supplier, namely the HC Precast System (HCPS). The system used load-bearing precast infill panel which was connected to adjacent columns through shear keys and dowel bars protruded by both sides of the wall panel. This type of precast system is not currently covered by Eurocode 8. A full-scale single bay, double storey prototype structure consisted of HCPS was constructed and tested under lateral quasi-static loading at laboratory of Construction Research Institute of Malaysia (CREAM). Displacement-controlled cyclic loading of 0.05%, 0.20%, 0.40%, 0.50% and 0.70% roof drift was applied to the prototype structure to obtain the force-displacement hysteresis loops. Observation from the quasi-static test revealed concentration of damage along the wall-to-column interface. Thus, a finite element modeling method was proposed to represent the nonlinearity of the interface element in the numerical model. Next, a 1:3 scaled down of the prototype HCPS was designed and constructed for shake table test. Besides scaling of the test specimen, characteristics of 8 selected ground motions were also scaled correspondingly according to similitude law including the time steps and peak acceleration values. The proposed FEM model was found to be in good agreement with both quasi-static and shake table tests. The verified FEM model was used to generate capacity curves of HCPS by pushover analysis with four different lateral loading configurations respectively. The characteristic of the capacity curves and obtained behaviour factor was compared to the Equal Displacement Rule (EDR) method recommended by Eurocode 8. Thus N2Disp, a method for engineers to estimate the nonlinear displacement of HCPS from linear analysis was proposed. Seismic response of HCPS under Malaysia earthquake loading was carried out with Modal Response Spectrum Analysis (MRSA) and pushover analysis with design ground acceleration a_g values of 0.05g, 0.075g and 0.1g. It was found that in all three a_g levels, the performance of HCPS remained within Immediate Occupancy (I0) level. High damping rubber bearing (HDRB) was designed to provide seismic base isolation of HCPS at target period of 2.5s. The HDRB was designed, manufactured and tested at real size to obtain the dynamic property such as compressive and lateral stiffness as well as hysteresis damping ratio. The nonlinear base isolated model of HCPS was analyzed for 33 time histories representing a wide variety of epicenter distance, magnitude, soil classification and acceleration to velocity (a/v) ratio. It was revealed that while base isolation provided effective reduction in floor acceleration responses (up to 97%) in most time history cases, adverse results (amplification) were observed in ground acceleration having low (a/v) ratio and providing higher damping ratio (i.e. $\beta = 24\%$) at the isolation system.

ABSTRAK

Kerajaan Malaysia telah mulai menggalakkan pembinaan tempatan untuk menggunakan *Industrialized Building System (IBS)* untuk mengurangkan pergantungan terhadap tenaga buruh luar serta meningkatkan keselamatan dan juga masa pembinaan. Kajian ini menjurus kepada prestasi gempa bumi sistem dinding pra-tuang tempatan, *HC Precast System* (HCPS). Sistem tersebut terdiri daripada dinding pra-tuang menanggung beban yang dihubungkan kepada tiang bersebelahan melalui kekunci ricih dan tetulang tertonjol dari kedua-dua belah tepi dinding. Jenis struktur dinding ini masih belum dirangkumi oleh *Eurocode 8* sehingga kini. Struktur prototaip HCPS dua tingkat dibina lalu diuji dengan pembebanan sisi *quasi-static* di Makmal Kerja Raya (CREAM). Pembebanan sisi dikenakan pada 0.05%, 0.20%, 0.40%, 0.50% dan 0.70% anjakan bumbung untuk mendapatkan lingkaran histerisis daya-anjakan. Pemerhatian daripada ujian tersebut menunjukkan kerosakan tertumpu di sepanjang perantaraan tiang ke dinding. Justeru itu, model analisis unsur terhingga telah dicadangkan untuk mewakili sifat tidak lelurus unsur perantaraan tersebut. Seterusnya, saiz prototaip HCPS tersebut dikecilkan skalanya kepada 1:3 untuk ujian meja getar. Sifat-sifat 8 data gempa bumi yang telah dipilih turut diselaraskan demi memenuhi hukum *similitude*, termasuk skala masa dan pemecutan puncak. Model kaedah unsur terhingga yang dicadangkan telah menunjukkan hasil analisis yang memuaskan dengan data ujian *quasi-static* dan meja getar lalu digunakan untuk menghasilkan lengkung kapasiti HCPS melalui analisis *pushover* dengan empat pembebanan sisi yang berlainan. Sifat lengkung kapasiti dan faktor tingkah laku dibandingkan dengan kaedah *Equal Displacement Rule* (EDR) dalam Eurocode 8. Jadi, N2Disp, kaedah baru untuk anggaran anjakan tidak lelurus HCPS melalui analisis linear telah dicadangkan. Tindak balas seismik HCPS terhadap gempa bumi Malaysia dilakukan menggunakan *Modal Response Spectrum Analysis* (MRSA) dan *pushover* dengan nilai pemecutan rekabentuk a_g 0.05g, 0.075g dan 0.1g. Kajian menunjukkan dalam ketiga-tiga nilai a_g, HCPS masih berada dalam status *Immediate Occupancy* (IO). Galas getah berendaman tinggi (HDRB) telah direncana untuk memberi pemencilan seismik HCPS pada tempoh getar 2.5 s. HDRB telah direncana, dihasilkan dan diuji pada skala penuh untuk mendapatkan sifat dinamik seperti kekakuan tegak dan ufuk. Analisis unsur terhingga tidak lelurus bagi model HCPS dengan HDRB dilakukan dengan 33 rekod gempa bumi yang merangkumi pelbagai jarak pusat gempa, magnitud, klasifikasi tanah dan nisbah pemecutan terhadap halaju (*a/v*). Hasil analisis menunjukkan bahawa walaupun tindak balas pemecutan di bumbung bangunan telah dikurangkan sebanyak 97% dengan menggunakan HDRB, namun peningkatan telah diperhatikan dalam rekod gempa bumi yang mempunyai nisbah *a/v* yang rendah. Adalah diperhatikan bahawa dengan memberikan nilai rendaman yang tinggi (i.e. $\beta = 24\%$) pada sistem pemencilan seismik, tindak balas yang diperolehi tidaklah selalunya memberikan kesan yang positif.

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LIST OF ABBREVIATIONS

1F	-	First floor
ACI	-	American Concrete Institute
ASCE	-	America Society of Civil Engineers
BS	-	British Standards
CIDB	-	Construction Industry Development Board
CIMP	-	Construction Industry Master Plan
CREAM	-	Construction Research Institute of Malaysia
CSI	-	Computer and Structures, Inc.
DOF	-	Degree of freedom
D.P.	-	Dowel pullout
EC2	-	Eurocode 2
EC8	-	Eurocode 8
FEM	-	Finite Element Model
FEMA	-	Federal Emergency Management Agency
GF	-	Ground floor
HCPS	-	HC Precast System
HCPS-QST	-	HCPS quasi static test model
HCPS-STT	-	HCPS shake table test model
HCPS-VL1	-	HCPS vertical load 1
HCPS-VL2	-	HCPS vertical load 2
HCPS-VL3	-	HCPS vertical load 3
HDRB	-	High Damping Rubber Bearings
HDRB-VL1	-	HDRB vertical load 1
HDRB-VL2	-	HDRB vertical load 2
HDRB-VL3	-	HDRB vertical load 3
IBC	-	International Building Code
IBS	-	Industrialized Building Systems

IEM - Institute of Engineers of Malaysia
LRB - Lead rubber bearing
MCE - Maximum considered earthquake
MDL - Modal distributed load
MDOF - Multi degree of freedom
MMI - Modified Mercalli Index
MRSA - Modal response spectrum analysis
N2Disp - New Nonlinear Displacement
NBCC - National Building Codes of Canada
N.C.C.W. - No concrete crushing in wall
N.D.P. - No dowel pullout
NEHRP - National Earthquake Hazard Reduction Program
NZS - New Zealand Standards
PCI - Precast/Prestressed Concrete Institute
PEER - Pacific Earthquake Engineering Research
PGA - Peak ground acceleration
PGV - Peak ground velocity
RF - Roof floor
SDOF - Single degree of freedom
SF - Safety factor
SPL - Single point load
TC - Technical Committee
TDL - Triangular distributed load
UBC - Uniform Building Code
UDL - Uniform distributed load
UITM - Universiti Teknologi MARA
UTM - Universiti Teknologi Malaysia

LIST OF SYMBOLS

$\%$ - Percent

α - Parameter in pivot model

$a_{cc8\%}$ - Roof acceleration at 8 % damping ratio

$a_{cc24\%}$ - Roof acceleration at 24 % damping ratio

a_g - Design ground acceleration

A - Area

β - Damping ratio

B_D - Damping reduction factor

c - Viscous damping coefficient

Δ - Displacement

Δ_r - Displacement of wall at first yield loading

Δ_u - Ultimate lateral displacement

Δ_V - Vertical displacement

Δ_y - Yield displacement

$\emptyset$ - Diameter

$\emptyset_s$ - Diameter of steel shim (plate)

d^+ - Maximum lateral displacement in shear stiffness test

d^- - Maximum lateral displacement in shear test (in other direction)

D_D - Design displacement

D_f - Displacement factor

d_z - Maximum vertical displacement in compression test

ε - Concrete strain

ε_0 - Concrete strain at ultimate compressive strength

E_c - Young modulus of concrete

E_s - Secant modulus of reinforcement bars

f_c' - Uniaxial concrete compressive test results

$F_{eff}(t)$ - Effective load factor

f_H - Lateral frequency

f_r - Ultimate tensile strength of concrete

f_{su} - Ultimate strength of reinforcement bars

f_V - Vertical frequency

f_y - Yield strength of reinforcement bars

γ - Shear strain

g - Gravity force (= 9.81 m/s^2)

G - Shear modulus

$G_{1.5}$ - Shear modulus at 150 % shear strain

$G_{0.2}$ - Shear modulus at 20 % shear strain

H_r - Horizontal load that causes first yield of wall

H_u - Ultimate lateral force

H_y - Lateral force causing yielding of reinforcement bars

$\{I\}$ - Unit vector

I_g - Gross second moment area of wall

K - Bulk modulus of rubber compound

K_1 - Initial shear stiffness of HDRB

K_2 - Post-yield stiffness of HDRB

K_{ed} - Wall panel stiffness due to reinforcement

K_{eff} - Effective shear stiffness of HDRB

K_H - Shear (lateral) stiffness of HDRB

K_z - Vertical stiffness of HDRB

K_v - Vertical stiffness of HDRB

L_{ed} - Length of longitudinal reinforcement bars

l_w - Width of wall

λ_t - Tension deformability

m - Mass

M_X - Modal participation factor

n - Numbers (quantity)

P - Gravity load from top of wall

$P1$ - Pivot point

$P2$ - Pivot point

$P3$ - Pivot point

$P4$ - Pivot point

P_{crit} - Critical buckling load of HDRB

$PP1$ - Pivot point

$PP2$ - Pivot point

$PP3$ - Pivot points

$PP4$ - Pivot points

q_0 - Basic behaviour factor

q_d - Displacement behaviour factor

$Q1$ - Quadrant 1 in pivot model

$Q2$ - Quadrant 2 in pivot model

$Q3$ - Quadrant 3 in pivot model

$Q4$ - Quadrant 4 in pivot model

R_I - Response modification factor

ζ - Critical damping ratio

S - Shape factor of HDRB

S_e - Elastic response spectrum

T - Period

T_D - Design period of base isolated structure

t_r - Total rubber thickness

$V_{b8\%}$ - Base shear of base isolated structure with 8 % damping ratio

$V_{b24\%}$ - Base shear of base isolated structure with 24 % damping ratio

V_{Eb} - Elastic base shear

ω_V - Vertical angular frequency

W - Self-weight of wall panel

$\ddot{x}$ - Relative acceleration

$\dot{x}$ - Relative velocity

x - Relative displacement

$\ddot{x}_g$ - Ground acceleration

θ - Drift ratio

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CHAPTER 1

INTRODUCTION

1.1 General

Cost of construction in the Asian countries throughout 2011 has been observed to increase tremendously as compared to the Western countries, and it is expected to escalate over the next few years. Globally, this will sooner or later affect the booming of construction prices over the world (Sugandy, 2012). Table 1.1 ranks the countries position in descending orders on rising construction cost. The annually published International Construction Cost Comparison report found that shortage in skilled labours is the main root causing such a high construction cost. Contractors around the world are in difficulty in getting affordable and adequate skilled workers for their jobs. In Southeast Asia alone, there are 10 countries which are listed in the top 50 in the global rankings on rising construction cost. To add matter worse, most of these nations such as Japan, Thailand, Vietnam, etc. are located in the seismic regions. Reducing construction cost through compromising structural materials and techniques needs to be engineered.

In response to such high increment of construction cost, the government of Malaysia have been strongly encouraging fellow builders to utilize Industrialized Building System (IBS) as dominant components especially in large constructions. In Malaysia, the local government had long ago foreseen the needs of transforming the conventional cast-in-situ construction practices which are being widely practiced in the current construction sector into the technique of IBS. Besides reduction in construction material wastage, requiring less volume of building materials, creating cleaner, safer, more organized construction site and shortening project completion time, one of the main reasons in which the government concerns the most is the utilization of IBS construction method will reduce greatly the reliance of the construction sector in employment of foreign-unskilled workers. Currently, billions of Ringgit Malaysia is flowing out of the country due to the heavy employment of foreign workers especially in the construction sector (CIDB, 2003a). The registered foreign workers occupied 75 % of total labours available in the construction industry as of 2003. Henceforth, the government has targeted to reduce the dependence of the construction sector in employment of unskilled-foreign workers to only 15 percent by the year 2009.

Table 1.1: Rising of construction cost particularly in Southeast Asia countries

2011			2010
Asia ranking	Global ranking	Country	Country
1	4	Japan	Japan
2	19	Hong Kong	Hong Kong
2	19	Singapore	Singapore
4	24	South Korea	South Korea
5	31	Macau	Thailand
6	40	Thailand	China
7	47	China	Malaysia
8	49	Malaysia	Taiwan
8	49	Philippines	India
8	49	Vietnam	Sri Lanka
11	52	Indonesia	
12	54	Taiwan	
13	55	India	
13	55	Sri Lanka	

The term ‘Industrialized Building System’ (IBS) refers to a construction process of a building or other structure where its structural components are either wholly or partly being prefabricated as well as manufactured off-site for assembling and installation at building sites. Prefabricated steel formwork systems (e.g.

permanent metal decks and tunnel forms), steel structural systems such as hot-roll manufactured steel beams, columns or trusses and precast concrete elements are among some of the popular IBS products. Although steel structures are relatively lighter in mass, it also possesses higher overall cost. Hence, expensive metal cladding systems are often required in order to enhance durability and meeting certain architectural demands. Precast concrete systems, on the other hand seems to be more economic, practical and durable, especially with the prices of steel which fluctuates according to supply and demand.

The utilizations of precast concrete as construction method had been widely practiced by many countries such as the Western Europe, Britain, California and Turkey. Taking Turkey as an example, most of the industrial structures and facilities were precast frame buildings since the introduction of precast concrete construction methods to the country in the 60s (Posada and Woods, 2002). Unfortunately, despite the advantages reflected in its construction procedures and processes, many of the precast structures collapsed during series of earthquakes in Turkey throughout the year of 1999. Apart from Turkey, some other examples which include the completed precast concrete structures are the Olympic Stadium (Li *et al*, 1998) in San Pedro Sula, Honduras which was completed in November 1997, and the B.C. Rail Yard Control Tower (Gerald, 1998) in British Columbia, completed in February 1995.

The introductory of precast concrete structural systems has, over the years, shown advantages in concrete structure constructions such as improved quality control, easier management of construction schedule, efficient use of materials and project cost reduction (Megally *et al*, 2002). The conventional wet concrete construction techniques or some called it the cast in-situ construction methods, which relatively requires more construction space at sites, high dependence in employment of unskilled-foreign workers, longer pending time for concrete curing and hardening process, and poorer quality control had seems to be replaced at a slower rate, but at a wide scale by precast concrete structural systems. However in the following discussion it was found that this was not the case in Malaysia.

1.2 Problem Background

The problem background that leads to the motivation of this study can be categorized into three different parts as shown in Figure 1.1. Firstly, the current status of precast construction in Malaysia was studied. Then, the awareness of seismicity in the country was reported. Together, these two factors would determine the importance to investigate and improve the seismic performance of locally developed precast concrete structural system and thus, the problem statement of this study is formulated.

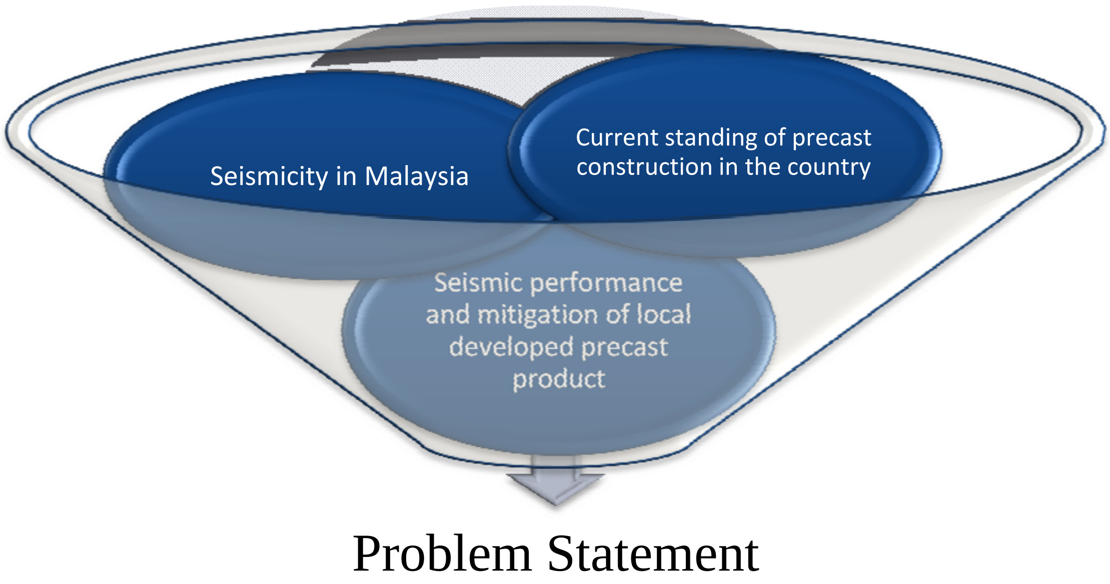


Figure 1.1 Formulation of problem statement through related problem background

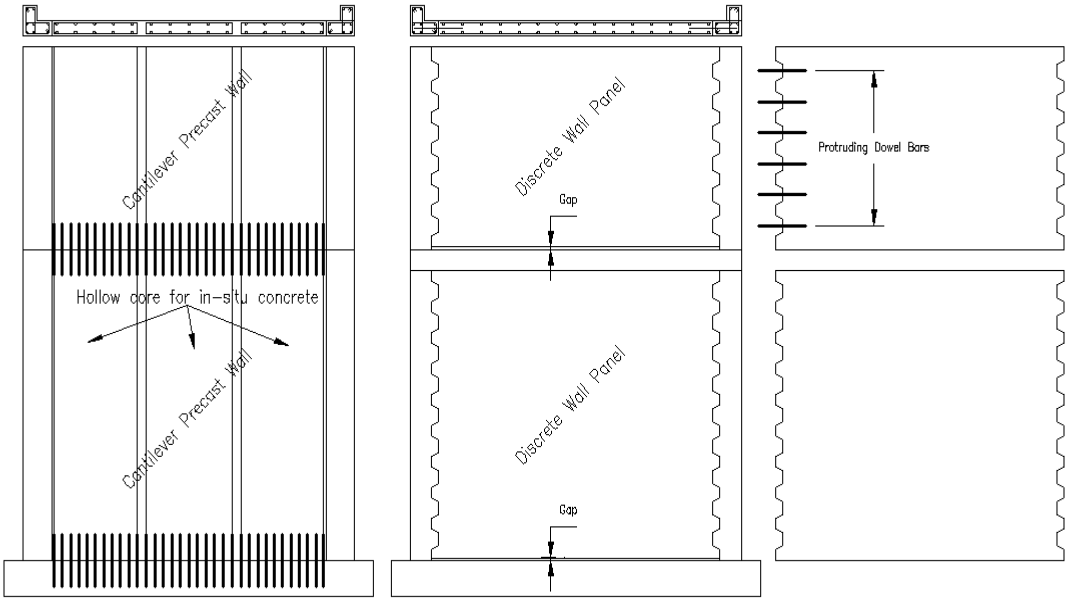
1.2.1 Precast Construction in Malaysia

Despite the effort of the Construction Industry Development Board (CIDB) under the Construction Industry Master Plan 2006-2015 (CIMP 2006-2015), as well as the 2008 law enforcement from government to make it compulsory for large government projects to utilize at least 70 % of IBS product, its level of acceptance was still reportedly low (Hassim *et al*, 2009). Although many large and important projects in Malaysia such as the Petronas Twin Towers, one of the tallest buildings in the world, Kuala Lumpur Tower, and Kuala Lumpur International Airport (KLIA) were constructed using the IBS method by most of the world class Malaysian developers, IBS is still not the primary construction method over the conventional cast-in-situ system especially in residential housing area projects.

A survey conducted by the Construction Industry Development Board (CIDB) in 2003 had revealed that the usage level of IBS in the construction sector was as low as only 15 percent (CIDB, 2003b). Therefore, to enhance the competitiveness of local construction industry in the international level, the government had issued Treasury Circulars (*Surat Pekeliling Perbendaharaan*) at the end of year 2008. The official letter had made it compulsory for large government construction projects to use at least 70 percent IBS components with effect from the year 2010 onwards.

With this new regulation from the government, it will soon be the epoch of IBS technique deployment in the construction sector in Malaysia, overriding the conventional cast-in-situ methods. As most of the large and important projects are government based, so either willing or not, the players in the construction sector will eventually heed to this call in order to qualify themselves to participate in the bidding of public projects. As a result, it becomes significant and obvious that there are vital needs for the development of researches regarding the IBS techniques to value-add the 2020 vision of the government. However, as the market is currently competitive in the nation and there is no unique precast technology owned by local manufacturers, most of them required heavy subsidy from government to keep the business running (CIDB, 2011) which would not be beneficial to both parties in the long run.

Hence, it has become important for the private industry to initiate relevant researches regarding prospective precast system that best suits the needs of local industry. Among them is the HC Precast System (Figure 1.2(b)). The system, having its patent granted in 2011 or in short HCPS comprises load-bearing precast concrete wall panels that are connected only to the supporting cast-in-place column at both ends. This terminology will be used throughout this entire thesis. The wall panels eliminated the necessity of having brick wall and beam element. There is no horizontal connectivity provided between the top and bottom wall to restrain it from sliding against each other. Due to the relatively humid and wet tropical climate of the region, wet interface provides a better water resilient capability for precast structures in the country (Hamid, 2009). The proposed precast concrete wall structure is replacing the existing cantilever wall system (Figure 1.2(a)). The cantilever wall system was normally made of hollow-core wall sections. The wall panels on top were connected to the bottom wall through insertion of heavier reinforcement and concreting at site. This cantilever wall system has been said to become unpopular among builders in recent years due to involvement of relatively heavier site works to fill in the hollow-core sections between the walls (Elliot, 2002).



(a) (b)

Figure 1.2 (a) Cantilever wall system and (b) HC precast wall system (HCPS)

The precast wall panels are connected to the supporting columns located at both ends through series of in-built shear keys and also dowel bars (Figure 1.3) protruded alongside the vertical edges of the wall panels. Wet joints would then be cast at site, forming the columns which also at the same time served as vertical connections that held the wall in place (Figure 1.4). The key innovative component of HCPS was that the wall panels were disconnected along their horizontal connection which made the site work easier and faster. The amount of steel works required at site was also reduced significantly. These two factors were the main reasons causing the conventional cantilever precast wall system to lose its popularity over the years. Detail of the construction and assembly process of HCPS can be found later in Chapter 4.

Figure 1.3 Shear keys and dowel bars alongside vertical edges of wall panel

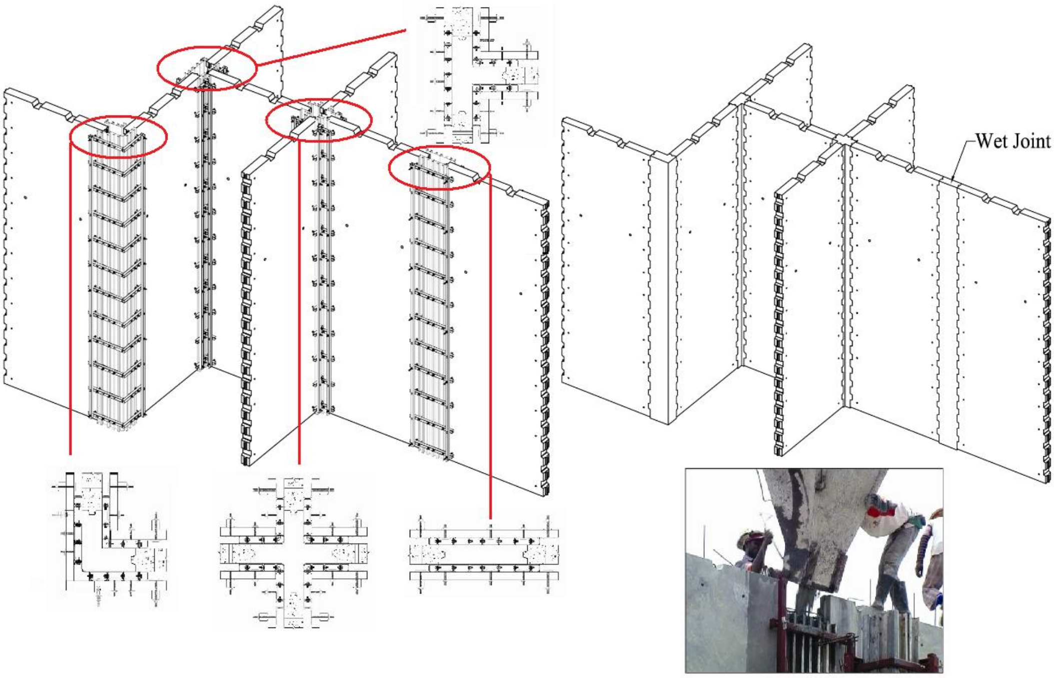


Figure 1.4 Wet joint casting at site forming columns as well as vertical connections

History and development of shear key connection in precast wall could be traced back to as early as in the 80s' studied by Chakrabati (1988). In BS8110:1997-Part 1 (British Standards Institution, 1997), a small portion of design specifications of castellated joints or shear keys was included. The precast construction industry has then shifted to dry connection method such as unbonded post-tensioned walls (Kurama, 2005). The main reason was the requirement of timber formwork usage during casting of wet joint which would be costly as most timber formwork had limited reusable time span. Until recently in the year 2007 when HC Precast System had patented a type of modular mould (Figure 1.5) that is reusable for shear key casting plus the key feature of extremely effective water-proofing by HCPS, the system had been implemented in constructing more than a thousand units of residential housing as well as commercial buildings over the country. Detail of invention of the reusable modular mould can be found in Tiong *et al* (2011).

Nevertheless, the system is not designed for seismic resistant. As Malaysia is now moving forward in formulating local seismic design guidelines based on Eurocode 8 (CEN, 2003), it has become a necessity for the system to be analyzed accordingly in terms of seismicity effects.

Figure 1.5 Innovated modular moulds for wet-joint grouting at site

1.2.2 Seismicity in Malaysia

Currently, the common design and construction practices in Malaysia have often ignored and neglected the consideration of seismic effects towards the stability of structures especially in the implementation of lower cost projects such as residential estates, erection of relatively lower buildings, and etc. as the history of earthquakes in the country have not been intense. Needless to say, the constructed precast concrete buildings or structures were never tested to resist earthquake loadings. The conventional reinforced concrete structures also faced detailing problem when it comes to seismic design. Very often, reinforcement congestion occurred at joints which caused impracticality of the design practice. Nevertheless in actual fact, the country may not be as earthquake-free as majority of its public regarded.

Despite the geographical location of Malaysia at a stable part of the Eurasian Plate, the existence of three major earthquake faults with a distance of a few hundred kilometers away from the country had often caused tremors to be felt in some of the places especially by the residents of tall buildings in Peninsular Malaysia. These three earthquake faults are the Sumatran Subduction Zone, the Sumatran Strike Slip Fault with both of them respectively measured about 600 km and 400 km away from Peninsular Malaysia, and another slip fault near to Tawau, at the eastern district of Sabah state. Over the years, the Meteorological Department of Malaysia (*Jabatan Meteorologi Malaysia)* has recorded numerous earthquake events with a wide range of intensities. Table 1.2 reflects the list of recorded past earthquake events reported in Malaysia obtained from the Meteorological Department of Malaysia.

Table 1.2: Recorded past earthquake events in Malaysia up to September 2007

State	Event Frequencies	Earthquake Maximum Intensity Observed (based on Modified Mercalli Scale)
Peninsular Malaysia (Events from 1909 till September 2007)		
Johor	27	VI
Kedah	13	V
Kelantan	3	IV
Malacca	15	V
Negeri Sembilan	7	V
Pahang	7	III
Penang	36	VI
Perak	22	VI
Perlis	2	IV
Selangor (incl. KL)	46	VI
Terengganu	1	IV
Sabah (Events from 1923 till September 2007)		
Sabah	27	VII
Sarawak (Events from 1923 till September 2007)		
Sarawak	5	V

The state of Sabah has experienced the strongest earthquake intensity of MMI Scale VII when compared to the other remaining states of the country as it is located relatively near to an active earthquake fault. According to an earthquake report from USGS, a 10 km deep earthquake having the Magnitude of 4.9 Richter Scale occurred on Sunday, 18th May 2008 in Sabah region. The epicenter as shown in Figure 1.6 was 45 km from Tawau and 145 km away from Sandakan. In the Peninsular Malaysia, the nearest active earthquake faults are located a few hundred kilometres away. According to Balendra (1993), the low frequency seismic waves generated by the Sumatran earthquakes are capable to propagate and travel very long distances before reaching the Singapore-Malaysia region due to the nature of the long period waves which is more vigorous to energy dissipation while the high frequency waves are dissipated rapidly during proliferations. This mechanism, shown in Figure 1.7 is identified as far-field effects of earthquakes. The arrival of the amplified waves as they travel upward though the relatively softer soil near the earth surface causes resonance in buildings and the movements of the buildings shaking could be felt by the residents (Balendra and Li, 2008). This is the main reason for residents particularly in higher buildings to experience minor tremors over the years.

At the time of this thesis writing, the Technical Committee (TC) formed by the Institute of Engineers of Malaysia (IEM) is looking into the proposal of national annex for Eurocode 8 (EC8) in Malaysia. One of the major decisions would be deciding on the ground acceleration a_g for Malaysia. Currently, there are three different a_g levels to be considered, 0.05 g, 0.075 g and 0.1 g. Therefore when the map is officially released, the impact on HCPS needs to be investigated to avoid large amount of retrofitting work in the future.

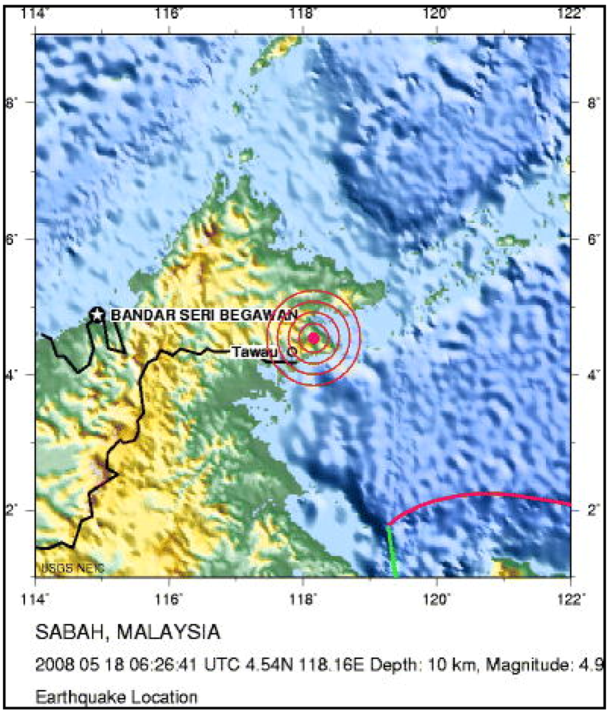


Figure 1.6 Location of epicenter of the 18th May 2008 earthquake in Sabah Region

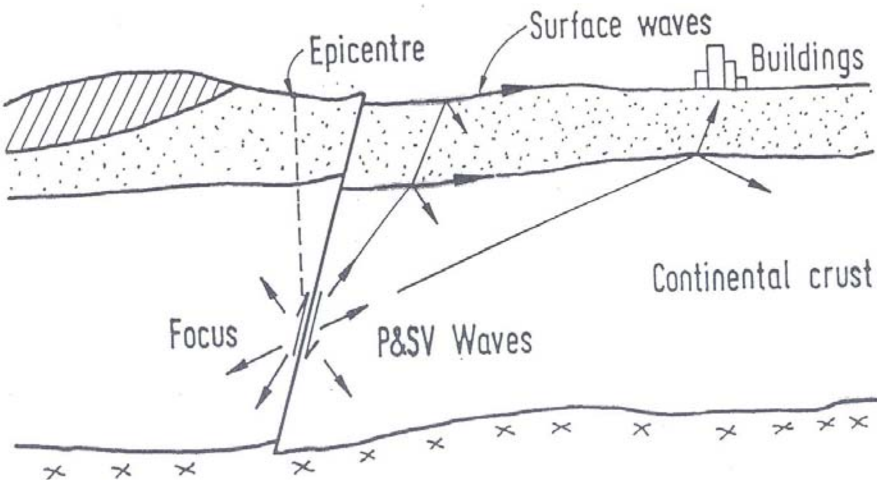


Figure 1.7 The far-field effects of earthquakes (Balendra and Li, 2008)

1.2.3 Seismic Performance and Mitigation of HCPS

The main concern of the manufacturer of HCPS and the industry would be how the precast system would behave due to ground acceleration, and the effect of future implementation of Eurocode 8 (EC8) design code in the country onto the system. The precast concrete structure is only as strong as its weakest link or element when it comes to deal with seismic responses. In the conventional cast-in-situ construction, the structural continuity is inbuilt and will mechanically follows as the construction proceeds. Dissimilar to the conventional monolithic concrete structures, the site erection works of precast concrete structures involves of assembling, connecting and jointing numerous pieces of discontinued and discrete precast concrete panels to form the whole building structural components. The interfaces connecting the precast concrete elements together will determine the overall performance and stiffness of the precast concrete systems.

Under earthquake loading, the connection or joint of precast elements will be the most critical area to resist the lateral seismic reaction forces (Dowrick, 1987; Xiao *et al*, 2013 and Babu *et al*, 2013). The behaviour and characteristics of precast joint under seismic effects are rather complex and must be seriously accounted for in the design stage (Lu *et* al, 2012). This is where the critical problem arises. A good design must not only be able to withstand the required loadings, but must also be practical and possible to construct. In addition to that, it has been shown by Bljuger (1988) that for protruded reinforcing bars or dowel reaction, the difference between a single bar and a U-shaped bar is not significant. This makes proper reinforcement of such dowel connection to be perfectly rigid difficult to construct and not fully established.

Most people have the common misconception that precast concrete structures are incapable to provide adequate seismic resistance until recent improvements in research development have introduced efficient precast structural systems that are capable of maintaining structural integrity under cyclic loading, among which are the hybrid post-tensioned frame and unbonded, post-tension jointed precast walls (Priestley *et al*, 1999). Therefore, it became questionable whether the non-earthquake designed HCPS is able to withstand earthquake loading, and to make matter worse when the EC8 for Malaysia is released by IEM Technical Committee in the near future, will HCPS be deemed satisfactory or if there are any changes required to the original system?

The conventional seismic resistance design approach posed a challenge for designers to obtain a balance between minimizing both floor accelerations and interstory drifts at the same time in the designed structures (Mayes and Naeim, 2001). It is understood that excessive interstory drifts can be eliminated by constructing a stiffer building. However, a stiffer building, which is now becoming less flexible, will cause high floor accelerations. On the contrary, a flexible structure, though it will lead to lower floor accelerations causes large interstory drifts. Both of these two factors cause greater force demand from either the building structural component or its contents within (Figure 1.8). The presence of wall in HCPS has increased the overall lateral stiffness of the structure as compared to a bare frame system. As it would be revealed in the later part of this study particularly in Chapter 6 that the acceleration responses of HCPS were significantly higher than the ground acceleration due to such attribute and the other half of this study is focused on using locally produced high damping rubber bearing (HDRB) as base isolation system for seismic mitigation of HCPS.

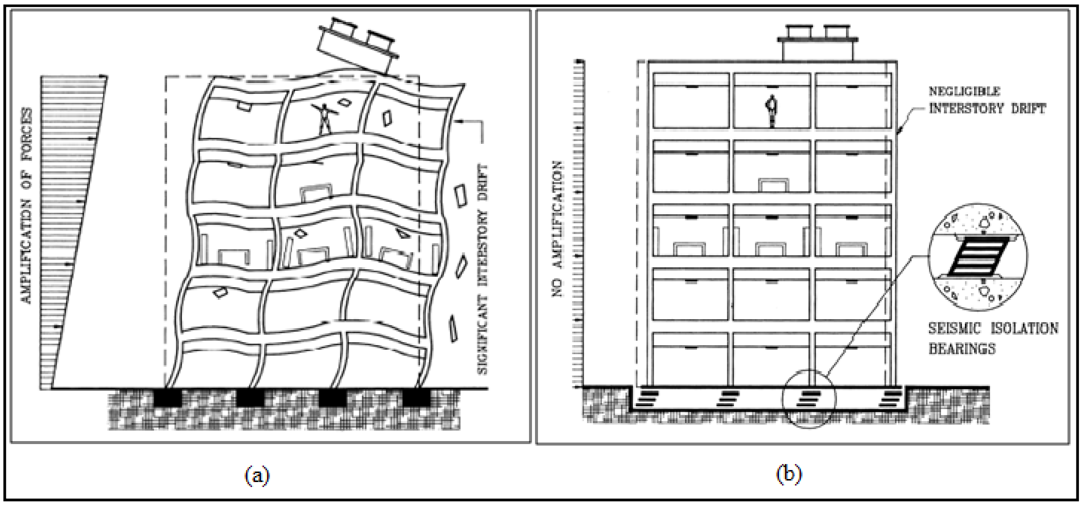


Figure 1.8 (a) Large interstory drift and disruption to a fixed base building contents and (b) Mitigation of seismic force by base isolation system (Mayes and Naeim, 2001)

Earthquake itself does not kill. It is the structure that collapse costs the lives of many. The earthquake forces are generated within the structural system of a particular building due to the inertia of the structure when it responded to the ground dynamic motion. In other words, the heavy mass of the building which reacts in the opposite direction from the ground movement causes effective base shear as the restraining force transmitted from the ground to the top of structure. With such understanding of earthquake force transmission, separating the structure from ground could be an alternative to minimize such inertia response due to ground movement, which is termed as seismic base isolation. Thus, seismic base isolation had been proposed, studied and investigated by numerous researchers all over the world over the past decades as an alternative to the conventional ductility design concept. Although the earliest recorded history of seismic base isolation was as early as 1909, the growth of its application was not too apparent only until early 1980's with the development of multilayered elastomeric rubber bearing base isolators (Naeim and Kelly, 1999).

There are varieties of devices available for seismic isolation of structures such as rollers, friction slip plates, sleeved piles and rocking foundations. Nevertheless, an elastomeric rubber bearing appears to be one of the most practical and widely used seismic base isolation systems (Forni, 2010; Warn and Ryan, 2012). A typical elastomeric rubber bearing, or sometimes termed as high damping rubber bearing (HDRB) or laminated rubber bearing is shown in Figure 1.9.

Figure 1.9 High damping rubber bearing (HDRB) showing internal layers

The simple basic concept for seismic base isolation is just to decouple the superstructure from the horizontal loading of ground motion as shown in Figure 1.10. This is achieved through introducing an interface with relatively low horizontal stiffness between the foundation and the base of the superstructure. This interfacing element is the so-called base isolation system. The main purpose of the isolation system is to increase the natural period of a rigid structure as a rigid structure usually possesses very short first mode period. Thus, it creates a structure with very much lower fundamental frequency compared to its fixed-base frequency and also the predominant frequencies of the ground motion.

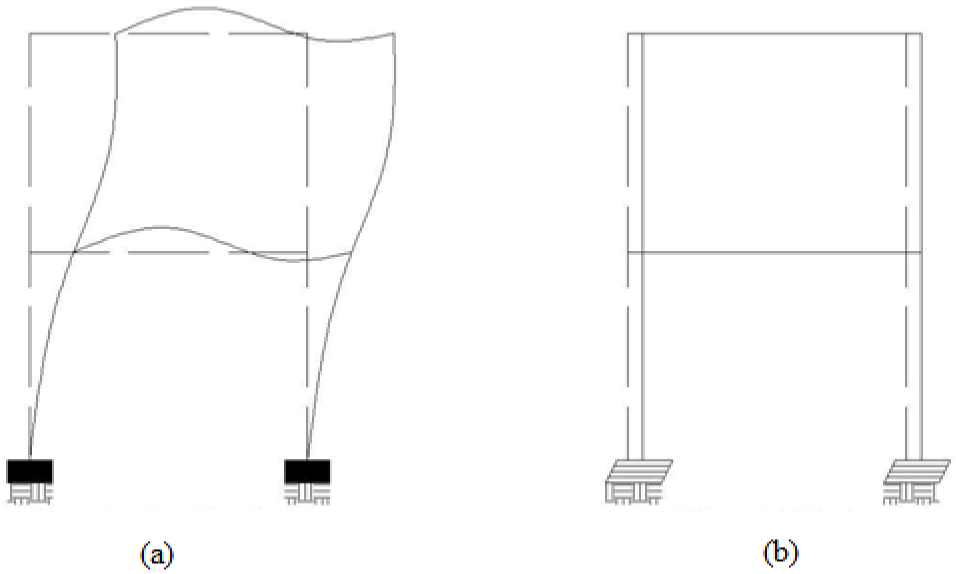


Figure 1.10 Structural response of (a) fixed base and (b) base isolated structure

The main principle of seismic isolation is to prolong the period of the isolated structure. Logically, it works effectively for short structures as their period is usually very small, typically less than 1 second. Meanwhile, the natural period increases with increment of the structure’s height. For very tall structure where the natural period is long enough to attract low earthquake forces, seismic isolation is considered redundant.

The second school of thought regarding seismic base isolation is the reduction of seismic force demand through providing additional damping capability of the vibrating system, besides prolonging the fundamental period. In linear equivalent static analysis of base isolation system using the constant velocity approach, the reduction of spectra acceleration (Fig 1.11(a)) and displacement (Figure 1.11(b)) is apparent when damping ratio increases. In countries like Japan, China and Turkey, the earthquake engineering committee required at least 24% damping ratio to be used in base isolation system. According to EN15129 (CEN, 2007), elastomeric rubber bearing possessing damping ratio above 6 % is deemed as HDRB, and typical damping of HDRB is in the range of 8 to 12 percent depending on the shear modulus of rubber compound used. This leads to development of lead rubber bearing and other mechanical damping devices to go along with HDRB. This not only causes very expensive base isolation system but to some extend compromising the durability and strength of rubber compound by altering the vulcanization process to increase damping value which is widely practiced in Japan.

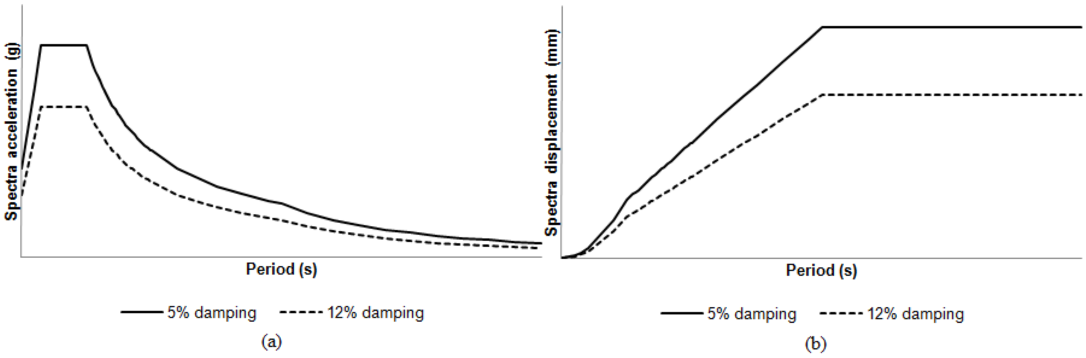


Figure 1.11 Damping ratio effect on spectra (a) acceleration and (b) displacement

1.3 Problem Statement

HCPS is considerably a new structural configuration having its patent granted in the United States and Malaysia in the year 2011. The system is not covered in the EC8 currently. Although the design and analytical tools for normal precast infill panels were not new (Rath, 1977; Bljuger, 1988; Elliot, 2002; and Mainstone, 1972), the configuration of HCPS is different from conventional infill structure and therefore, the performance of such system is not established yet particularly in terms of earthquake loading. Thus, a reliable tool or model to analyse the structure is not available especially in the nonlinear response region. This leads to questionable performance of the system when EC8 is implemented in Malaysia in the near future. With the national annex of EC8 for Malaysia to be released soon, would HCPS be deemed satisfactory for the country due to seismic design provision or retrofitting work is needed?

Secondly, the structural vulnerability of HCPS under dynamic loading such as earthquake remained unknown as mentioned earlier that the system was not covered by EC8. The only known fact according to EC8 was that HCPS belonged to the DCL category. However, information regarding the resistance of the HCPS structural system to earthquake ground excitations was unavailable.

Thirdly, the presence of wall panels would logically increase the stiffness of HCPS in its lateral direction, causing the structure to possess shorter predominant period. The rule of thumb in seismic behaviour is stiffer structure attracts higher floor acceleration. Therefore, the second part of this study also included application of base isolation system using elastomeric rubber bearings to investigate its efficiency in reducing floor accelerations. Since HCPS would be used ideally for low-rise residential housing or commercial shop-houses which would be relatively lighter compared to most base isolated structures such as towers, hospital buildings, and bridges which were heavier in mass, the capability of the base isolator to meet required lateral displacement became questionable (Naeim and Kelly, 1999). In other words, the HDRB becomes unstable when the imposed vertical load gets smaller if the designed lateral displacement remains the same. Investigation was also carried out to examine the rationale behind choosing higher damping ratio of 24% in the design of base isolation system for HCPS as compared to the typical damping ratio obtained from natural HDRB.

1.4 Research Aim and Objectives

This study is aimed to promote and enhance the usage of locally developed HCPS as alternative for fast as well as economic building system to both local industry and abroad, including earthquake prone regions. The main objectives of the research will be as follow:

a. To obtain capacity curve of HCPS from hysteresis behaviour in order to evaluate the behaviour factor of the system for seismic design
b. To investigate structural vulnerability of HCPS in terms of roof acceleration and drift demands under earthquake loading
c. To study reduction of base shear and acceleration response of base isolated HCPS by normal HDRB and also HDRB with different damping ratios

1.5 Scopes of Work and Research Boundaries

The present investigation comprises 50 percent laboratory as well as experimental studies and the other 50 percent includes finite element analysis and results interpretation. The research scopes cover the following areas, fields and tasks:

a. Performing laboratory test of large-scale HCPS under lateral-cyclic loading at CREAM’s laboratory
b. Performing scaled-down shake table test of HCPS using recorded ground motion data obtained from Pacific Earthquake Engineering Research Center (PEER) ground motion database (PEER, 2010)
c. Proposing finite element model of HCPS for both lateral-cyclic loading condition and ground excitations
d. Verification and calibration of the proposed finite element model with laboratory results
e. Obtaining global capacity curve of HCPS through pushover analysis with various lateral loading patterns as recommended in Eurocode 8
f. Investigating the performance point of HCPS under local seismicity of Malaysia
g. Designing and manufacturing of high damping rubber bearings (HDRB)

to elongate the fundamental period of base isolated HCPS to 2.5 s

h. Performing laboratory test of the HDRB to obtain hysteresis loops of force-deformation to be used in nonlinear time-history analysis of base isolated HCPS with 33 earthquake records
i. Feasibility of applying proposed base isolation as seismic mitigation of HCPS would be investigated

The framework of this study would be conducted within the following boundary and limitations:

a. It is worth to mention that this study focused only on HCPS as one of the possible types among many other components of IBS.
b. The prototype HCPS was designed accordance to BS8110: 1997 following standard consultant practice and vetted by qualified industry experts which was also later checked by the author according to Eurocode 2 (CEN, 2002)
c. To keep the structural geometry unchanged throughout the study, the number of stories of HCPS was kept to be not more than two stories which would otherwise required larger column sections to be used.
d. This study classified the strong ground motion data into three intensity groups of low, normal and high based on the *PGA/PGV* ratio of the time history (Zhu *et al*, 1988; NBCC, 1985; Elnashai and Mcclure, 1996).
e. The laboratory shake table test was performed only with fixed-base HCPS in order to verify the proposed finite element model (FEM) of the connection system, while the isolation system test was only performed by individually testing the elastomeric rubber bearing due to the well-established modelling technique for the base isolation component in SAP2000 (CSI, 2010; Naeim and Kelly 1999).
f. The thickness of HCPS was kept at 150 mm, which was used in construction of most residential housing and shop houses within the country.
g. It is worth mentioning that while it is in the scope of this study to perform investigation on the established current construction sequence of HCPS in

terms of its performance under seismic loading, the study does not cover the optimization of its structural system design contained in the Damage Avoidance or Capacity Design for the system. Improving the connection detail of the precast wall system (HCPS) is not within the scope of this study.

1.6 Research Significance

Significance of the study is achieved by meeting all the listed research objectives listed earlier. Thus, the performance of HCPS subjected to seismic loadings either through dynamic or quasi-static excitation is established. In addition to that, the effectiveness of mitigating earthquake effect particularly in reducing floor acceleration through HDRB as base isolation is also ascertained. Detail discussion and findings can be found in relevant chapters contained within this thesis.

1.7 Thesis Layout

This thesis report is divided into eight main chapters, with each chapter having their respective major topics. Chapter 1 covers the introduction of the thesis. Chapter 2 presents literature review in several aspects related to this study including brief history of past researches, followed by the state-of-the-art works done by other authors. In Chapter 3, theories concerning the background of relevant subject matters such as dynamic performance of precast wall and base isolated system, laboratory test procedures as well as code requirement on modelling of precast wall and base isolation. The methodology of this study will be reported in Chapter 4. Chapter 5 presents the verification of finite element modelling used in this study through laboratory lateral cyclic loading test of 2-storey full scale HCPS prototype and shake table test of 1:3 scaled down model from the prototype building. Subsequent chapter covers the seismic performance of fixed base HCPS. The behaviour of seismically base isolated HCPS will be presented in Chapter 7. The final chapter, Chapter 8 comprises summary, conclusions and recommendations for future work.

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APPENDIX A

LIST OF PUBLICATIONS

1. Tiong, P.L.Y., Adnan, A., and Hamid, N.H.A. (2013). “Behaviour Factor and Displacement Estimation of Low-Ductility Precast Wall System under Seismic Actions.” *Earthquakes and Structures,* 5(6): 625-655pp. (IF 2012 = 1.381)
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