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Effect of Inadequate Lap Splice Length on the Seismic Fragility of Ground Soft-story Reinforced Concrete Frames

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Abstract. In this study, numerical analysis was used to derive seismic fragility curves for 3-, 6- and 9-story reinforced concrete (RC) frame with inadequate lap splice length and ground soft-story condition. The structural models were subjected to 15 far-field natural earthquake records. The peak ground acceleration (PGA) of the selected records was scaled in the range of 0.05g to 0.50g with an increment of 0.05g. Incremental dynamic analysis was employed to determine their inter-story drift demand and capacities. The obtained results indicated that the probability of severe damage to the RC frames increased as the number of stories decreased. It was also observed that the RC frames with inadequate lap splice length exhibited significantly higher probability of collapse when compared with RC frames with adequate lap splice length.

1. Introduction

Majority of buildings in Malaysia have not been designed for seismic actions mainly because of the low seismicity of the country and the lack of locally prepared design guidelines. The 2015 Ranau earthquake with a moment magnitude of 6.0 revealed that many of existing buildings in Malaysia may not be safe even against moderate earthquakes. The field investigation after the earthquake which was conducted by Alih and Vafaei [1] indicated that ground soft-story buildings were among the most damaged structures. In this type of building, which has been widely adopted in the country, the ground level has significantly smaller lateral stiffness compared to upper levels mainly because the infill walls are removed for car parks. The difference in the lateral stiffness of ground floor compared with upper floors increases significantly the drift demand in the ground floor [2]. Therefore, as can be seen from Figure 1, damage mostly occurs in the beams and columns of ground level. Such damage to the ground soft-story buildings have been reported by many researchers during past earthquakes [3,4]. In literature, different techniques have been proposed for seismic strengthening of ground soft-story buildings. For example, metallic dampers [5,6], buckling restrained braces [7], and Gapped-Inclined Bracing System [8] have been successfully used for the seismic retrofitting of such structures.

Although different strengthening methods can be applied to ground soft-story buildings, it is of great importance for authorities to have an estimation on the number of existing buildings that require such retrofitting. This kind of information can help decision makers to allocated appropriate amount of budget for the strengthening of vulnerable structures. Since decades ago, seismic fragility curves have been employed for the quantification of different damage states that are expected for different types of structures [9–12]. In Malaysia, seismic fragility curves have been derived for bridges [13], short reinforced concrete buildings [14,15], tall concrete wall buildings [16], and industrial buildings [17]. However, former studies have not considered the effects of inadequate lap splice length on the vulnerability of structures in Malaysia. Since many of buildings in Malaysia have been designed only for gravity loads, the employed lap splice length in their columns often do not satisfy the requirements of seismic codes like Eurocode 8 [18]. Owing to the bond deterioration, columns with inadequate lap splice length exhibit an impaired strength, stiffness, and ductility [19–21]. Therefore, in this study, the seismic vulnerability of ground soft-story buildings with inadequate lap splice length in Malaysia was investigated through the frame work of derivation of fragility curves.

(a)

(b)

Figure 1. (a) A ground soft-story building in Ranau, Malaysia (b) Observed damage to the ground floor of the same building after the 2015 Ranau earthquake

2. Selected Structures

In this study, 3-, 6-, and 9-story low-ductile partially infilled reinforced concrete frames were selected to represent the typical RC buildings in Malaysia. The frames were considered to be part of a symmetrical architectural plan with four 6m length spans in both principal directions. A typical story height of 3m was considered for all frames. The height of the ground floor was assumed 4m in all frames. Frames were designed in compliance to BS 8110 [22] for dead, superimposed dead, live and notional loads using ETABS v2016 software. The self-weight of brick walls was applied to the beams of frames as a uniform load. The yield line method was adopted to distribute the weight of slabs to the beams of frames. The considered details in the design of frames have been shown in Table 1. The elevation view of the 3-story reinforced concrete frame with the open space ground floor is shown in Figure 2.

Table 1. Details of reinforced concrete frames and their design parameters

Number of stories	3, 6, 9
Height of buildings considered	10m, 19m and 28m
Structural System	Open space ground floor with partially infilled RC frames
Floor height	Typical floor story height = 3m; ground floor = 4m
Yield strength of rebar	460 MPa
Compressive strength of concrete	30 MPa
Dead load	Finishes = 1.2 kN/m^2 RC slab with 150mm thickness = 3.75 kN/m^2 M&E Services = 0.5 kN/m^2 150 mm thick brick wall with plaster finishes at both sides = 2.9 kN/m^2 per 1 m height.
Live load	Typical floor = 1.5 kN/m^2; Roof = 1.0 kN/m^2
Notional load	equivalent to 1.5% of the characteristic dead load

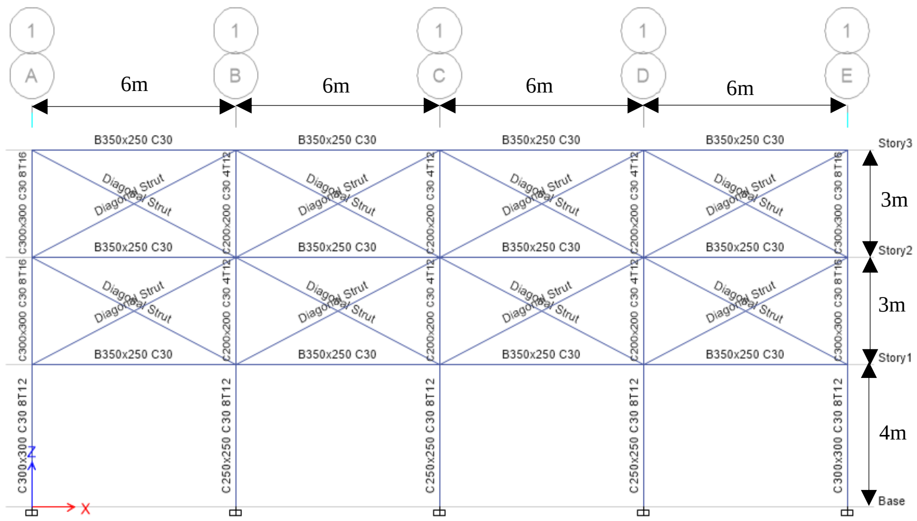

Figure 2. Elevation view of 3-story reinforced concrete frame with open space ground floor

2.1. Finite Element Simulation of Frames

The finite element models of all frames were established in ETABS v2016 software. This software allows for nonlinear static and nonlinear dynamic analysis of RC frames. The lumped plasticity model was used to simulate the inelastic behaviour of beams and columns [23]. In the nonlinear analysis, the elastic stiffness of beams and columns was reduced to 0.3 and 0.7, respectively [24]. Moreover, the moment-rotation relationships of beams and columns were established following the specifications of ASCE 41[24]. The moment-rotation relationships of columns with inadequate lap splice length was simulated based on the condition (iv) of ASCE 41[24] (i.e., columns controlled by inadequate development or splicing along the clear height). The inelastic behaviour of beams was simulated assuming the domination of the flexural failure. Moreover, the transverse reinforcements in beams and columns were assumed to be not conforming to the confined conditions required by ASCE 41[24]. The elastic behaviour of infill walls was simulated using the diagonal strut model proposed by Paulay and Priestly [25]. The strength of infill wall was calculated using the equations provided in ASCE 41[24]. Following the recommendations of ASCE 41[24], three different damage states were adopted for beams, columns and infill walls which included Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP). These damage states correspond to low, medium and severe damage to structural elements.

2.2. Seismic Ground Motion Records

In this study, 15 far-field natural earthquake records were selected for conducting incremental dynamic analysis. Selection of far-field records was based on this fact that the west Malaysia is mostly affected by Sumatra fault which is several hundreds of kilometres away from the country [1].The peak ground acceleration (PGA) to peak ground velocity (PGV) ratio of selected records are less than 0.8 g/m/s. Ground motions with small PGA/PGV ratio often have long duration with energy in the low frequency range [26]. Table 2 summarises the details of the ground motions used in this study which have been obtained from Tso et al. [26]. It should be mentioned that before conducting the nonlinear time history analysis the PGA of the selected records were scaled to the range of 0.05g to 0.5g with an increment of 0.05g.

Table 2. Details of selected far-field ground motion records

Seismic Records	Duration (s)	PGA (cm/s^2)	PGV (cm/s)	PGA / PGV
TH1	30.0	95.635	23.686	4.038
TH2	30.0	62.328	17.343	3.594
TH3	25.0	156.821	20.856	7.519
TH4	20.0	98.747	19.303	5.116
TH5	25.0	129.816	21.584	6.015
TH6	25.0	126.889	18.633	6.810
TH7	20.0	111.844	18.564	6.025
TH8	20.0	114.976	21.535	5.339
TH9	20.0	116.964	17.311	6.757
TH10	20.0	103.784	16.965	6.117
TH11	45.0	221.500	33.400	6.632
TH12	35.0	200.900	27.500	7.305
TH13	35.0	101.300	15.020	6.744
TH14	30.0	32.000	7.380	4.336
TH15	59.98	38.830	7.370	5.269

3. Derivation of Seismic Fragility Curves

The following expression was used for the derivation of seismic fragility curves [27]:

$$P(LS|GMI) = 1 - \Phi\left(\lambda_{CL} - \lambda_{D|GMI} / \sqrt{\beta_{D|GMI}^2 + \beta_{CL}^2 + \beta_M^2}\right) \quad (1)$$

Where, P(LS|GMI) is the probability of exceeding a limit state given the ground motion intensity (GMI). Φ is the standard normal cumulative distribution function. λ_{CL} stands for the natural logarithm of median of drift capacities for a particular limit state. $\lambda_{D|GMI}$ denotes the natural logarithm of calculated median of drift demands given the ground motion intensity from the best fitted power law equation. $\beta_{D|GMI}$ shows the demand uncertainty and equals $\sqrt{\ln 1 + s^2}$, where s^2 is the standard error of the drift demand data. β_{CL} is the uncertainty in the calculation of drift capacity and β_M is the modelling uncertainty.

Table 3 shows the median of inter-story drift capacities for all studied frames which have been obtained from incremental dynamic analysis (IDA) results. As can be seen from the table, no drift capacity has been associated to the IO and LS damage states of 3- and 6-story frames, and LS damage state of 9-story frame. The main reason behind this observation relies on this fact that columns with inadequate lap splice length exhibit a brittle failure mode. In other words, soon after passing the elastic limit state they reach their ultimate capacity. It is also noteworthy that the obtained drift capitates are significantly smaller than those expected for RC frames with adequate lap splice length. ASCE 41 [24] suggests 0.5%, 1% and 2% as drift capacities for the IO, LS, and CP damage states of RC frames. It

can be also seen that while the median of drift capacities for 6-and 9-story frames are close to each other, the 3-story frame exhibits significantly smaller drift capacity.
Figure 3 depicts the relationship between the median drift demand and PGAs of earthquake records for all studied frames. Besides, the obtained best fitted power law equations have been shown in this figure. As can be seen, for all frames, there is a strong correlation between the median drift demands and PGAs of earthquake records when the fitted power law curves are used. Figure 3 also shows that, at small PGAs (i.e. less than 0.2g), the median drift demands in all frames are close to each other. However, as the PGA increases, 6- and 9-story frames exhibit larger drift demands. As can be seen, compared to the 9-story frame the 6-story frame has larger median drift demands mainly due to the frequency content of earthquake records which have been closer to the natural frequency of this frame.

Table 3. Summary of the median inter-story drift capacities

Limit State	Inter-Story Drift Capacity		
	3-Story Frame (%)	6-Story Frame (%)	9-Story Frame (%)
IO	-	-	0.91
LS	-	-	-
CP	0.65	1.11	1.17

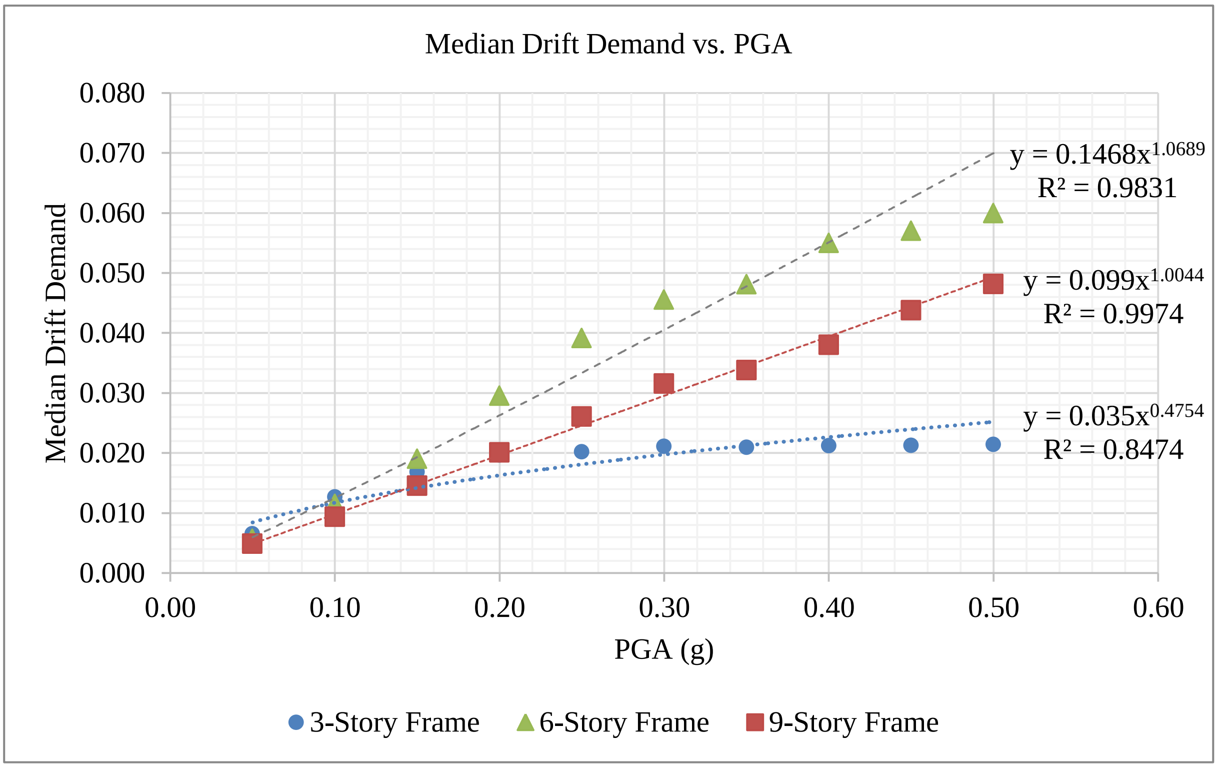

Figure 3. The relationship between the median drift demand and PGAs for 3-, 6- and 9-story frames

The uncertainty in the obtained drift capacities (β_{CL}) for 3-,6-, and 9-story frames were calculated using the IDA results and equaled, respectively, 0.37, 0.41, and 0.25. Beside, following the previous studies [10,28], the modelling uncertainty (β_M) was assumed to be 0.3.
Figure 4 illustrates the obtained seismic fragility curve for 3-, 6-, and 9-story frames considering different damage states. It is evident from the obtained fragility curves that the probability of collapse in the frames increases as their height decreases. At the PGA of 0.05g, the probability of collapse of 3-story frame is 70% while that of 6-story and 9-story frames are 11% and 1%, respectively. This clearly indicates the vulnerability of 3-story frames under weak earthquakes. Figure 4 also shows that as the

PGA increases the difference in the probability of collapse of frames decreases. It is also noteworthy that at the PGA of 0.3g the probability of collapse in all frames is 100%. Besides, in the 9-story frame, as the PGA increases the probability of collapse approaches to the probability of minor damage (i.e. IO). According to the seismic hazard map of Malaysia [29] the expected PGA at bedrock for a return period of 475 years is 0.08g for Kuala Lumpur city. Therefore, based on the obtained results, 3- and 6-story ground soft-story RC frames that have been constructed with inadequate lap splice length are expected to experience severe damage.

Figure 5 compares the seismic fragility curves of this study for CP damage states with those calculated by Amalina [30] for RC frame with adequate lap splice length in Malaysia. It is evident that the inadequate lap splice length has significantly increased the probability of exceeding the CP damage state in all frames. It is also noteworthy that the probability of exceeding CP damage state in taller frames has been more affected by the inadequate lap splice length in columns when compared with the shorter frames. While at the PGA of 0.3g the probability of exceeding CP in the 9-story frame with inadequate lap splice length is 100%, it is only 2.3% when the lap splice length in columns is adequate. Figure 5 also shows that the inadequate lap splice length in columns has made the slope of fragility curves in all frame’s steeper. This implies that a small increase in the PGA of earthquake records increases significantly their probability of collapse.

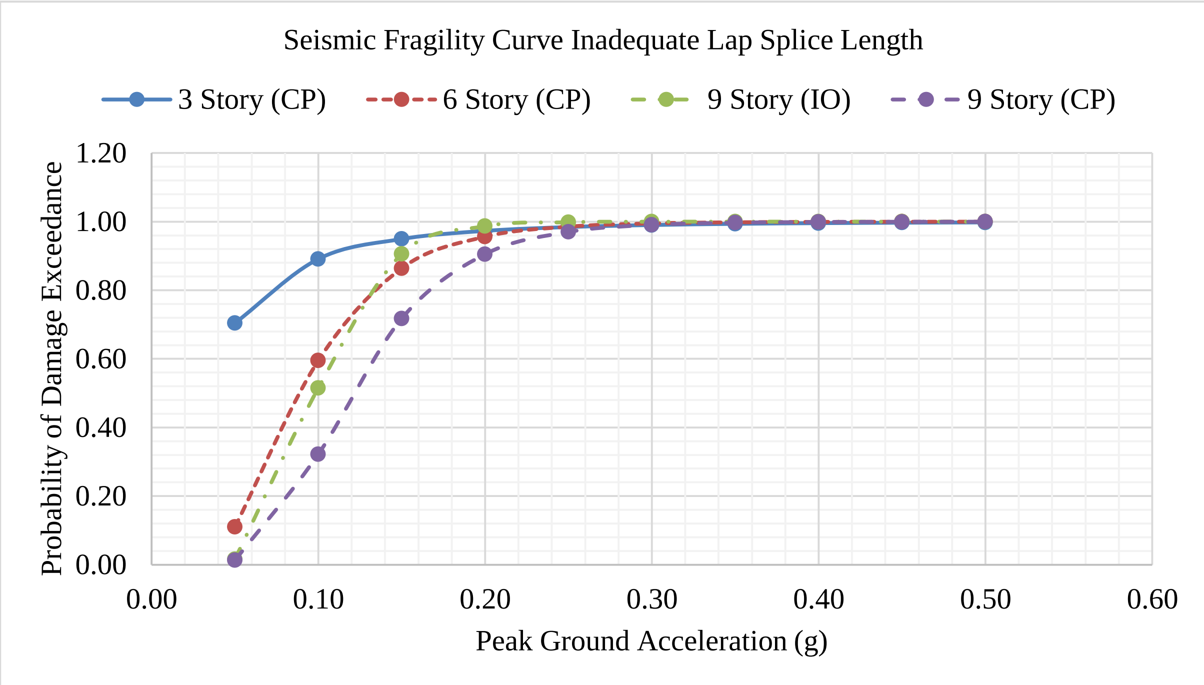

Figure 4. Effect of building height to probability of damage exceedance

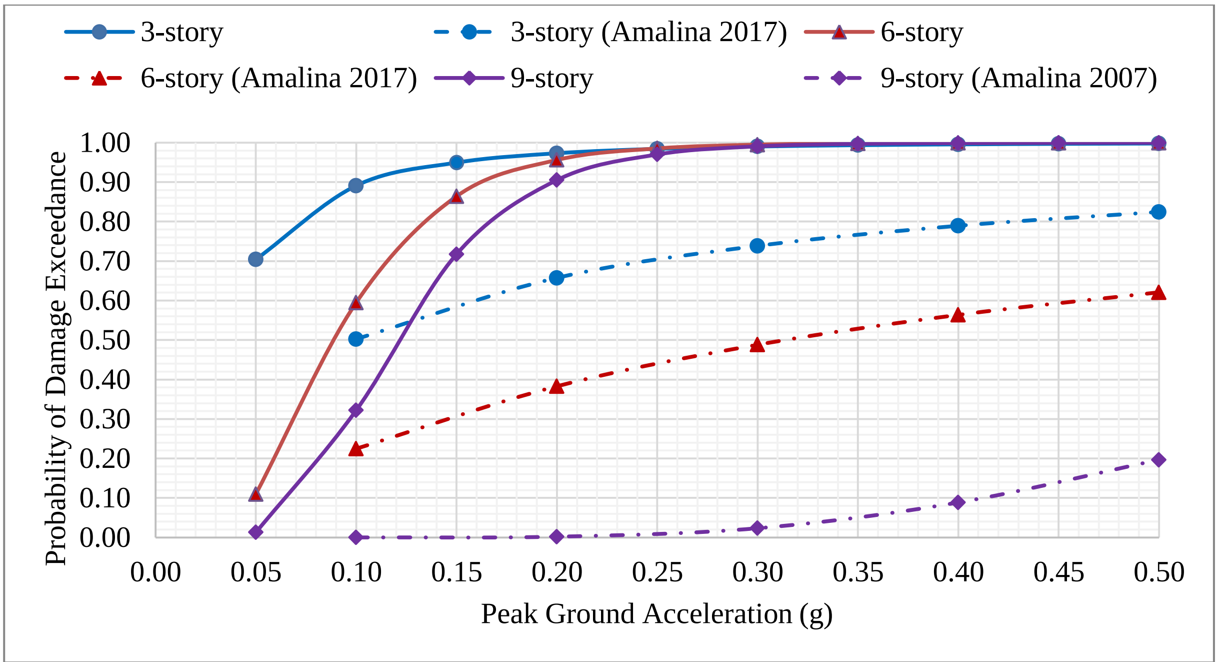

Figure 5. Comparison of seismic fragility curves considering the effect of lap splice length

4. Conclusion

This study focused on the development of seismic fragility curves for the ground soft-story low-ductile reinforced concrete frames that have inadequate lap splice length. For the derivation of seismic fragility curves, 3-, 6-, and 9-story RC frames were excited by 15 far-field natural earthquake records that their PGAs were scaled to the range of 0.05g to 0.5g. The median of inter-story drift capacities and demands were calculated for each frame based on the results of an extensive nonlinear time history analysis. It was observed that shorter frames had relatively smaller drift capacities and demands. Besides, an increase in the height of buildings decreased the probability of collapse. Moreover, the obtained results also showed that 3- and 6-story ground soft-story RC frames constructed in Kuala Lumpur city with inadequate lap splice length were expected to experience severe damage. Comparison with RC frames with adequate lap splice length revealed that when the lap splice length was not adequate in columns the probability of collapse increased significantly. In such condition, the increase in the collapse probability of taller frames was more than shorter frames.

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