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Effect of Infill Panels on the Seismic Vulnerability of Non-Ductile Reinforced Concrete Frames

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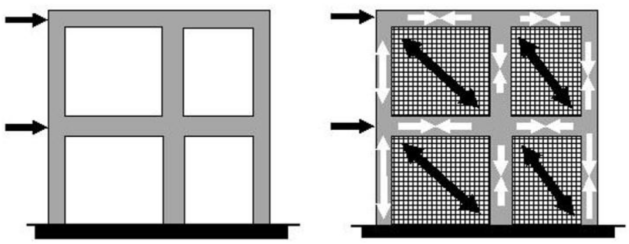
Abstract

Infill panels can increase seismic performance of reinforced concrete, RC frames if it is uniformly distributed in plan and along the height of the structures. This study investigates the effect of infill panels in seismic vulnerability of low-ductile RC frames which is commonly constructed in low-to-medium seismicity countries like Malaysia. This type of structures is seismically vulnerable since it has insufficient strength and ductility to resist earthquake loads. Fragility curves are used in this study to assess the vulnerability level of fully infilled RC frames under different intensity and characteristic of earthquake loads. RC frames with three, six, and nine stories designed for gravity and lateral loads based on the common practices in Malaysia were modeled and analyzed using incremental dynamic analysis (IDA). 45 earthquake records were used and divided into three groups based on their peak ground acceleration (PGA) to peak ground velocity (PGV) ratios. Three structural performance levels namely immediate occupancy (IO), life safety (LS), and collapse prevention (CP) were considered for the selected frames. Results show a significant improvement in the seismic performance of low ductile fully infilled RC frames compared to the bare frames. The probability of exceeding CP damage level for PGA of 0.2g (maximum PGA for East and West Malaysia) in fully infilled frames is less than 20%. This is 30% lower than bare RC frames. It can be concluded that infill panels increases seismic capacities of non-ductile RC frames if it is distributed fully in the structures. Unlike bare RC frames that need to be retrofitted, fully infilled RC frames satisfy the no-collapse requirement for maximum PGA stated in the national annex.

Keywords: Incremental dynamic analysis, non-ductile reinforced concrete frame, seismic fragility curves, seismic performance level, vulnerability assessment.

I. INTRODUCTION

In the past decades, seismic behavior of masonry infilled frames has been the topic of many researches. It has been demonstrated that infilled walls can enhance the seismic behavior of structures through the increase in the damping ratio, stiffness and strength if they are irregularly placed in plan or continuously constructed along the height of structures. Otherwise, it can be the main reason for structural collapse as been experienced from past earthquakes. When they are regularly placed, the masonry wall can give positive response on structures especially in avoidance of shear failure. Infilled walls have been generally accepted that it acts as a diagonal strut when dealing with lateral loads. Therefore, lateral stiffness is added to the building. With that, the structural load transfer mechanism transformed from frame action to predominant truss action which increases the axial forces but bending moments and shear forces are reduced. The lateral load transfer mechanisms are shown in Fig. 1 [1].



(a) (b)

Fig. 1 Load transfer mechanism (a) bare frame (b) infilled masonry wall frame [1]

Since the lateral load transfer mechanism changed with the existence of masonry infill panel, it has been proven that masonry infills give significant effects to structure with lateral stiffness of 4.3 times that of bare frame, 70% more strength and higher overall ductility [1]. Stiffness of an infill panel could increase up to 7 times that of bare frame while the lateral strength increased up to 1.9 times [2]. Even though the degradation of masonry occurs as the displacement of structure increases, the stiffness would still remain higher than that of bare frame. In comparison of displacement in between bare frame and infill frame, it shows a decrement by 40% with the presence of masonry infill in the frame [2].

Due to the fact that structural performances under earthquake are affected not only by the structural types but also the characteristic of earthquake loads, many researches have been conducted to evaluate structural performances of infilled frames under different structural conditions and types of seismic loads. These evaluation processes are challenging issues due to the characteristic of seismic loads which have a complex and usually unpredictable effects on structures [3]. Non-linear static or dynamic analyses were used to assess seismic induced damage to structures [4-6]. Seismic fragility curves have been used by many researchers to estimate seismic vulnerability of structures. This approach shows the probability of exceeding a given damage level in a structure due to a seismic hazard. Rapid structural assessment can be conducted after an earthquake event using the developed fragility curves. Empirical approaches, experimental data, and analytical methods are used to derive the fragility curves. Analytical methods been widely used due to its ability to assess different seismic hazard scenarios and structural systems through extensive analytical simulations [7,8].

Assessment of seismic performances for structures and infrastructures in Malaysia is still very limited. Fragility curves were developed to determine differences in structural performance between steel moment resisting frame and reinforced concrete frame of 3 and 6 story [9]. Seven seismic records were used which was chosen based on the distance of more than 20 km and in the range of 7 to 8 magnitude. The study concluded that the steel frame has better performance than moment resisting concrete frame when subjected to earthquake load. Fragility curves were also used to investigate the vulnerability of a three story reinforced concrete structure considering different soil conditions [10]. The results of this study indicate that the seismic performances are affected by both the number of story in the building and soil conditions. In an earlier research conducted by the authors, structural performances of low-ductile RC bare frames in Malaysia subjected to different earthquake scenarios were assessed by means of fragility curve [11]. Three type of structural models; three, seven, and nine stories were analyzed using near, medium and far field earthquake. It was observed that the probability of seismic induced damage increased as the height of structures increased. The three story RC bare frame showed brittle failure mechanism when subjected to the employed earthquake records. It was concluded that three and nine stories RC bare frames constructed in the East Malaysia did not satisfy the no-collapse requirements as the probability of exceedance was more than 50% and needed to be retrofitted.

In this study, the effect of infill walls on the seismic vulnerability of low ductile reinforced concrete frames in Malaysia was assessed using fragility curve. The main aim of this study is to determine how much infill panels could affect seismic performance of RC frames that has not been designed using any seismic provision compared to the bare frames. Three types of structural model were selected with differences in their height that include three, six, and nine story RC frames. Infill walls were designed as regularly distributed along the height of the RC frames which is referred herein as fully-infilled frames. The selected structures were designed based on the common practices in Malaysia. Incremental dynamic analyses together with pushover analysis were used to determine drift capacities of the selected structures. Totally 45 earthquake records scaled between 0.1g to 0.5g were used. The earthquake records were divided into three groups based on their PGA/PGV ratios. The three groups included low, medium, and high class records which represented far, medium, and near field earthquakes respectively. Three structural performance levels namely immediate occupancy, life safety and collapse prevention were considered for structural elements. Seismic fragility curves were developed for all three groups of earthquake records separately. A total of nine fragility curves were developed in this study. Results from this study were used to determine the probability of damage to fully infilled RC frame buildings when subjected to seismic hazard given in Malaysian National Annex [12]. These results can provide further insight to the vulnerability of low ductile RC frames with and without infill walls under different earthquake intensities and frequency content. As low ductile RC frames consist of the majority of structures in Malaysia [13], findings from this study could assist in determining seismic rehabilitation plan for these structures. This may include strengthening of structural components through concrete jacketing, steel jacketing, usage of fiber reinforced polymer materials, and dampers [14-16].

II. SELECTED STRUCTURES

Fully infilled low ductile RC frames with three different heights were selected to be analyzed in this study. In order to represent the common buildings in Malaysia, 3 reinforced concrete frame structures are analyzed with different height; 3, 6 and 9 story which represents low rise and mid-rise structure. Each frame has four 6m bays with same height of 3m except for the ground story i.e. 4m. The total height of building is 10m, 19m, and 28m respectively similar to the previous published works [11]. The structures are designed in compliance to BS 8110-1997 [17] code specification by using ETABS 2015 Software [18]. In this study, the live load and dead load are considered based on the chosen highlighted frame as shown in Fig. 2. The figure illustrates plan view of the structure with the highlighted frame which is fully infilled with masonry wall.

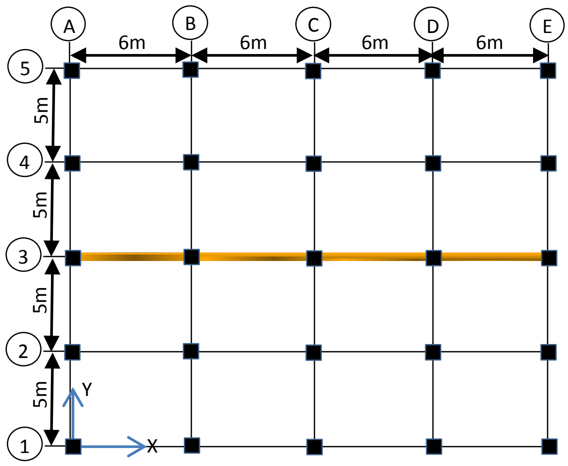


Fig. 2 Plan view of the building and the location of selected frame

Commonly older age structures are more vulnerable to seismic lateral load due to insufficient demand of the structure therefore in this study, the main focus is on older buildings that the properties of concrete in the structure are made to behave like a low ductile reinforced concrete. Compressive strength of concrete is 20Mpa. Yield strength and the ultimate tensile strength of rebar is 300MPa and 420MPa respectively. Live and dead load of the frame is 12 kN/m2 and 51 kN/m^2 respectively including self-weight of walls except for the top story; 31.08kN/m^2. Lateral wind load is taken as 1.5% of the total dead load. It should be mentioned that in all frames beam had a rectangular cross section with the size of 350 x 250 mm while columns dimensions are varies between levels; similar with the previous study [11]. Selections of the columns and beams sizes are made to reflect the low ductile design of RC frames.

Nonlinear behavior of beams and columns was simulated by using lumped plastic hinges assigned to the end of each member. Fig. 3 displays the typical force–deformation relationship of a plastic hinge in beam and column [19]. In this figure, segment AB indicates the elastic behavior, segment BC represents the post-yield behavior and segment CD shows the beginning of the failure. The parameters for each member in the figure were extracted from the tables provided in ASCE 41-13 [20] considering material properties, internal forces and sizes of beams and columns.

In order to model the masonry infill, the most common analytical modelling technique is to apply compressive diagonal struts with the tension limits is set to zero [21]. In another research, infill wall was also proposed to act as bracing in frames with the same thickness and material properties to the infill wall. It is proven that the overall deformation of infill frame was more similar to diagonal brace frame system compare to homogenous shear walls [22]. In this study, single strut model is used to simulate the infilled frame. The width of equivalent strut (Eq. 1) is determined based on Fig. 4 [23].

$$a = \frac{r_{inf}}{4} \qquad \text{[Eq. 1]}$$

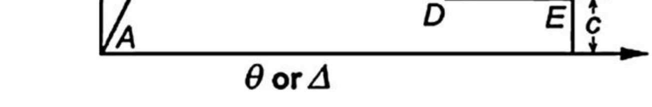


Fig. 3 Generalized chord rotation model used for inelastic behavior of beams and columns [19]

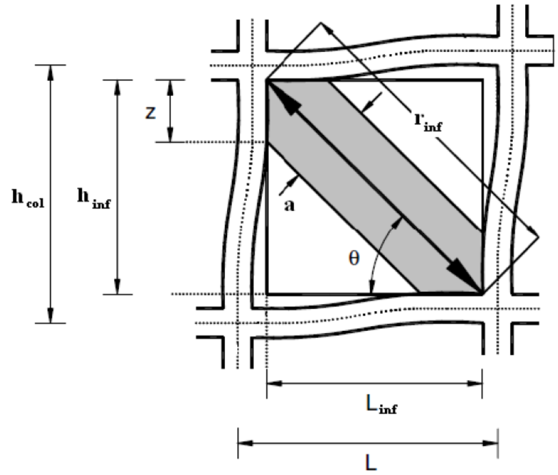


Fig. 4 Masonry infilled frame sub assemblages [23]

III. CONSIDERATION OF UNCERTAINTIES

Uncertainties that contribute to the seismic fragility can be classified into two types; random and the one caused by lack of knowledge [24]. It has been also demonstrated that the variability in ground motions has a significant impact on fragility curves compared to uncertainties in material properties [11]. This also applies to non-ductile RC frames in which material and structural parameters like structural damping, concrete strength, and cracking strain in beam–column joints have less impact on the obtained seismic fragilities when compared to uncertainties in seismic demands from earthquakes [25]. Therefore, in addition to the building height this study considered the variability in the ground motions for the derivation of seismic fragilities.

In order to include uncertainty in seismic demands, 45 earthquake records were used in this study. The records are divided into three groups of earthquake data consisting of low, medium and high group based on the peak ground acceleration (PGA), and peak ground velocity (PGV) ratio of the records. The PGA/PGV ratio is a simple parameter that can indicate the relative frequency content and duration of earthquake ground motions generated by different seismic environments [26]. Based on the PGA/PGV ratio, low group is classified for the PGA/PGV ratio between 0.3 to 0.8, medium is from 0.8 to 1.2 and high is the value of more than 1.2. High PGA/PGV ratio represents near field earthquake, low PGA/PGV ratio represents far field earthquake, while medium is in the middle between the two. Fig. 5 and 6 illustrate the relationship of source distance with the ratio of PGA and PGV and the magnitude [26].

Near-field earthquakes are defined as the earthquakes that happen near to the epicenter. There are clashes between researchers on the exact distance of the consideration of the near-field earthquakes and therefore they concluded that it is between 10 – 60 kilometers around the fault and far-field is more than 150 km. For instance, UBC-97 Code states a distance of less than 15 kilometers from the earthquakes epicenter as the near-field range. Far field earthquake that would affect Malaysia is most probably from Sumatera fault [27].

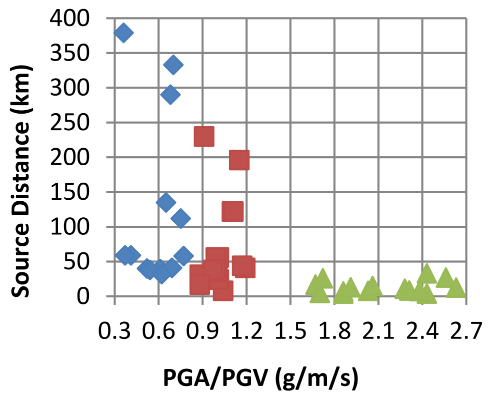


Fig. 5 Relationship of source distance and PGA/PGV [26]

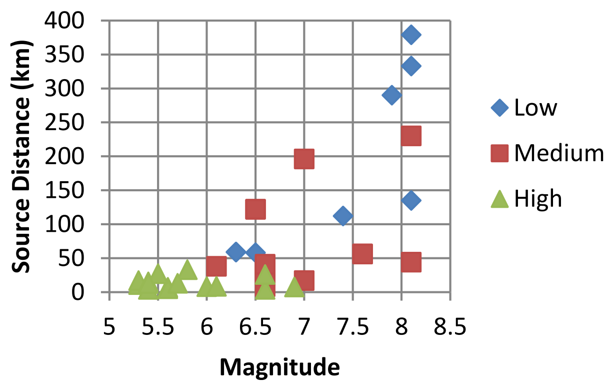


Fig. 6 Relationship of source distance and magnitude [26]

IV. DERIVATION OF FRAGILITY CURVES

Fragility curve is a probability that determine the level of damages experienced by the structure that is modelled at a certain ground motion records. Parameters such as PGA, spectral acceleration and peak ground velocity can be used in developing fragility curve. In this study, PGA is used to develop the fragility curve using Eq. 2 [28]. Total of nine fragility curves were developed in this study for the three, six, and nine stories fully infilled RC excited with high, medium, and low group of earthquake records.

$$P(DS|SI) = 1 - \varphi\left(\frac{\lambda_C - \lambda_{D|SI}}{\sqrt{\beta_{D|SI}{}^2 + \beta_C{}^2 + \beta_\mu{}^2}}\right) \qquad [2]$$

With

$$\beta_{D|SI} = \sqrt{\ln(1 + S_E{}^2)} \text{ and } S_E = \frac{\sigma}{\sqrt{total\ number\ of\ seismic\ records}}$$

Where DS is Damage State; SI is seismic intensity; φ is standard normal distribution; λ_C is natural logarithm of the median of drift capacities for a particular damage state; $\lambda_{D|SI}$ is the natural logarithm of calculated median demand drift given the seismic intensity from the best fit power law line; S_E is the standard error of demand drift; σ is the standard deviation of each PGA and β_C, β_μ are the uncertainties related to capacity and modelling which is approximately equals to 0.3 [28].

Incremental Dynamic Collapse Analysis (IDA) is used to predict the structural response, as well as the relationship between drift ratio and ground motion. Different levels of damage were defined based on the maximum inter-story drifts obtained for each structure. Three performance levels, namely immediate occupancy (IO), life safety (LS) and collapse prevention (CP) were considered for the structural elements. Immediate occupancy means that the structure is lightly damaged, facility can return to full use as utility systems are back in operation and the cleanup is completed. Meanwhile, life safety shows a significantly damaged structure that does not cause life-threatening injuries. The collapse prevention is referring to a structure that heavily damaged and it is at the verge of collapse [29]. Nonlinear time history analysis was carried out under each ground motion by using ETABS 2015 Software. Total of 675 seismic records scaled between 0.1g to 0.5g were used in this study to determine the drift capacities and the probability of IO, LS and CP in each frame.

Accurate determination of drift capacities in structures is vital for the development of fragility curves. Table 1 shows the drift capacities of the selected frame that are obtained from conducted analysis. The results show that as the number of stories increase, drift capacities in fully infilled RC frames decrease. This is similar to the findings obtained from analyses involving bare frames [11]. Fully infilled RC frame with six stories has the smallest capacities followed by the nine and three stories frames. This shows the six stories frame has higher intensity of damages compared to the other structures. It should be mentioned that the nine stories frame experienced a sudden transition from the IO damage level to the CP level without indication of the LS level. This indicated that the nine stories frame had a brittle failure mechanism such that as the seismic intensity was slightly increased the CP level was achieved without going through the life safety level. However in bare frames, this behavior is observed in three stories structures. Moreover, all structural models for fully infilled frames show lower drift capacities in each damage level compared to the one obtained in bare frames. The presence of infill panels caused the frames to be stiffer. This shows the effect of infill panels in structural performance under different earthquake records.

Table 1: Drift capacities of fully infilled RC frames for each damage state

	IO	LS	CP
3 story	1.06%	1.14%	1.24%
6 story	0.80%	0.88%	0.99%
9 story	0.90%	-	1.03%

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Seismic fragility curves developed for three, six, and nine stories of fully infilled RC frame under low, medium and high class earthquake records are shown in Fig. 7 to Fig. 15, respectively. It can be observed that, the medium-class earthquake imposes the highest damage to all studied RC frames. This shows that the fully infilled RC frames are more sensitive to earthquakes in medium distances. From the figures, it can be observed that the intensity of seismic induced damage for fully infilled frames are high in the three and nine stories frames. Comparison in the slope of the developed fragility curves show that for medium-class earthquake, the slope is steeper for lower PGAs i.e., 0.1g to 0.3g especially in the three and nine stories frames. This indicates that, a small increase in PGA will cause significant increase in the seismic induced damage to the structures. On the other hand, the high-class earthquake results in minimum damage and almost have no impact to all frames up to 0.3g.

As mentioned earlier, the nine stories fully infilled RC frame exhibited the CP damage level right after passing the IO level. Hence, the derived fragility curves for the nine stories RC frame in Figs. 13, 14, and 15 only represent the IO and CP damage levels. In other words, the nine stories fully infilled RC frame that was designed shows a brittle seismic behavior and has the risk for sudden collapse. The observed brittle failure mode for the nine stories frame disappears as the height of the frame decreases. Tangible difference in the probability of exceedance for IO, LS and CP damage levels can be observed in three and six stories of fully infilled RC frames.

The effect of infill panels in low ductile RC frames

In order to investigate the effects of infill walls in the performance of non-ductile RC frames in Malaysia under different earthquake records, results from this study are compared with the one obtained in bare frames analyses [11]. According to Malaysia's National Annex [12], for structures that are built on the ground type with the site natural period of more than 0.7s, the maximum PGA for Peninsular and Sarawak is 0.1g while for Sabah is 0.2g. Based on maximum PGA of 0.2g, and design seismic action i.e., 475 return period, all fully infilled RC structures; three, six, and nine stories frames satisfy the no-collapse requirement as required by the code with less than 20% of probability of exceedance for CP level under all earthquake records. This probability of exceedance is far lesser than the bare RC frames; more than 50% for structures subjected to low-class earthquakes records do not satisfy the expected performance objective and needs to be retrofitted. As for the damage limitation requirement, all fully infilled RC frames in Peninsular, Sarawak and Sabah generally satisfy the IO performance objective when subjected to all earthquakes records although medium-class earthquake records show slightly higher probability of exceedance; an average of 30%. As for the bare frames however, all structures do not satisfy the IO performance objective when subjected to the low-class earthquakes. This findings show the positive effect of infill walls on the structural performance of RC frames subjected to earthquakes. It is also worth mentioning that medium-class earthquake records imposed highest probability of seismic induced damage in fully infilled frames compared to bare frames when low-class earthquake records are more damaging.

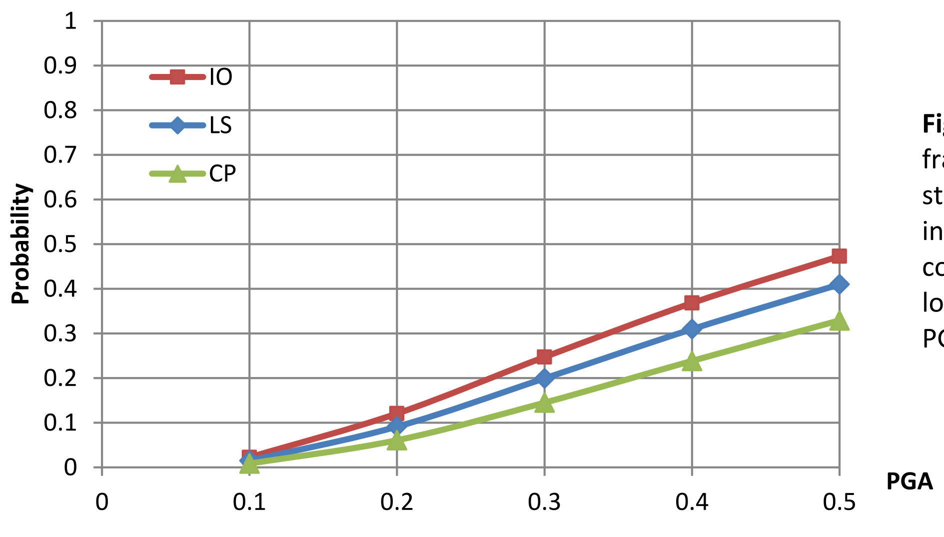

Fig. 7 Seismic fragility of three stories fully infilled RC frame considering the low class PGA/PGV ratio

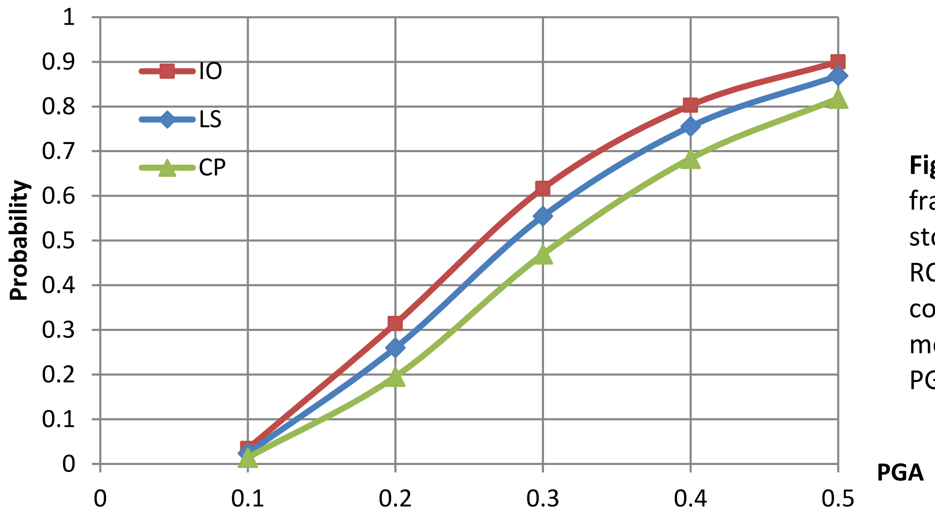

Fig. 8 Seismic fragility of three stories fully infilled RC frame considering the medium class PGA/PGV ratio

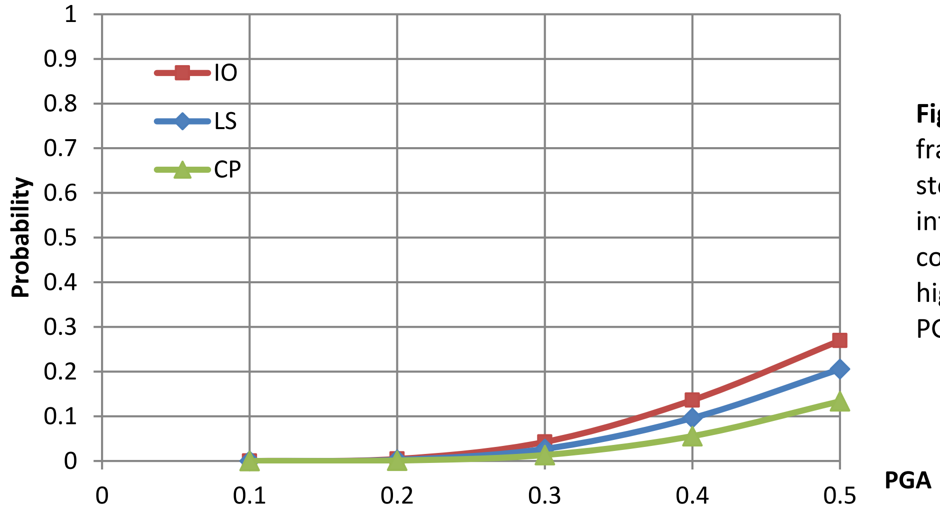

Fig. 9 Seismic fragility of three stories fully infilled RC frame considering the high class PGA/PGV ratio

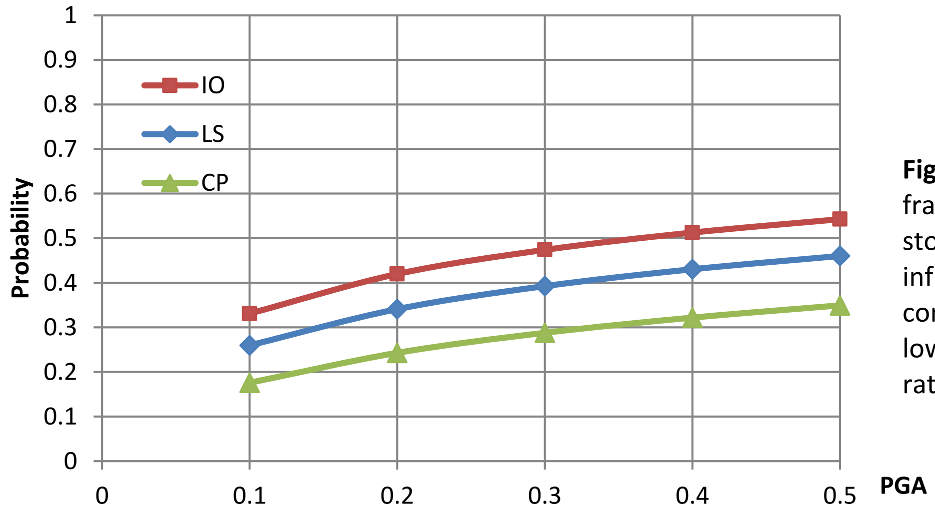

Fig. 10 Seismic fragility of six stories fully infilled RC frame considering the low class PGA/PGV ratio

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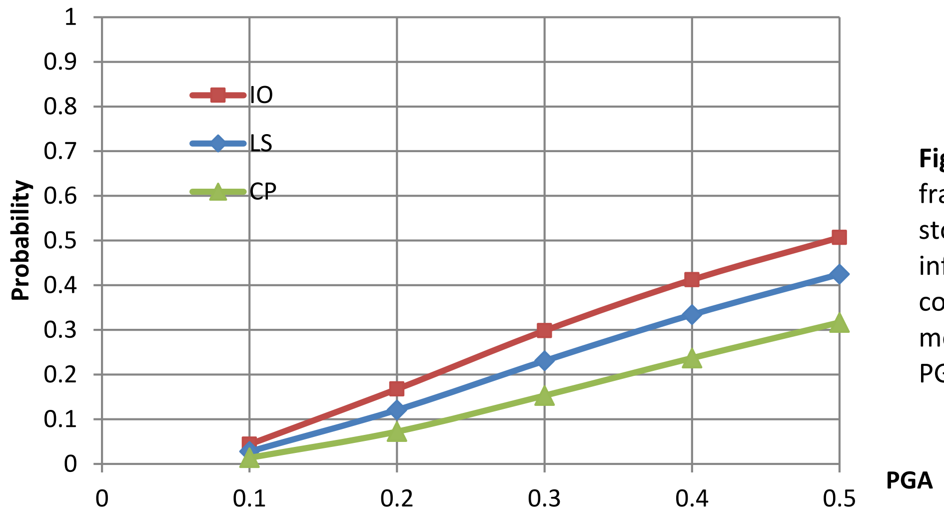

Fig. 11 Seismic fragility of six stories fully infilled RC frame considering the medium class PGA/PGV ratio

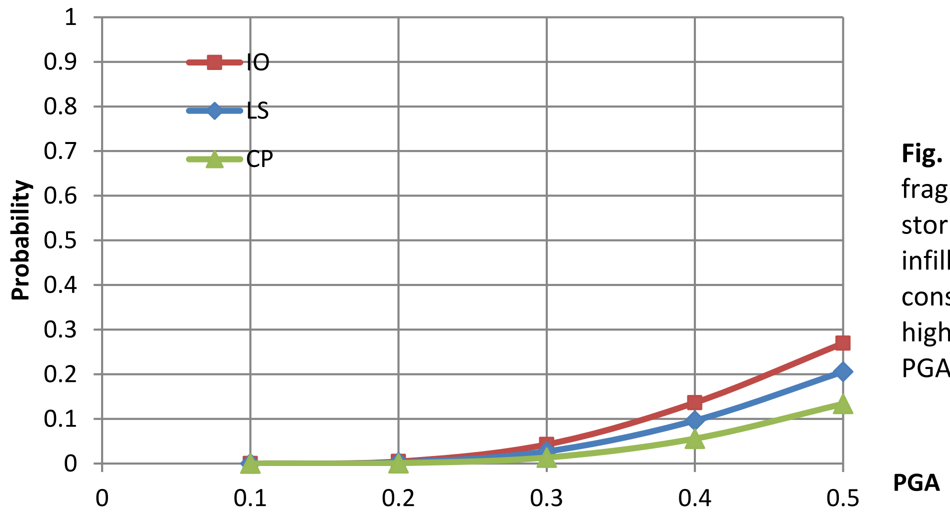

Fig. 12 Seismic fragility of six stories fully infilled RC frame considering the high class PGA/PGV ratio

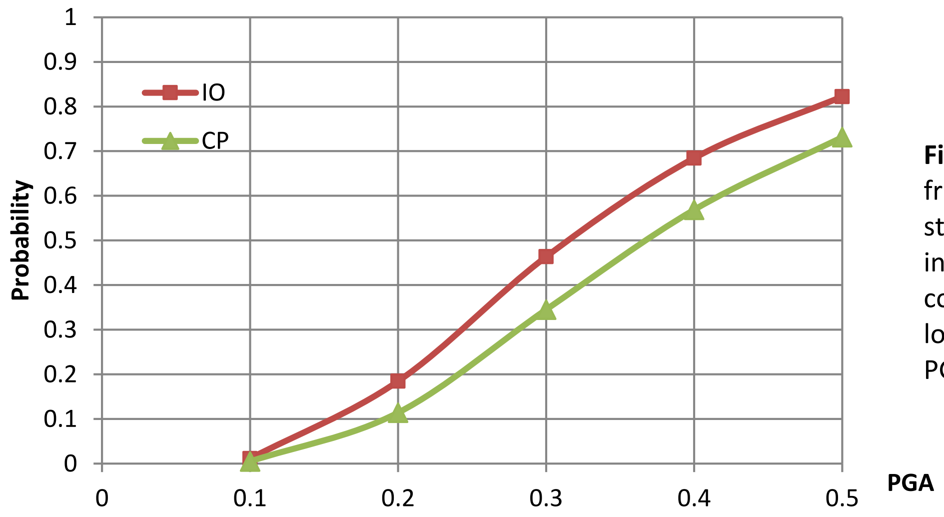

Fig. 13 Seismic fragility of nine stories fully infilled RC frame considering the low class PGA/PGV ratio

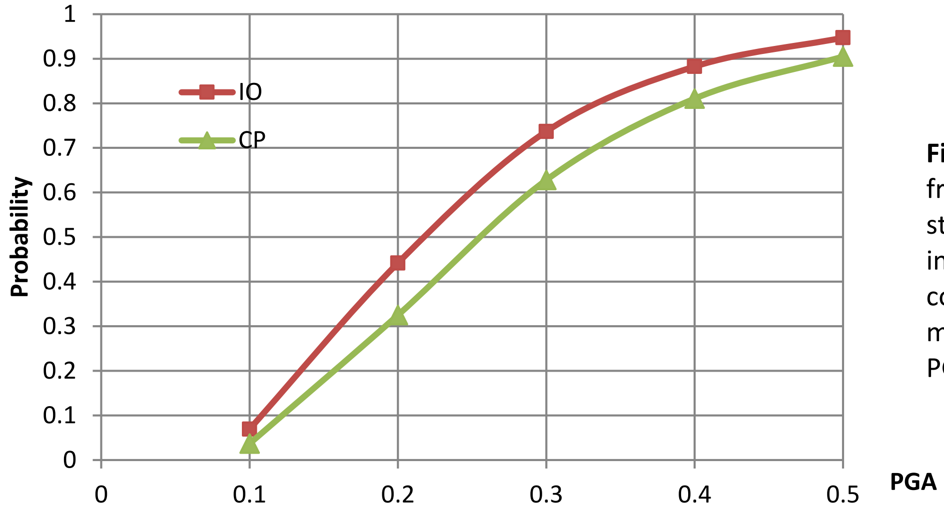

Fig. 14 Seismic fragility of nine stories fully infilled RC frame considering the medium class PGA/PGV ratio

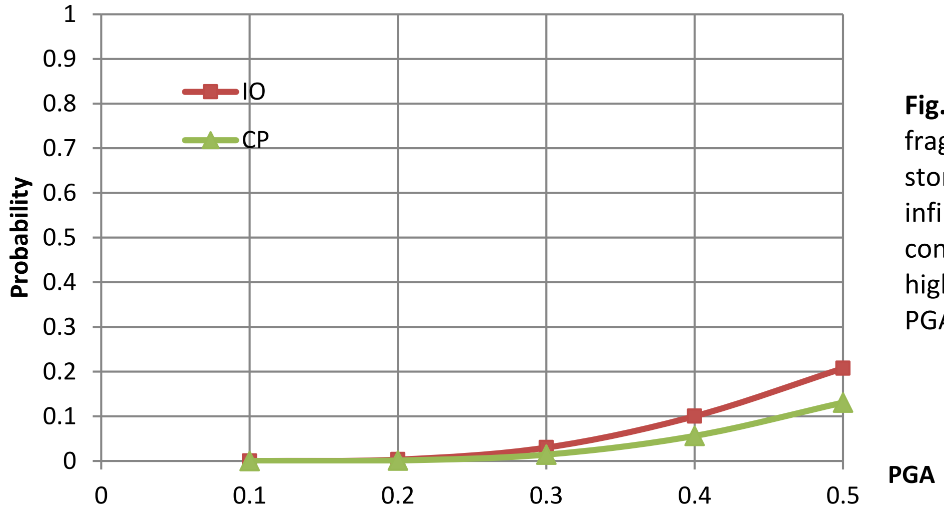

Fig. 15 Seismic fragility of nine stories fully infilled RC frame considering the high class PGA/PGV ratio

V. CONCLUSIONS

In this study, non-ductile fully infilled RC frames with three different height; three, six, and nine stories were analyzed using IDA to determine its vulnerability towards earthquake loads. The analysis involved 45 records of ground motions classified in three groups based on their PGA/PGV ratios which represent near, medium, and far field earthquakes. Fragility curves were used to determine probability of exceedance for three damage levels; IO, LS and CP in the selected RC frame under three earthquake group records. The results show that the presence of infill panels had significantly reduced seismic vulnerability of the non-ductile RC frames. The infill panels which distributed uniformly in the frames acted like additional bracing system to the structure. It increased the stiffness of the frames and reduced drift capacities for each damage levels compared to bare frames with similar configuration. Brittle behavior is observed in nine story fully infilled frame, while in bare frame the brittle behavior is observed in the three story structure. In fully infilled frames, the medium-class earthquake imposes the highest damage while in bare frames low-class earthquake records which represented the far-field earthquakes is more damaging. The presence of infill walls reduces the probability of exceedance for all damage levels compared to bare frames. All fully infilled RC structures; three, six, and nine stories frames satisfy the no-collapse requirement as required by the Malaysian code with less than 20% of probability of exceedance for CP damage level under all earthquake records (for PGA 0.2g). Under similar earthquake intensity, the bare frames however do not satisfy the expected performance objective as it has more than 50% probability of exceedance for CP damage level in all structures. This findings show the positive effect of infill walls on the structural performance of non-ductile RC frames subjected to earthquakes.

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