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SEISMIC PERFORMANCE EVALUATION OF A HYBRID RC FRAME–PRECAST WALL BUILDING IN MALAYSIA

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ABSTRACT

This study evaluates the seismic performance of a hybrid reinforced concrete (RC) frame–precast wall building in Malaysia to assess the building's response to seismic forces, identify potential vulnerabilities, and propose strategies to enhance its seismic resilience. To do this, various methodologies, including modal analysis, first and second screening methods based on the Japan Building Disaster Prevention Association (JBDPA) guidelines, and response history analysis (RSA) are employed. The building's behavior under different seismic scenarios is investigated through comprehensive evaluations. The findings reveal critical insights into the building's seismic capacity. The original design exhibits certain shortcomings, particularly in withstanding higher peak ground acceleration levels. However, the building's seismic performance can significantly be enhanced with the careful consideration and implementation of specific design improvements. This work highlights the importance of incorporating the best practices in structural design and retrofitting to better withstand the potential seismic events in Malaysia. The results obtained herein contribute valuable knowledge to the seismic engineering field, offering practical implications for the construction and safety standards of hybrid RC frame–precast wall buildings in seismic-prone regions.

Keywords: seismic performance, Hybrid RC Frame-Precast Wall Building, JBDPA, RSA

1. INTRODUCTION

Malaysia is geographically located in a tectonically inactive seismic region which deals very lowly with the risk of tremors or earthquakes. Over the past decades, it is common for Malaysians to think Malaysia is safe from holocaust tremor. The trend has been rapidly changing, and numerous studies have proved that Malaysia is vulnerable to the risk of tremors. According to Amir et al. (2016), Peninsular Malaysia is specifically exposed to Sumatra's fault and subduction zones, where the Malaysia Meteorology Department (MMD) has documented numerous instances of minor localized earthquakes occurring within Peninsular Malaysia.

The presence of non-seismic reinforcing details in Malaysian structures highlights the inadequacy of incorporating sufficient seismic considerations during the design phase. Consequently, this issue emerges as a substantial concern, as it not only poses the potential for extensive structural damage but also carries the risk of tragic loss of life for occupants. Therefore, in this study, it is important to evaluate the seismic performance of RC buildings especially and therefore propose suggestions for better seismic performance. This study will evaluate the mode shapes of the structure by using ETABS software, study the strength and ductility of vertical members by using JBDPA, and verify those results by using response history analysis.

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2. DATA

For the purpose of this study, a residential building comprising eight stories has been specifically chosen. Notably, this building was designed without considering any seismic considerations. The architectural configuration of this structure employs a hybrid system, featuring a reinforced concrete moment-resisting frame at the first story and a precast wall system in the upper stories. Furthermore, this construction exhibits irregularities both in its floor plan and vertical alignment. The height of the first story measures 5.3 meters, while subsequent stories are 3.3 meters each, encompassing overall dimensions of 48.2 meters longitudinally and 31.5 meters transversely. The concrete's material strength (f_c) is rated at 30N/mm², while the steel (f_y) possesses a strength of 500N/mm².

Figure 1. 3D view of the target building

Table 1. Description of sites

Location	Lahad Datu, Sabah
Soil Type	B
agR = PGA (%g)/100	0.16
Importance Class, Factor	II,1.2
ag = agR. γ_i	0.192
ag. S	0.2688
Depth of Soil Deposit	Not exceed 30m

Table 2. Column Types

Column	C1	C2	C3
Size	300 x 800	450 x 800	250 x 500
Main bar	10D20	12D20	6D16
Hoop	D10-175mm	D10-175mm	D10-175mm

3. METHODOLOGY

3.1. Modal Analysis

Within the context of this investigation, the modal analysis was effectively conducted by employing the state-of-the-art ETABS software that enabled a comprehensive examination of the dynamic characteristics of the studied building. The structure was subjected to a uniform unit weight of 12 kN/m^2 across all floors, reflecting realistic loading conditions. The intricate structural behaviour was captured by modelling the beams and the columns using frame elements. The concrete shear wall surrounding the lift was represented by utilizing shell elements. A layered and membrane-type modelling approach was applied to accommodate the precast wall intricacies.

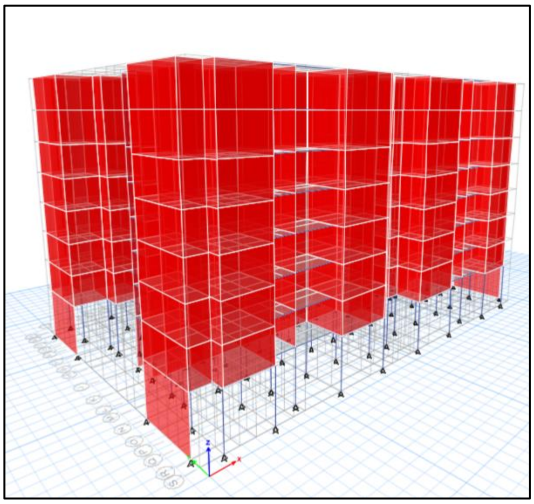

Figure 2. Numerical model of the building in ETABS software

3.2. Implementation of the JBDPA

Based on guidelines, evaluating how well a building can withstand an earthquake is done by considering its seismic capacity, which is measured using a seismic index, *Is*. It is calculated by multiplying the

$$I_s = E_o \cdot S_D \cdot T \quad (1)$$

building's strength and ductility (E_o), irregularity (S_d), and time indices (T). It represents the amount of energy the building can handle during an earthquake. Essentially, the seismic index, I_s indicates the intensity of an earthquake that the building is capable of resisting in each primary direction of impact. The seismic index of structure, I_s is expressed as Eq. (1) and should be compared with the demand index, I_{so}. For this study, I_{so} for Malaysia is adjusted by multiplying with the modification factor of 0.65 to the I_{so} Japan (0.8 for the first screening, 0.6 for the second screening). Therefore, I_{so} Malaysia for the first screening method is 0.52 and the second screening method is 0.39.

3.2.1. First and Second Screening Method by JBDPA

The initial level screening methodology provides a rapid evaluation of the seismic resilience of reinforced concrete (RC) structures, focusing solely on the cross-sectional areas of vertical members while disregarding their reinforcement details. In the first screening procedure, when assessing the index, E_o for the structure, a crucial step involves comparing and selecting the greater value obtained from both Eq. 2 and Eq. 3.

$$E_o = \frac{n+1}{n+i}\,(C_w + \alpha_1 . C_c).F_w \qquad (2)$$

$$E_o = \frac{n+1}{n+i}\,(C_{sc} + \alpha_2 . C_w + \alpha_3 . C_c).F_{sc} \qquad (3)$$

where n denotes the number of stories of a building, i signifies the number of story for evaluation, C_w, C_c, C_{sc} are strength index of the wall, columns, and extremely short columns. $\alpha 1$, $\alpha 2$ and $\alpha 3$ represent the effective strength factor of the columns at the ultimate deformation of the wall, short columns, extremely short columns, F_w and F_{sc} represent the ductility index of the walls and extremely short columns respectively.

3.2.2. Second Screening Method by JBDPA

The classification of the structure involves dividing it into two distinct groups: ductility-dominant structures and strength-dominant structures. In order to determine the basic seismic index of the structure, denoted as E_o, the larger value between Eq. 4 and Eq. 5 is selected. The evaluation of this index, E_o, is subject to the constraints imposed by the minimum ductility index of the second-class prime elements. By considering these criteria, the classification and determination of the seismic index provide a comprehensive framework for assessing the structural behavior and response to seismic forces.

$$E_o = \frac{n+1}{n+i}\sqrt{{E_1}^2 + {E_2}^2 + {E_3}^2} \qquad (4)$$

$$E_o = \frac{n+1}{n+i}(C_1 + \Sigma\alpha_j C_j).F_1 \qquad (5)$$

where αj is an effective strength factor in the j-th group at the ultimate deformation R1 corresponding to the first group.

3.3 Non-Linear Response History Analysis

The meticulous analysis is carried out utilizing Dr. Azuhata's custom-developed software, named IISEE Analysis Tools. The approach employed in this methodology encompasses an extensive assessment of the building's direct response, encompassing the scrutiny of its behavior under distinct seismic scenarios, comprising one actual earthquake (Ranau) and four artificial ground motion earthquakes (with phase angle of El-Centro, Kobe, Northridge, and Random). Spectral matching is done based on the target spectra from Eurocode 8, Malaysian annex.

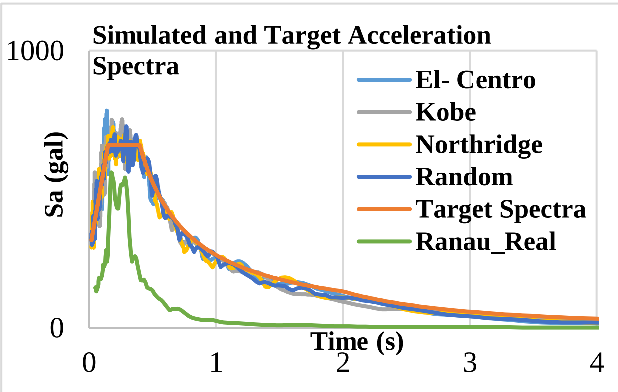

Figure 3. Spectrum Matching based on El-Centro, Kobe, Northridge earthquakes and Random Phase

4. RESULTS AND DISCUSSION

4.1. Results and Discussion on Modal Analysis

Figure 4 shows the first mode shape of the building containing four blocks connected to each other. The first mode shape exhibits a rotational behaviour, wherein individual blocks of the building respond independently. This rotational behaviour raises significant concerns, particularly when the building is situated in a seismic region. Further evaluation is crucial because excessive rotational behaviour during seismic events can pose risks of structural instability and potential damage to the building's integrity. Therefore, Block 3 is investigated in detail in the following parts of the study.

Figure 4. First mode shape in plan layout

4.2. Results and Discussion on the First Screening Method

Figures 5 and 6 show the first screening evaluation for x and y directions. Upon analysis, the irregularity index (S_d) was determined as 0.9 and 0.8 for the x and y directions, respectively, with the classification associated with the elevation balance to account for the potential soft story effects adhering to the guidelines set forth by the JBDPA. A careful examination of the findings revealed that, if this building were located in Malaysia, all stories would possess a sufficient and secure seismic capacity, except for the first story, depicting the shortcomings in both directions. Certain enhancements must be implemented to the structural design, with a special emphasis on addressing crucial aspects, particularly concerning the first floor's resilience and stability, to successfully erect this particular building type within any seismic region in Malaysia. However, in the case of a location like Japan, the seismic capacity of this building from the first to fourth stories is considered insufficient for the horizontal direction. This highlights the importance of assessing the building's structural strength and safety against seismic events, especially in earthquake-prone regions.

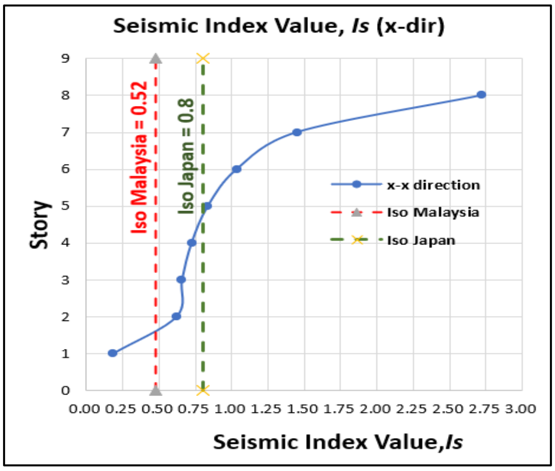

Figure 5. First Screening Evaluation according to JBDPA for x direction

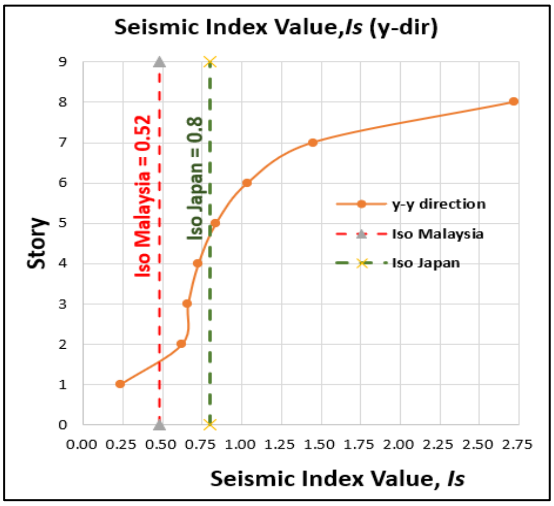

Figure 6. First Screening Evaluation according to JBDPA for y direction

4.3. Results and Discussion on the Second Screening Method

The impact of ductility on each column was assessed by performing a thorough evaluation using the second screening method prescribed by the JBDPA. Both directions were carefully analyzed to determine the failure type (i.e., extremely brittle column, flexural failure, or shear failure) exhibited by each column. All columns in the x direction experienced flexural failure, with only column N/9 showing signs of shear failure. Conversely, the majority of columns in the y direction experienced shear failure, while the remaining columns exhibited flexural failure. The two following methods are recommended herein to enhance the column ductility: 1) increasing the column size and 2) elevating the value of the shear reinforcement ratio. Increasing the shear reinforcement ratio specifically involves reducing the spacing between the reinforcement bars from 175 to 100 mm. A substantial improvement in column ductility was observed when both methods were employed. A strength–ductility index graph was created (Fig. 7-8) to facilitate a clearer comprehension of the original and newly proposed designs. This graph illustrates the relationship highlighting the substantial enhancement in the seismic index (I_s) for both directions.

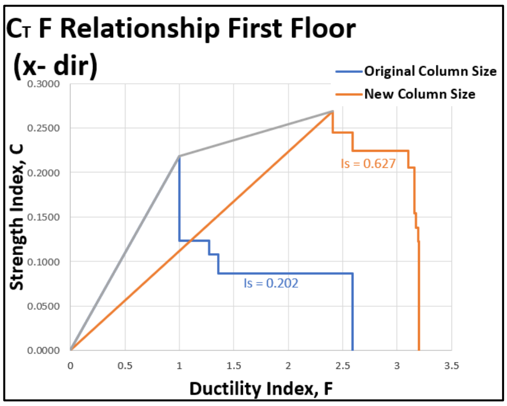

Figure 7. Strength-Ductility Index Relationship for x direction

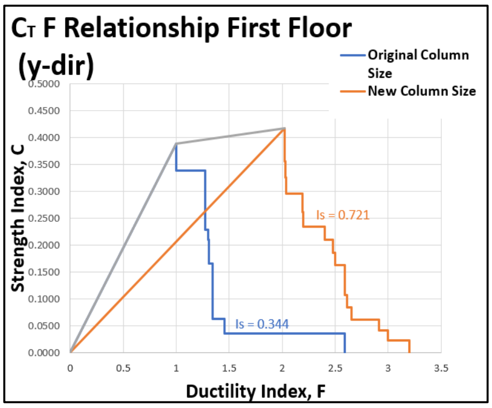

Figure 8. Strength-Ductility Index Relationship for y direction

4.4. Results and Discussion on Response History Analysis

Figures 9-12 illustrate the maximum displacement values in both the x and y directions for the original and proposed designs under various PGA sets. In the case of the x and y directions in the original design, the structure remained in a safe condition when subjected to 0.03g PGA. However, at a higher PGA of 0.16g, only the real Ranau Earthquake resulted in displacements within a permissible limit. The other artificially simulated earthquakes with similar PGA values exceeded this limit. The displacement limit was calculated using the second screening method to assess how different PGA sets would affect the resulting displacements. The findings led to the conclusion that the original design lacks adequate seismic capacity for handling such scenarios. An analysis of the revised design revealed that, in the x direction, all artificially generated earthquakes exceeded the displacement limit at a 0.4g PGA, with only the real Ranau Earthquake remaining within the allowable range. This poses a significant concern because the structure may suffer from severe damage or collapse if subjected to similar PGA levels occurring in Malaysia. In the y direction of the revised design, however, only the artificially simulated

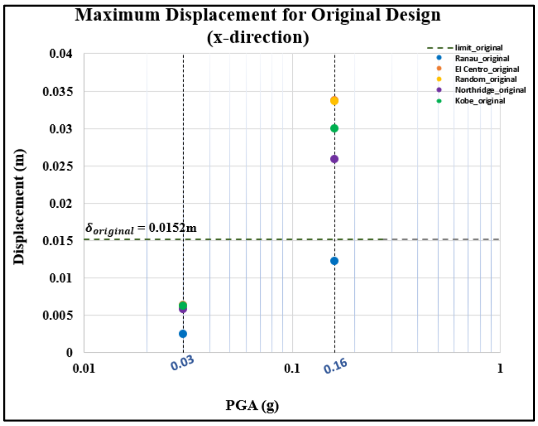

Figure 9. Maximum Displacement for Original Design (x-direction)

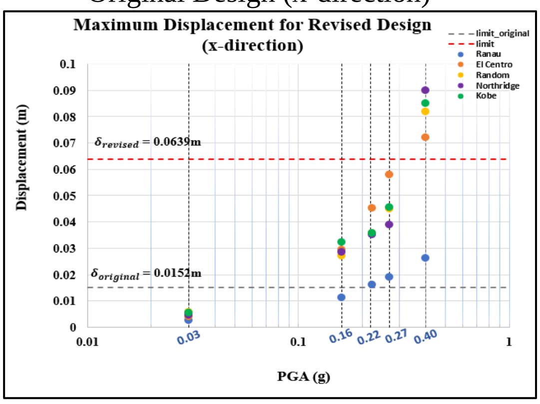

Figure 10. Maximum Displacement for Revised Design (x-direction)

earthquakes with a random phase and the Kobe Earthquake exceeded the deflection limit. In other words, after the revised design was implemented, the y direction exhibited greater strength and resilience compared to the x direction.

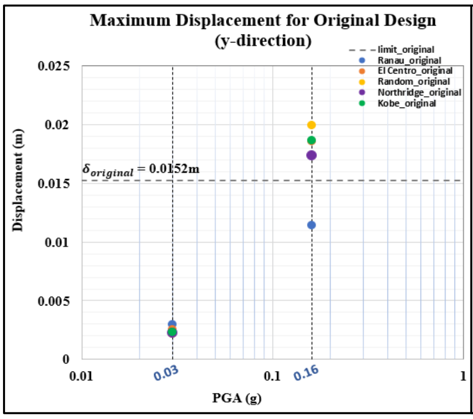

Figure 11. Maximum Displacement for Original Design (y-direction)

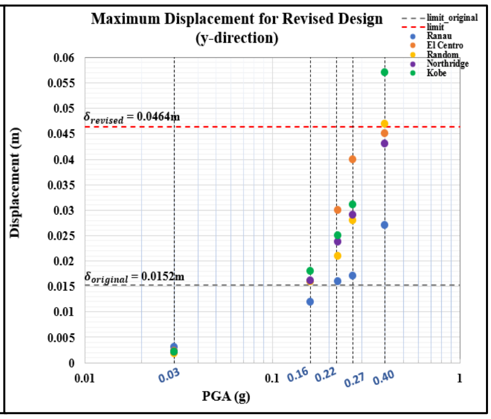

Figure 12. Maximum Displacement for Revised Design (y-direction)

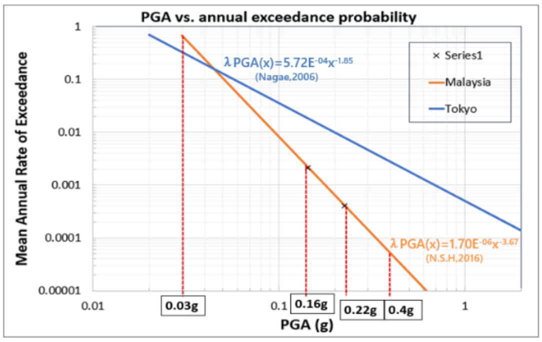

Figure 13. PGA vs annual exceedance probability for Japan and Malaysia

Fig. 13 serves as a highly informative tool for understanding the probabilities associated with different PGA levels in the two regions. The likelihood of a 0.4 g PGA earthquake transpiring in Malaysia during any given year is exceedingly low, measuring only less than 0.01% (Noor, 2013). The occurrence of such a formidable earthquake in the region appears to be highly improbable, which provides reassurance that building construction in Malaysia is safe, even if it surpasses the prescribed displacement limit, given the remote possibility of encountering a seismic event with such a magnitude.

5. CONCLUSIONS

In modal analysis, this building shows rotational behaviour has occurred. The JBDPA's initial screening identifies a soft-story effect in the building, both x and y directions. The second screening evaluation reveals the original design had weak seismic capacity in the columns, prompting two methods to improve it: increasing column size and raising the shear reinforcement ratio. After evaluating diverse earthquake scenarios, it was found that the structure could not withstand a seismic impact of 0.4g PGA. However, it was noted that the probability of experiencing such high PGA values in Malaysia is remarkably low. Considering this, the revised design ensures the building's safety for construction in Malaysia, as the rarity of extreme seismic events provides substantial reassurance for its overall stability.

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