A CONCEPT DEVELOPMENT AND PROPOSED DESIGN PROCEDURE FOR ROCKING PRECAST HOLLOW CORE WALL IN WAREHOUSE

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ABSTRACT

Precast hollow core unit is commonly used in the construction of flooring system in precast reinforced concrete building in Malaysia. One of the technical challenges is to design and use precast hollow core unit without any transverse reinforcement bars to resist earthquake loading. One of the approachable methods is to combine the basic concept of rocking structure together with Damage Avoidance Design (DAD) philosophy. Moreover, Performance-Based Seismic Engineering Design concept is also incorporated in this study so that reinforced concrete structure can survive under Design Basic Earthquake (DBE) and Maximum Considered Earthquake (MCE). In this study, the total effective viscous damping ξ_{eff} plays an important role in designing seismic wall panel which comprises of hysteresis damping (ξ_{eq}), radiation damping (ξ_{rock}) and intrinsic damping (ξ_{inst}). Another attributes which also plays a significant role in plotting capacity-demand spectrum for any location in seismic regions is damping reduction factor (B). By combining the capacity-demand spectrum and concept of rocking structure, a proposed design procedure of warehouse buildings using PHCW is developed and proposed. The proposed design procedure consists of seven steps which are determination of seismic demand, maximum response displacement for MCE and DBE, estimation of total effective damping, calculation of base shear, design of energy dissipator and unbonded tendons, evaluation hysteresis and total damping, and finally, the assessment of seismic capacity of rocking wall. In this study, it is expected that the rocking precast hollow core wall can reduce a substantial amount of structural damage and remain functional after an earthquake.

Keywords: *Steel-armouring, Rocking Structures, Damage Avoidance Design Philosophy, Hysteresis Loops, Performance-based Seismic Engineering*

1.0 INTRODUCTION

From past earthquakes records such as the 1999 Kocaeli Earthquake, the 1999 Chi Chi Earthquake and the 1994 Northridge Earthquake which caused quite substantial damage to the industrial facilities and warehouses, high-tech computer industries, parking garages and precast concrete structures. The conventional method of designing shear wall using ductile design philosophy has failed in preventing these buildings from surviving under major earthquake and did not maintain post-earthquake serviceability. Normally in seismic regions, longitudinal and transverse reinforcement bars were used in shear wall to resist earthquake loading. Therefore, it is a motivation for civil engineers to design shear wall such precast hollow core unit without transverse reinforcement as shear wall panel which can resist ground motion without any structural damage. Thus, one of the challenging tasks is to design and modify precast hollow core units to resist vertical and seismic loading with the existence of longitudinal prestressed strand only. By adopting the concepts of Damage Avoidance Design (DAD) philosophy and rocking structures along with damage protection, the rocking toe at wall-foundation interfaces could litigate high stress zone and resist these loads efficiently. However, it is legitimated to provide transverse reinforcement bars in precast wall panels and shear wall as required by most of standard design seismic code such as Eurocode 8 [1], IBC 2000 [2], NZ 3101 [3], ATC-40 [4] and others.

Due to poor performance of industrial and warehouse buildings during these earthquakes, the conventional design philosophy needs to change to the new design philosophy which could maintain post-earthquake serviceability of the structures. Which mean that a new design concept together with a new form of construction for industrial facilities is necessary to avoid any damage entirely during earthquakes. Therefore, the main objective of this paper is to develop a rocking concept and proposed a new design procedure for precast hollow core wall system which can be used in the construction of industrial facilities. In this procedure, the discontinuous interface between wall-foundation could prevent the occurrence of plastic hinge zone and at same time could avoid any spalling and crushing of concrete at toe of the wall. The rocking concept between interfaces plays an important role in dissipating energy after the impact of earthquake excitation.

2.0 FINDING FROM PREVIOUS RESEARCH

A significant amount of research has been conducted on rocking structures under earthquake motion. The first rocking rigid body kinematic concept was developed by Housner [5] who studied the free vibration of rigid block during earthquake excitation. Then, Meek [6] investigated the aspects of structural flexibility rocking on foundation beam. The improvement of rocking concept was followed by Priestley *et. al* [7] who introduced the seismic dynamic response of rocking structures on their foundation. Aslam *et. al* [8] considered the influence of initial prestress with some resistance to the rigid structure by anchoring the concrete block to the ground floor. Further research was carried out by Yim *et. al* [9] who studied the effect of sizes, slenderness ratio and ground motion to the seismic response of rigid blocks. Subsequently, Psycharis and Jennings [10] discovered that there was a partial separation between the base of block and foundation during ground shaking. Then, they modelled two types of foundation beams as two-spring foundation and Wrinkler foundation which allowed uplifting but did not permit any slip in horizontal direction. Later on, Lin and Yim [11] examined the nonlinear rocking motions under noisy periodic excitations and overturning of rigid body under random excitations.

The concept of prestressing unbonded tendons in beam-column connection was developed by Priestley and Tao [12] and demonstrated through experimental work by Priestley and MacRae [13]. This was followed by Kurama *et al*. [14] who proposed a seismic design procedure of unbonded post-tensioned tendons walls by taking into account the horizontal slip. Subsequently, Kurama [15] recommended a simplified seismic design procedure under performance based design using unbonded post-tensioned precast wall panels with supplemental viscous damping. Even though Precast Seismic Structural System (PRESSS) adapted direct displacement based design procedure but it did not specified the steel-armoured detailing especially at wall-foundation and beam-column connections [16]. Consequently, Damage Avoidance Design (DAD) was introduced by Mander and Cheng [17] using a steel-armouring rocking interface at the rocking toe to accommodate high contact point forces and prevent any local damage. By adopting the rocking rigid body concepts on the design and construction of bridge piers, the structural damage can be avoided by using special steel-armoured details at the bottom of the bridge column. Some other researchers who used Damage Avoidance Design philosophy in designing and constructing precast reinforced concrete wall panels are Holden *et al*. [18], Surdano [19], Ajrab *et al*. [20], Liyanage [21] and Hamid [22] had proven that no structural damage occurred at wall-foundation interfaces. Contradictorily, Hamid and Surdano [23] had designed precast slender/thin wall using conventional method, constructed and tested under dynamic loading. The visual observation during experimental work showed that a lot of damage occurred at bottom of wall such spalling of concrete, fractured of longitudinal bars and lateral torsional buckling. A substantial damage was also observed on monolithic based connection of slender/thin wall which designed using ductile design approach when tested under biaxial loading [24]. Further improvement was made on thin/slender wall panel by designing rocking base connection and tested under biaxial quasi-static loading. The experimental results showed that less damage was occurred but the outermost longitudinal reinforcement bars were fractured after applying the lateral loading [25]. Therefore, the intentions of this paper are to develop the basic concept of rocking wall panel using precast hollow core units, derive the effective viscous damping and proposed a new procedure for construction rocking structures.

3.0 DAMAGE AVOIDANCE CONCEPT (DAD) IN WAREHOUSES

Figure 1 shows the prototype model of warehouse building constructed using precast hollow core walls and designed under Damage Avoidance Design philosophy. The multi-panel walls consist of seismic and non-seismic walls which are designed to resist gravity, longitudinal and transverse loads (wind and seismic load). The rafter of portal frames is sitting on seismic wall which carrying the roof loads and resist the transverse loads. Figure 1(a) shows the horizontal bracing elements along the top edges of the roof which are designed to resist longitudinal loads and the portal frame with seismic wall as a vertical element to resist transverse loads. The longitudinal and transverse loads represent the loads which coming from earthquakes.

Figure 1(b) shows the plan view of a warehouse with their seismic and non-seismic walls, wind trusses and rafter with portal frame. The numbers of non-seismic walls are depending on the spacing of rafter sitting on seismic walls. The portal frames are bolted to a steel channel web using unbonded tendons located in the center of the void sections of seismic walls and it also activated as a load bearing wall without constructing external columns.

Figure 1(c) shows the cross-section *x-x* of the portal frame together seismic wall panel. The detail connection ‘A’ shows the connection between top of the walls and edges of portal frames and connection ‘B’ depicted detail joint between wall-foundation interfaces. The seismic walls are attached to the foundation beam using couplers (RB25C). They allow to rock freely on foundation beam and at the same time acting as external column. The detailing of drawing can are shown in Hamid [22].

Figure 2 shows the overall behaviour of a seismic wall comprising a pair of unbonded tendons and energy dissipators. By using the concept of rocking structures and Damage Avoidance Design (DAD) are adopted in designing this type of warehouse building. The rocking seismic wall is modelled as Single Degree of Freedom (SDOF) where the combination behaviour of unbonded tendons and gravity load behaved as Bi-Linear Elastic as shown in Figure 2(a). The radiation damping, ξ_{rock} from unbonded tendons is produced during uplifting and yielding of unbonded tendons. Figure 2(b) represents the behaviour of fuse bars/tapered energy dissipator as Ramberg-Osgood hysteresis loop and the hysteretic damping, ξ_{hyst} creates after yielding energy dissipators. Figure 2(c) produce the total effective damping, ξ_{eff} which behaved like a “flag-shape”. The initial prestressing, locations and cross-sectional area of unbonded tendons and energy dissipators are the important attributes in determining the amount of base shear capacity, yielding drift, and the behaviour of a rocking wall system.

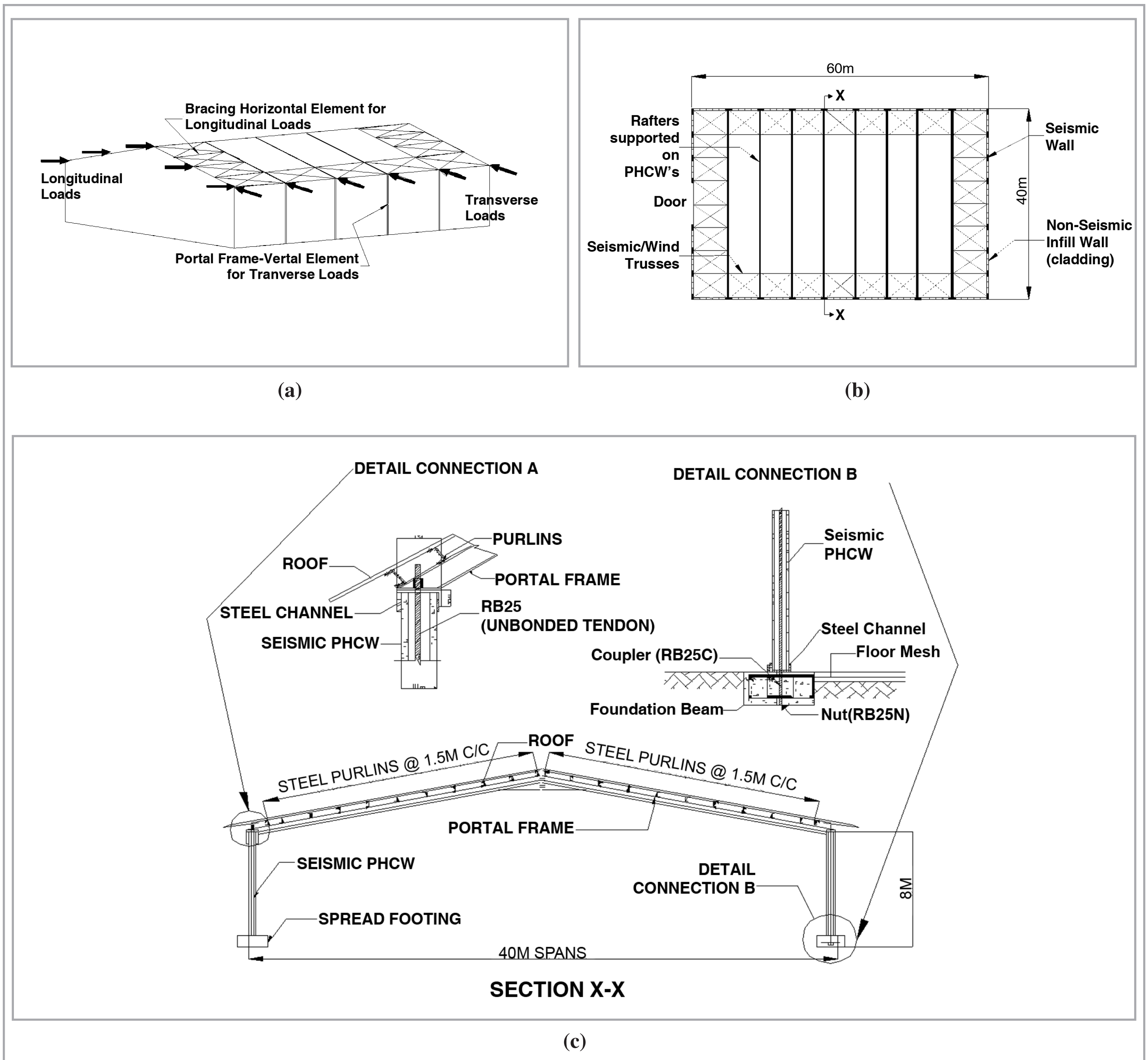

Figure 1: Concept overview of warehouse building; (a) distribution of transverse and longitudinal loading arising from either wind or earthquake effects; (b) plan view of warehouse showing lines of portal frames seated on PHCW; (c) steel portal frame setting on PHCW together with detailing connection at top and bottom of the wall

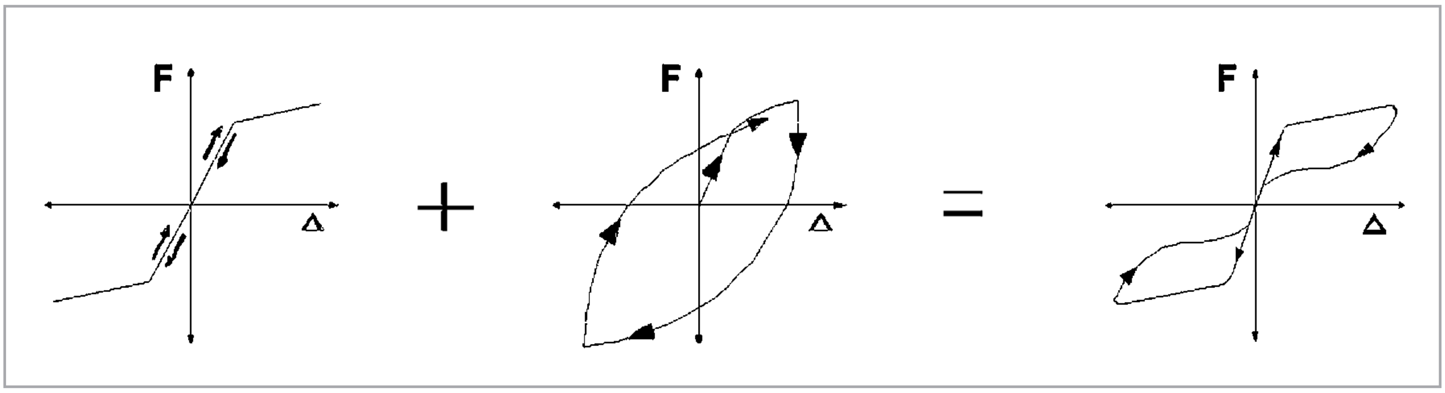

Figure 2: The mechanics of a rocking wall; (a) Bi-Linear Elastic behaviour due to self-weight and unbonded tendons; (b) behaviour of energy dissipators; (c) hysteresis of flag-shape

4.0 DAMPING IN ROCKING STRUCTURES WITH ADDED HYSTERETIC ENERGY DISSIPATION

4.1 Effective Viscous Damping

In the rocking system and Damage Avoidance Design (DAD), the total effective viscous damping, ξ_{eff} comes from hysteretic loops, intrinsic structures damping and radiation damping which can be expressed:

$$\xi_{eff} = \xi_{rock} + \xi_{hyst} + \xi_{inst} \quad (1)$$

where ξ_{hyst} is the additional damping from the energy dissipator devices, ξ_{rock} is the radiation or dissipated energy from each rocking cycle including tendons, ξ_{inst} is the intrinsic damping due to the internal structures of the system. The typical values of intrinsic damping used by the structural engineers are 2% for steel and 5% for reinforced concrete building [26].

It is also can be written as follows [24]:

$$\xi_{eff} = \xi_{inst} + \xi_{rock} + \frac{2\eta}{\pi}\left[\frac{1}{1-r(\mu-1)} - \frac{1}{\mu}\right] \quad (2)$$

In Equation 2, the term ξ_{hyst} is replaced by energy absorption efficiency factor (η) ; while r = the post-elastic to initial stiffness ratio and μ = the structural displacement ductility.

4.2 Radiation Damping in Rocking Structures

The radiation damping can be assessed by considering two conditions as pre-rock damping when unbonded tendons is not yielding and post-rock damping after unbonded tendons yielded. The radiation damping for one impact per half-cycle of the rocking system is given by

$$\xi_{rock} + \frac{E_p(1-r)}{\pi F \Delta} \quad (3)$$

where r is ratio of rotation kinetic energy after to before impact; F is the uplift force and Δ is the displacement amplitude. The amount of potential energy, E_p when the tendons did not yield is given by the following equation:

$$E_p = \frac{B \sin\theta}{2}\left[W + \frac{1}{2}\left[K_p\theta + \frac{2K_pL_T\varepsilon_o}{B} + \varepsilon_o\right]\right] \quad (4)$$

By substituting $r_s = \frac{K_pL_T}{WB}$ into Equation 4, and the equation becomes:

$$E_p = \frac{B\,\theta W}{2}\left[1 + \frac{r_sB\theta}{2L_T} + r_s\varepsilon_o\right] \quad (5)$$

The amount of potential energy when the tendons are yielding is given by:

$$E_p = \frac{WB\theta}{2}\,[1 + r_s(2\varepsilon_{max} - \varepsilon_y - \varepsilon_o)] \quad (6)$$

where B is the width of wall, W is total weight of wall, K_p is the initial stiffness of unbonded tendons, L_T is the total length of unbonded tendons, θ is the drift level, ε_{max} is the maximum strain, ε_y is the yield strain and ε_o is the initial strain of unbonded tendons.

The base shear capacity of the seismic wall at pre-rock is given by :

$$C_c = \frac{F}{W} = C_{c\,(pre-rock)} = \frac{B}{H_w}\left[1 + \frac{r_sB\Delta}{L_TH_w} + r_s\varepsilon_o - \frac{\Delta}{B}\right] \quad (7)$$

The base shear capacity of the seismic wall at post-rock is given by:

$$C_{c(rock)} = \frac{B}{H_w}\left[1 + \frac{r_sWH_w\varepsilon_y}{L_T} - \frac{\Delta}{B}\right] \quad (8)$$

Thus, radiation damping of the rocking wall under pre-rocking conditions is derived by substituting Equations 5 and 7 into Equation 3 and becomes:

$$\xi_r(pre-rock) = \frac{(1-r)\left[1 + \frac{r_sB\theta}{2L_T} + r_s\varepsilon_o\right]}{\pi\left[1 + \frac{r_sB\Delta}{L_TH_w} + r_s\varepsilon_o - \frac{\Delta}{B}\right]} \quad (9)$$

The radiation damping under post-rock conditions when the tendons are yielding is derived by substituting Equations 6 and 8 into Equation 3 and the equation becomes:

$$\xi_r(post-rock) = \frac{(1-r)\,\{1 + r_s(2\varepsilon_{max} - \varepsilon_y - \varepsilon_o)\}}{\pi(1 + \frac{r_sWH_w\varepsilon_y}{L_T} - \frac{\theta H_w}{B}} \quad (10)$$

4.3 Hysteretic Energy Dissipation and Equivalent Viscous Damping

The equivalent viscous damping by considering the energy absorption efficiency factor of energy dissipator is given by:

$$\xi eq = \frac{2\eta(1-r)\left[1 - \frac{1}{\mu}\right]}{\pi(1 - r + \mu r)} \quad (11)$$

where r is the post-elastic to initial stiffness ratio, μ is the structural ductility and η is energy absorption factor. Energy absorption efficiency factor (η) is defined as the ratio of area enclosed by the energy dissipater hysteretic loops over the Elasto-Perfectly-Plastic (E_{EPP}) which represented by area of trapezoid loops as given by the following equation.

$$\eta = \frac{Eh}{E_{EPP}} \quad (12)$$

where Eh is absorbed hysteretic energy observed during a characterisation and E_{EPP} is the total energy dissipated by a theoretical elasto-perfectly plastic system.

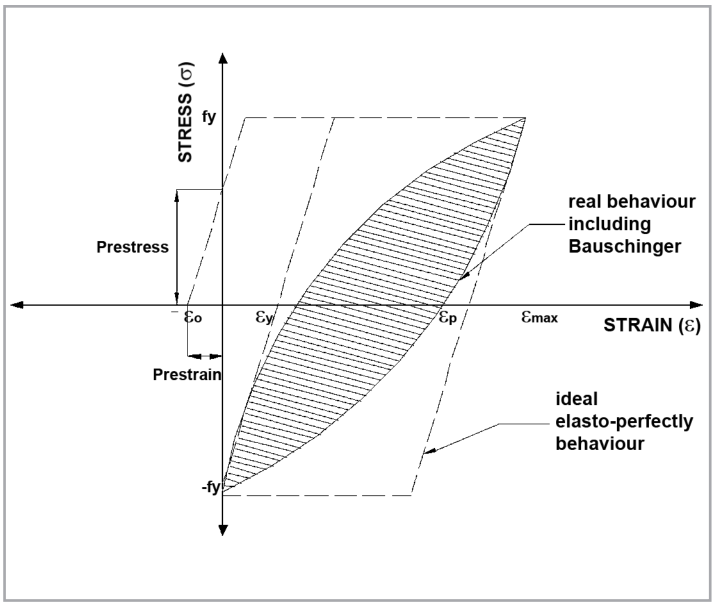

Figure 3: The Bauschinger effects on the hysteretic energy absorption efficiency of fuse-bars/energy dissipators

Figure 3 shows the Bauschinger effect on the energy absorption efficiency of fuse/energy dissipator. The trapezoidal area of ideal elasto-perfectly plastic area is given by the following equation:

$$A_{trapezoid} = 2F_y \times (\Delta_u - 2\Delta_y) \tag{13}$$

where $A_t = \frac{1}{4} A_{trapezoid}$, F_y is the maximum yield strength of energy dissipators, Δ_u is the ultimate displacement and Δ_y is the yield displacement.

5.0 REDUCTION DAMPING FACTORS

In the IBC-2000, the reduction damping factor B are independent of the soil types where the structures located. Lin and Chang [27] pointed out that the reduction damping factors, B had a great effects on the site soil characteristics. Figure 4 shows the proposed spectrum demand capacity based on reduction damping factors. Figure 4(a) proposed reduction damping factor based on acceleration response spectrum, B_a is given by Equation 14 and reduction damping factor based on displacement response spectrum, B_d is given by Equation 15. The linear interpolation in Equation 16 denote as B_v which derived between plateau B_a and plateau B_d based on site classes, period and damping ratio.

For $S_d < S_{da} = 0.079m$,

then $$B_a(\xi_{eff}) = \sqrt{\frac{2 + \xi_{eff}}{7}} \tag{14}$$

For $S_d < S_{da} = 0.469m$,

then $$B_d(\xi_{eff}) = \sqrt{\frac{8 + \xi_{eff}}{13}} \tag{15}$$

For $S_d = S_{dv}$ and $S_d < S_{da} < S_{dd}$, then

$$B_v(\xi_{eff}) = \frac{B_d(S_{dv} - S_{da}) - B_a(S_{dv} - S_{dd})}{S_{dd} - S_{da}} \tag{16}$$

Figure 4(b) represents the mean reduction damping factors corresponding to site classes *AB*, *C* and *D* for damping ratios of 10, 20, 30 and 50%. Figure 4(c) shows the spectral response acceleration at different damping factor by incorporating the reduction damping factors for period up to 2 seconds. Figure 4(d) represents the overall design capacity-demand spectrum at various effective damping of 5%, 10%, 20% and 30% by incorporating the reduction damping factors. In this study, the effective viscous damping of 10% is adopted for warehouse buildings.

6.0 CAPACITY SPECTRUM DESIGN METHODOLOGY

The capacity-demand spectrum becomes popular in seismic prone regions where a realistic evaluation of the earthquake hazard is analysed in assessing the structural response. The seismic demand spectrum of the hazard exposure can be predicted based on the statistical analysis of the past earthquake records. The equations that control a smooth model for 5% damped elastic response spectrum are according to equation derived by Martinez [28]. The evaluation of the seismic demand spectrum on various effective damping is depending on the portion of the spectrum that governs duration of structural response. The reduction damping factor can be categorised as short period and long period. The seismic demand spectrum of short period is in Equation 17 and long period is in Equation 18.

$$\mathrm{Cd} = \frac{F_a S_s}{B_a} \tag{17}$$

$$\mathrm{Cd} = \frac{F_v S_1}{T B_v} \tag{18}$$

whereby F_a and F_v are adjustments on spectral acceleration for short, intermediate and long periods for different site classes, S_s and S_1 are spectral acceleration at short periods and one second periods, B_a, B_v and B_d are the seismic displacement reduction damping factors for short, intermediate and long term period of the structures. For intermediate period of vibration, the capacity demand spectrum can be expressed as a function of spectral displacement. The demand of the natural period of vibration is given by the well-known Equation 19.

$$\mathrm{T} = 2\pi \sqrt{\frac{\Delta}{C_c g}} \tag{19}$$

By replacing $\Delta = S_d$ and substituting Equation 19 into Equation 17, then it becomes:

$$C_d = \left[\frac{F_v S_1}{2\pi B_v}\right]^2 \frac{g}{S_d} \tag{20}$$

By equating capacity demand spectrum, C_d with capacity base shear of the structures, C_c then spectral accelerations can be defined as:

$$F_v S_1 = 2\pi B_v \sqrt{\frac{S_d C_c}{g}} \quad (21)$$

To survive under DBE and MCE, the spectral acceleration generated by base shear capacity of rocking wall should be bigger than or equal to the capacity demand of the spectrum, as defined in Equation 22 must be satisfied:

$$\Phi\,(F_v S1)c \geq (F_v S1)d \quad (22)$$

where Φ = under capacity factor that relates global uncertainty of seismic performance = 0.65.

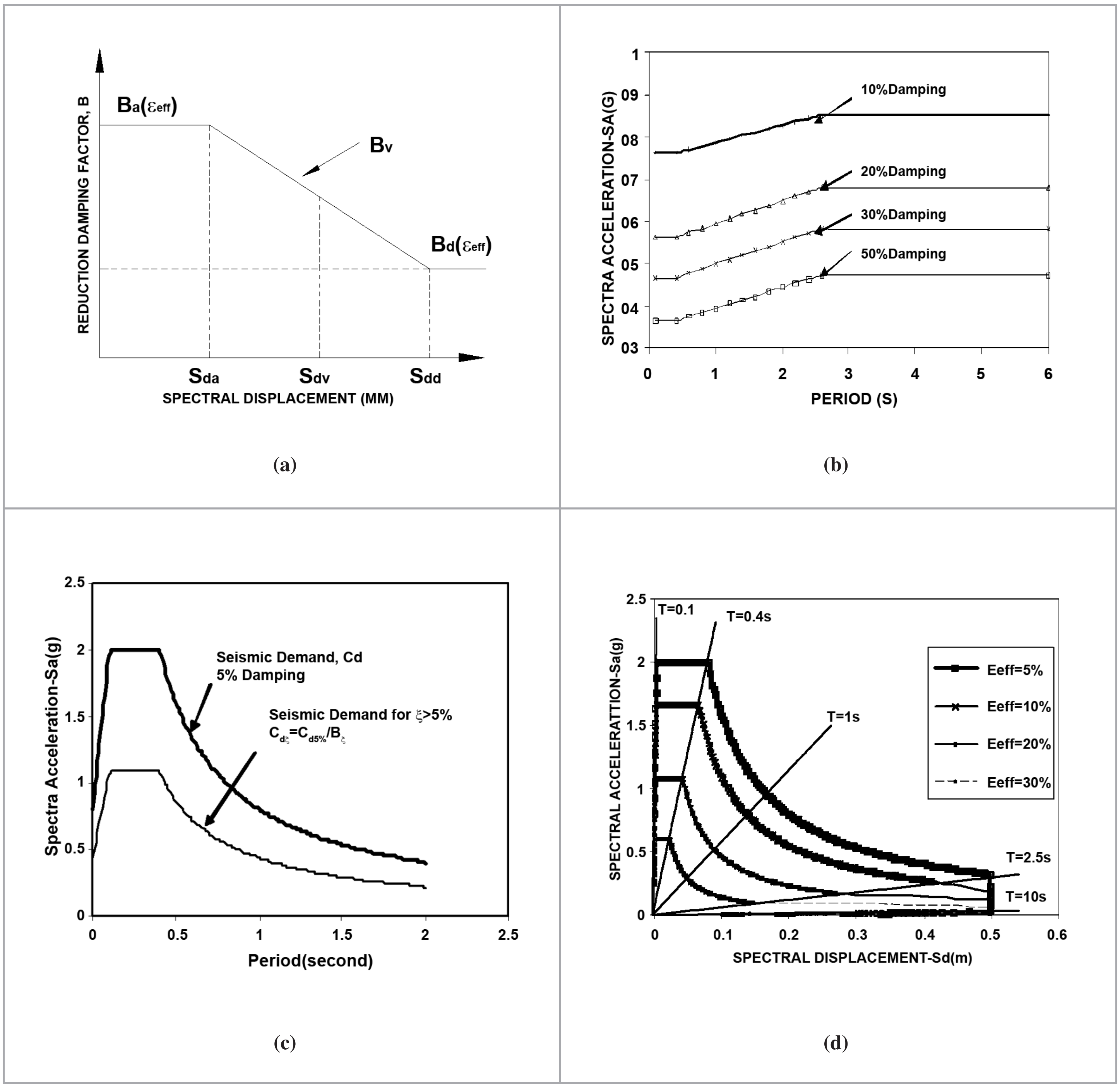

Figure 4 : The proposed reduction damping factor and spectrum demand capacity for precast hollow core wall ; (a) reduction damping reduction factor, B based on spectral amplitude; (b) mean damping reduction factors based on displacement response; (c) spectral acceleration vs period; and (d) the design spectra based on the reduction damping factor

7.0 PROPOSED DESIGN PROCEDURE FOR ROCKING WALL PANEL

After developing the theoretical parts of rocking wall, the next step is to proposed design procedure for this type of wall. There are seven steps involve in the proposed design as listed below:

STEP 1: Determine Seismic Demand of DBE and MCE based on the Hazard Exposure

First of all, select at least a set of 30 ground motion records based on different locations of past earthquake. Then, 5% damped response acceleration must be parameterised to the scale of 1*g* for 1 *sec* period curves. Table 3 shows the proposed 5% damped response spectrum curve.

STEP 2: Determine the Maximum Response Displacement, Δ^{DBE}_{max} and Δ^{MCE}_{max}

By substituting $Sd = \theta_{max} = H_{eff}$ as maximum response displacement into Equation 21, then the equation becomes:

$$Sd = \Delta^{DBE}_{max} = \Delta^{DBE}_{max} = \frac{(F_vS1)^2_d g}{4\pi^2 B_v C_c} \quad (23)$$

Table 3: Proposed 5% damped elastic seismic demand spectrum

Duration (second)	*Spectral Accelerations (g)*	*Spectral Displacement (m)*
$0 < Ti < 0.10$	$Sa = Sg\left[1 + 1.50\left[\frac{Ti}{0.10}\right]\right]$	$Sd = \frac{SaT_i^2 g}{4\pi^2}$
$0.1 < Ti < 0.40$	$Sa = 2.50Sg$	
$0.40 < Ti < 2.50$	$Sa = \frac{SgT1}{Ti}$	
$2.50 < Ti < 10$	$Sa = \frac{SgT1T2.5}{T_i^2}$	$Sd = \frac{SaT1T2.5g}{4\pi^2} = const$
$Ti > 10.00$	$Sa = \frac{4\pi^2 PGD}{g\ Fri}$	$Sd = \frac{SaT_i^2 g}{4\pi^2}$

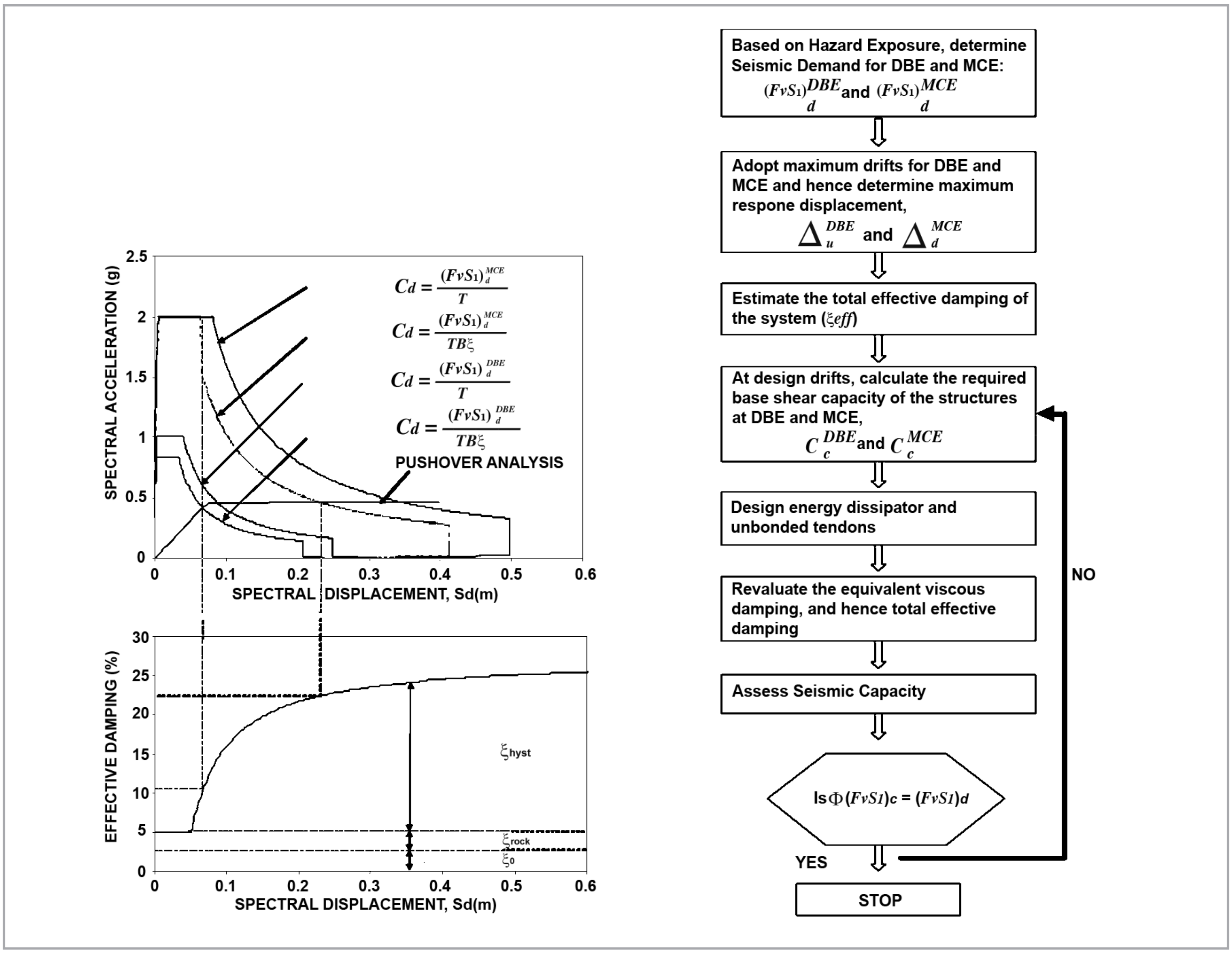

Figure 5: Flow chart showing the proposed design procedure for rocking precast hollow core walls using Damage Avoidance Design (DAD) philosophy

STEP 3 : Estimate Total Effective Damping of the System (ξeff)

Total estimate effective damping of the system can be found by projecting the vertical line from a point where the structural bilinear capacity curve meets the demand capacity spectra of DBE and MCE to the curve of effective viscous damping based on Equation 23.

STEP 4: Calculate Base Shear Capacity of the Structures, C_c^{DBE} and C_c^{MCE}

The base shear capacity of the structure can be determined using base shear demand of Equation 24. The hysteretic cyclic behaviour of rocking walls depends on the percentage of moment contribution coming from each of the tendons and energy dissipators.

STEP 5: Design Energy Dissipator and Unbonded Tendons

Once the percentage of energy dissipators and tendons are determined, the yield forces of energy dissipators and unbonded tendons can be calculated, where is the cross-sectional area of the energy dissipators and tendons, respectively and is the characteristic strength of energy dissipators and tendons, respectively.

STEP 6: Evaluation of Hystresis Damping and Total Effective Damping of the System

The pre-rock damping, $\xi_{pre-rock}$ and rock damping, ξ_{rock} of the wall system can be calculated using Equations 9 and 10, respectively. The actual hysteretic damping of energy dissipators can be calculated using Equation 11. Hence, the total amount of effective damping of the system is evaluate using Equation 2.

STEP 7: Assessment of Seismic Capacity

The seismic capacity of precast hollow core wall system can be assessed by checking that the base shear capacity of the system is bigger than the base shear demand at two levels of earthquakes using Equation 22. If these values do not converge, Steps 4 to 6 is repeated until they are converged and the design is accepted.

Figure 5 show flow chart representing the proposed design procedure using rocking precast hollow core walls by applying Damage Avoidance Design (DAD) philosophy. An example of a typical single storey warehouse building using precast hollow core wall which designed to resist earthquake loading with intensity VII is demonstrated in Hamid [22].

8.0 CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations which drawn from this paper are as follows:

1. The basic concept of rocking wall panel can be used for designing and construction of industrial/warehouses buildings, residential houses and commercial buildings in high and medium seismic regions.

2. The effective damping coming from unbonded tendons and energy dissipators can be determined by adjusting the level of prestressing and cross-sectional area of unbonded tendons and external energy dissipators. It is proposed that about 14% of total effective damping to be used in this design.

3. The proposed design procedure using Damage Avoidance Design (DAD) philosophy for the construction of warehouse buildings can be implemented in high seismic regions such Sumatra, Java Islands, New Zealand and others countries.

4. It is recommended that Damage Avoidance Design (DAD) philosophy together with rocking concept of structures can be extended to other structures components such as beam-column connection, slab-beam connection, bridge-piers and Industrialized Building System (IBS). ■

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