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The Effect of Span-to-Height Aspect Ratio to The Damage Index Ratio of RC Buildings with Vertical Irregularity Setbacks

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ABSTRACT

Many type irregularities exist in reinforced concrete frame buildings to accommodate the demand from architectural and aesthetic aspects. One of it is vertical irregularity setback. Its appearance affected the building seismic performance and the damage distribution. Previous researchers proposed equations to correlate between irregularity indices and damage index ratio of setback buildings. However, the aspect ratio between span and height were not included in the formula. This research presents the influence of span-to-height ratio to damage index ratio of the reinforced concrete buildings with setbacks. A set of 2D RC frames having setbacks are evaluated with nonlinear dynamic analyses under three seismic input motions. Several span-to-height aspect ratios were applied by changing the inter-story heights. The Park-Ang damage index was adopted to evaluate the damage index ratio between tower part and base part to represent the damage distribution and the inter-story drifts were observed to represent the building seismic performance. The result showed that under the same earthquake motions, the decrease in span-to-height ratio majorly increased the maximum inter-story drifts. The damage index ratio values between tower part and base part fluctuated, however the similar pattern of damage distributions between tower and base structure were obtained.

Keywords: Span-to-height ratio; setback buildings; damage index ratio; seismic performance analysis

INTRODUCTION

In the recent rapid development of society and technology, the demand for the building construction is also rapidly growing. Following the enhancement of architectural demand and functional demand, the building structure must adapt to any kind of demand, one of it to accommodate any irregularity, both horizontal and vertical. In terms of vertical irregularity, one of the types of it is vertical irregularity setback. The setback as vertical irregularity in building is generally noted the existence of disruption in strength, mass, and stiffness distribution along the height (Mwafy & Khalifa 2017; Soni & Mistry 2006). The presence of vertical irregularity setback may have considerable effect on building responses such as torsional response (Duan & Chandler 1995) and damage concentration on the notch area (Syamsi, Maulana, Widyantama, Ian, & Lesmana 2021). It also has a significant effect if the building is subjected to the high seismic loadings (Syamsi et al. 2021).

The seismic performance and damage distribution can be used as parameters to determine the effect of the setback existence in buildings. In terms of earthquake loadings, parameter displacement or inter-story drift can be the one representing the seismic performance of building (Maulana, Fonseca & Saito 2022). The damage distribution can also be represented by the story damage index (Belkacem, Bechtoula, Bourahla, & Belkacem 2020), which can be numerated by using popular damage indices, such as Park-Ang damage index (Park & Ang 1985; Park, Ang & Wen 1985). Many studies have proposed methods to calculate the damage degree of the building through the Park-Ang damage index, and furthermore predicted the damage indices by using some other general parameters, such as geometry effect from irregularity indices, developed by Karavasilis et al. (Karavasilis, Bazeos & Beskos 2008), which were originally proposed by Mazzolani and Piluso (Mazzolani & Piluso 1996).

For example, the study by Habibi and Asadi (Habibi & Asadi 2017) established formulas to calculate overall Park-Ang damage index of buildings with setback irregularity by using three variables, consisting of the natural period, irregularity indices, and overall drifts. This proposal can determine the overall damage index with adequate precision. However, it can only obtain the overall damage index without knowing the damage distribution and still needs mode analysis to gain the natural period of the building. The other proposal formula to determine the damage degree was made Varadharajan et al. (Varadharajan, Sehgal & Saini 2013, 2014) by inputting the parameter of modal participation factor ratio of regular and irregular building, the displacement ductility, and the stiffness ratio of structural element members. Although the overall Park-

Ang damage index can be predicted sufficiently, the mode analyses were still needed to be performed and the damage distribution along the height could not be directly harnessed. Other researchers also conducted the similar study, such as Hait et al. (Hait, Sil & Choudhury 2020a) using the seismic response buildings parameters, namely inter-story drift, maximum joint rotation, and peak top floor displacement. Hait et al. (Hait, Sil & Choudhury 2020b) also further their study by implementing artificial neural network to determine the damage index. Both proposals could forecast the damage index decently, but it is only overall damage index and only suits for horizonal irregularity, and to calculate the equations, dynamic analyses were still needed to retrieve the seismic responses. To overcome those limitations, Maulana, et al. (Maulana, Enkhtengis & Saito 2021) proposed simpler formulas by only considering the irregularity indices to retrieve the damage index ratio, a ratio between maximum damage index of the tower part to the maximum damage index of the base part, specifically for the reinforced concrete building with irregularity setback. The idea was tested on the experimental shaking table tests by other researchers. The fair result was obtained by using the formula. However, the consideration of different height or span length cannot be accommodated through the irregularity indices entirely, and the effect of it has not been studied yet.

In this study, the effect of span-to-height ratio to damage index ratio of the reinforced concrete buildings with setbacks were observed. Four sets of 2D RC frames having setback with stepped type are adopted by following the previous research (Maulana et al. 2021). The seismic response of the building is evaluated with nonlinear dynamic analyses under three different seismic input motions. Seven height-to-span ratios were implemented by changing the inter-story heights. The Park-Ang damage index was applied to evaluate the damage index ratio between tower part and base part to represent the damage distribution and the inter-story drifts were observed to represent the building seismic performance. The effect of span-to-height ratio could contribute to better understand on seismic damage distribution of vertical irregular buildings.

METHODOLOGY

NUMERICAL SIMULATION METHOD AND MODELLING IDEALIZATION

Nonlinear dynamic analyses of the specimens were conducted by using the STERA_3D, a software written by Professor Taiki Saito (Saito 2020). Figure 1 shows the STERA 3D user interface for building modelling. In STERA_3D, the dynamic earthquake response study is performed by adopting Newmark-β numerical integration method (Newmark 1959). All the details of implemented modelling approach are accessible in STERA_3D Technical Manual (Saito 2020). The structural elements such as beams and columns are modelled with certain idealizations, elaborated as follows.

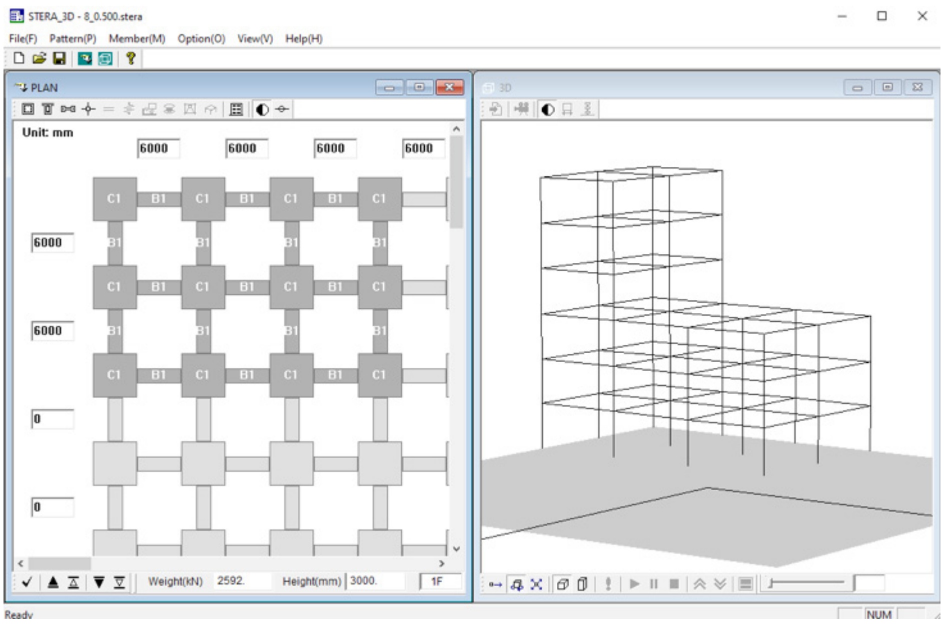


FIGURE 1. STERA_3D interface on setback building model, a tool developed by Saito (Saito 2020)

The RC beam and column elements are modeled as line elements with two nonlinear bending springs at both ends and one nonlinear shear spring at the middle as illustrated in Figure 2. The end displacement vector is obtained from Equation 1 as the sum of the displacement vector of each component. The RC column section is modelled by using the multi springs model, originally proposed by Lai, Will, and Otani in 1984 (Lai, S. -S., Will, G.T. & Otani 1984), as shown in Figure 3.

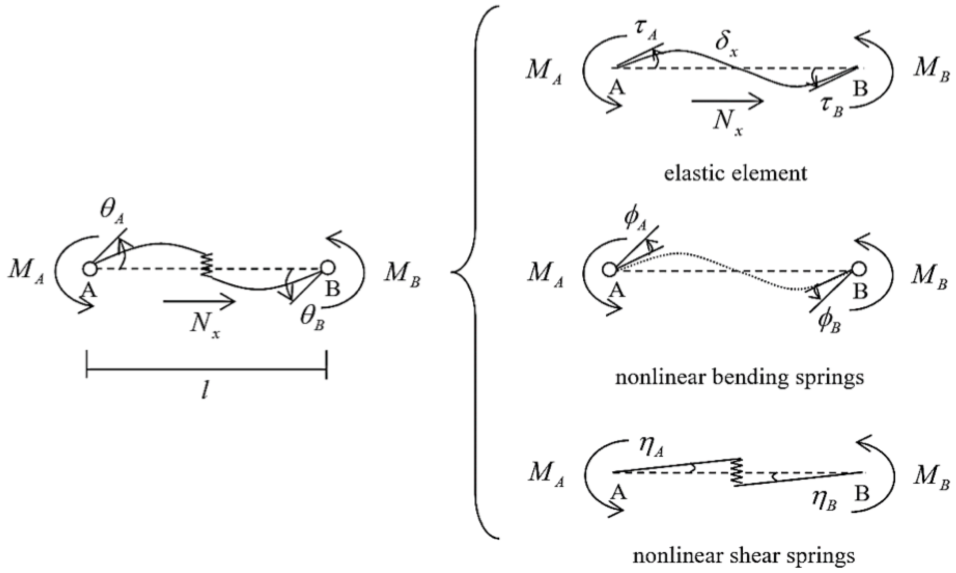


FIGURE 2. Elastic, nonlinear bending, and nonlinear shear springs for elements modelled by STERA_3D (Saito 2020)

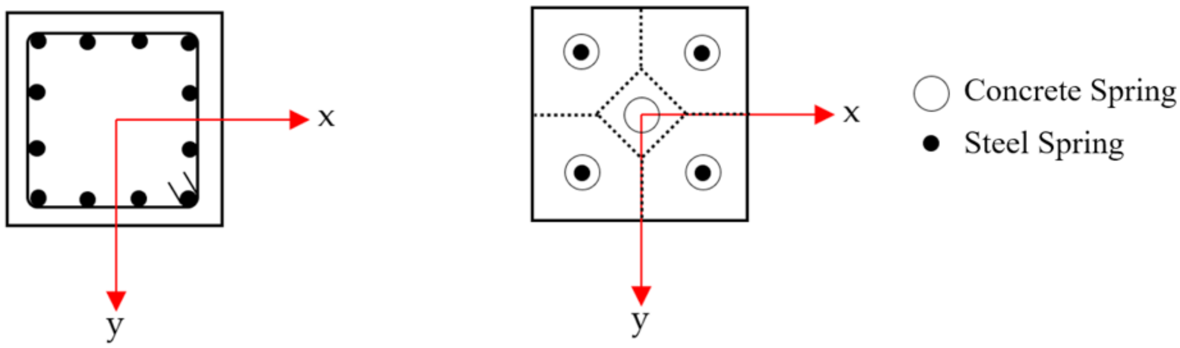


FIGURE 3. RC Column section modelling using multi spring models: (a) original column section, and (b) multi-spring model idealization (Saito 2020)

PARK-ANG DAMAGE INDEX AND DAMAGE INDEX RATIO

Park and Ang (Park & Ang 1985; Park et al. 1985) proposed a damage index, especially for element structures which were comprised from the reinforced concrete materials. To measure the degree of the damage, damage index can be calculated using Equation 1 as follow.

$$DI = \frac{u_m}{u_u} + \beta \frac{E_h}{F_y u_u} \quad (1)$$

Where u_m is the maximum drift response of the structural earthquake due to seismic input motions, u_u is the ultimate drift capacity of the element within the condition of monotonic loading, E_h is the total energy dissipated by the element, F_y is the yielding force of the element, and β is the non-negative parameter depending on the loading effect.

There are five levels of the damage degree based on the value of the DI, which is slight damage (DI value is less than 0.1), minor damage (DI value is less than 0.25), moderate damage (DI value is less than 0.4), severe damage (DI value is less than 1.0), and collapse state (DI larger than 1.0).

After calculating the damage index for every element with Park-Ang damage index (Park & Ang 1985; Park et al.1985) and story damage index proposed by Belkacem et al. (Belkacem et al. 2020), the damage index ratio between tower part and base part can be calculated by using Equation 2, which originally proposed by Maulana et al (Maulana et al. 2021) as follow.

$$DI_{ratio} = \frac{\max(DI_{tower})}{\max(DI_{base})} \quad (2)$$

Irregularity Indices

The geometry irregularities are accommodated in the calculation of geometrical indices φ_b and φ_s, which can be calculated based on the indices developed by Karavasilis et al. (Karavasilis et al. 2008) as written in Equation 3 and 4 as follows.

$$\varphi_b = \frac{1}{n_b - 1} \times \sum_{i=1}^{i=n_b-1} \frac{H_i}{H_{i+1}}$$

$$\varphi_s = \frac{1}{n_s - 1} \times \sum_{i=1}^{i=n_s-1} \frac{L_i}{L_{i+1}}$$

where n_s is the number of levels in the frame, n_b is the number of spans of the base story, L_i is the total span of the story, and H_i is the inter-story height every bay.

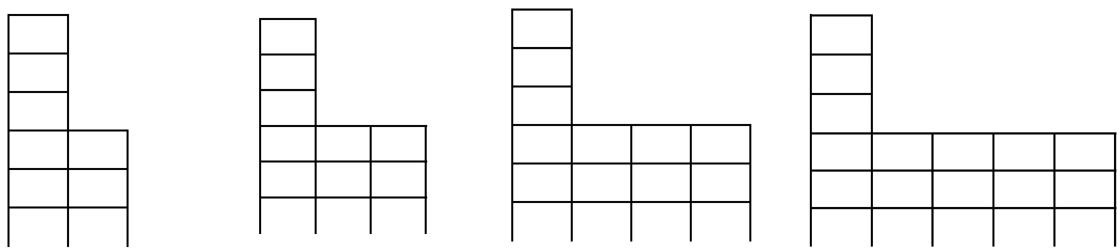
BUILDING SPECIMENS

The specimen in this study follows previous study conducted by Maulana et al. (Maulana et al. 2021), However, only four specimens are chosen, representing the location of the setback in the middle of the building. The reinforced concrete building has six story levels, and it comprises of two to five spans. In this study, the focus is only for the stepped setback type. The specimen illustration is shown in Figure 4. The building layout is comprising of structure with 5 × 2 bays for six story level buildings with 6 m× 6 m panel of x-y direction. The compressive concrete strength is determined as 30 MPa, with the column size of 700 mm × 700 mm with 8D-35mm longitudinal rebars and 2-D13mm at 10 cm for the transversal rebar. For the beam, the size is 600 mm × 300 mm with the 6D-35 cm longitudinal rebars and 2-D13mm at 10 cm for the transversal rebar.

There are 7 height-to-span ratio, which refers to the same span of 6 m but different height of building from 3 m to 6 m. The detail of implemented height-to-span ratio is presented in Table 1.

INPUT EARTHQUAKE MOTIONS

Following the original proposal by Maulana, et al. (Maulana et al. 2021), three input earthquake motions are utilized to be loaded in the specimens. The acceleration raw data was retrieved from PEER (PEER 2021) and the earthquake is scaled to have Peak Ground Velocity (PGV) of 50 cm/s, corresponding the design level earthquake for safety limit state. Table 2 shows the details of three input earthquakes, Figure 5 shows the spectrum response of the acceleration, and Figure 6 shows the waveforms of the seismic input motions.



(a) Specimen #3 (b) Specimen #8 (c) Specimen #13 (d) Specimen #18

FIGURE 4. Four specimen of stepped setback buildings, following previous study by Maulana et al. (Maulana et al. 2021)

TABLE 1. Implemented height-to-span ratio for four building specimens

Specimen	Building heights (in m)	Height-to-span ratio
#3	3.0	0.500
#8	3.5	0.583
#13	4.0	0.667
#18	4.5	0.750
	5.0	0.833
	5.5	0.917
	6.0	1.000

TABLE 2. Detail of three input earthquakes

No	Event	Year	Station	Component	Original max. acc. (cm/s²)	Scaled Max. Acc. (cm/s²)
1	Imperial Valley	1940	El Centro	NS	341.69	510.70
2	Kern County	1952	Taft	EW	152.69	496.50
3	Kobe	1995	JMA	NS	817.80	449.80

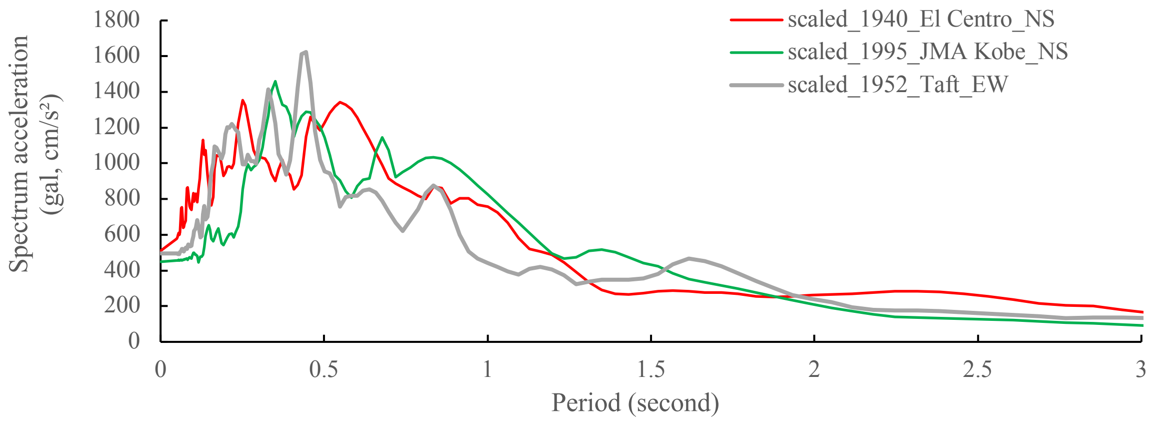


FIGURE 5. Three spectrum response of the accelerations

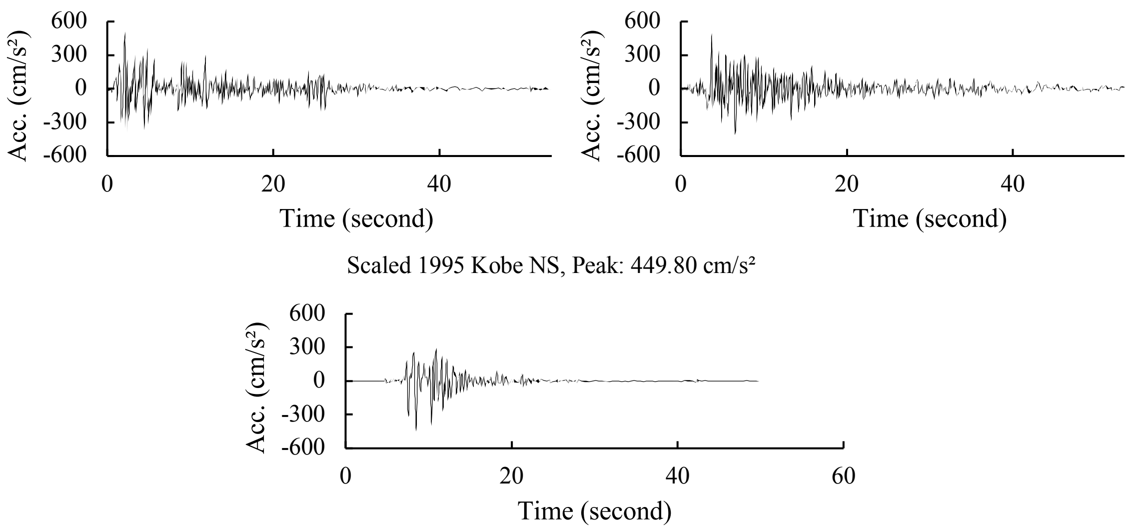


FIGURE 6. Three waveforms of the seismic input motions

RESULTS AND DISCUSSION

NATURAL PERIODS

In this study, the natural period of the first mode of all specimens is obtained from STERA_3D software by running the mode analysis. The complete results can be observed in Figure 7. From the results, it is known that the more bays that the specimen has, the smaller natural period of the first mode value will be produced. It is because there are more elements in the base part and thus, the strength and stiffness increase within increasing the panel. It can be seen from Specimen #3 that only has two bays in the base part, while Specimen #18 has five bays. Also, the increase of the height-to-span ratio is followed by the increase of the natural period. It is because with the same span, the height increased and the stiffness is decreasing, therefore the natural period of first mode is increasing. These results confirm the theory of natural frequency mentioned by Chopra (Chopra 2014) and the analysis by Maulana et al. (Maulana, Faturrochman, & Saito 2019) that building's natural period is depending on the mass and stiffness. Since the mass is uniform, the increase of the height weakened the building stiffness, thus the natural period increased along the increase of height-to-span ratio.

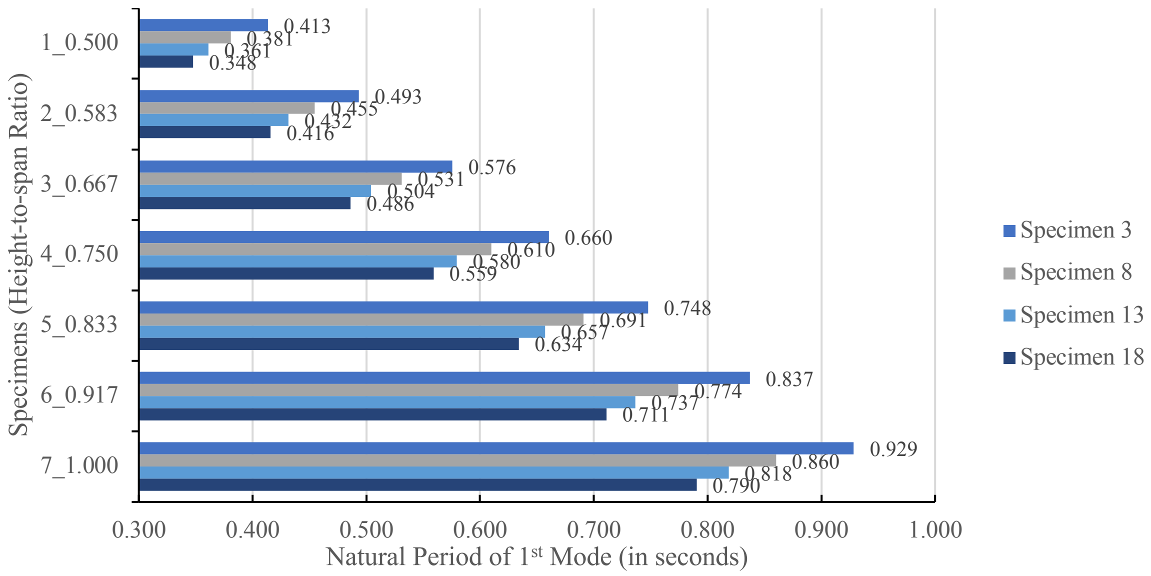


FIGURE 7. Natural period of the first mode of the buildings

EFFECT OF HEIGHT-TO-SPAN RATIO TO DAMAGE INDEX RATIO

As explained earlier in Table 1, four specimens are subjected to seven different height-to-span ratios, which are approached by maintaining the span length and changing the inter-story height. By going through this approach, the irregularity indices will be the same and not change if determined following Equation 3 and 4. By using the proposed method by Maulana, et al. (Maulana et al. 2021), one damage index ratio can only be obtained for one value of irregularity indices. However, as depicted in Figure 8, with the same value of irregularity indices but different height-to-span ratio, the value of damage index ratio is changing. Figure 8 is shown, representing the results from the implementation of three input earthquakes and the average responses from three input motions is represented as straight line. For the specimen 3, the average value of damage index ratio fluctuates between 0.9 to 1.2 along with the change of the height-to-span ratio. This means that, in some case, the tower part suffers more damage than the base and the definition of the damage index ratio by only using the irregularity index should be improved.

Furthermore, from Figure 9 which illustrates all the average results for specimen 3, 8, 13, and 18, there is a major trend that can be seen, which is the larger of the height-to-span ratio, the damage index ratio will increase. In the study by Varadharajan et al. (Varadharajan et al. 2013, 2014), the global damage index value increased when the column stiffness decreased, which confirm the result in this study. In this case, the damage distribution definition from Equation 2 will still suitable since the value of damage index ratio is always larger than one, meaning that the tower part will receive more damage concentration. Also, with the stronger of the base part, it will be followed by the larger damage in the tower part. This result could give the insight that height-to-span ratio could affect the value of the damage index ratio value in the building with a vertical irregularity setback.

INTER-STORY DRIFT RESPONSES

Regarding the effect of the span-to-height ratio to the average inter-story drift ratio responses, all specimens show the similar patterns, as can be seen in Figure 10. Figure 10 describes the results of average inter-story drift ratio for span-to-height ratio of 0.500, 0.750, and 1.000. With the same span-to-height ratio, the specimen that has less panel in base part suffered less inter-story drift at the top of the setback location. The value of inter-story drift and its differences will be more distinct after increasing the span-to-length ratio. This result is supported by the Hooke's law, mentioned by Rees (Rees 1997), where the drift of a structure is affected by force and stiffness. In this case, the ratio of stiffness between tower part and base part is more recognizable when the base part has a greater number of bays compared to the tower part, thus the inter-story drift is larger within the increase of span-to-height ratio.

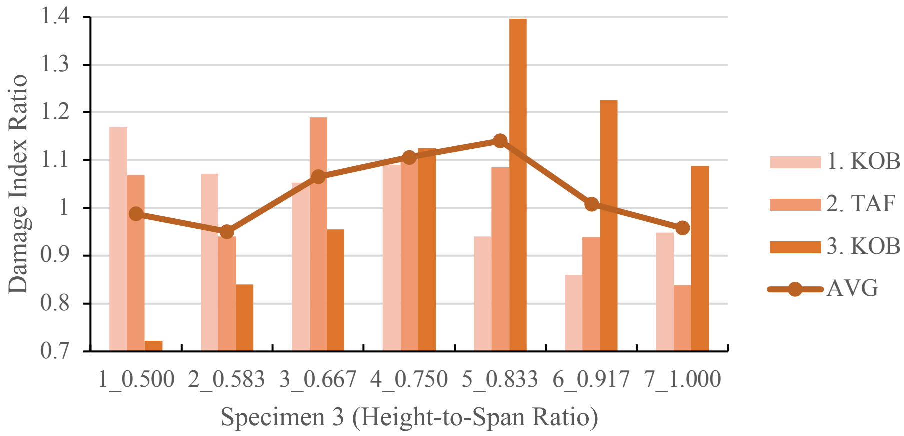


FIGURE 8. The effect of changing height-to-span ratio to the damage index ratio value for specimen #3

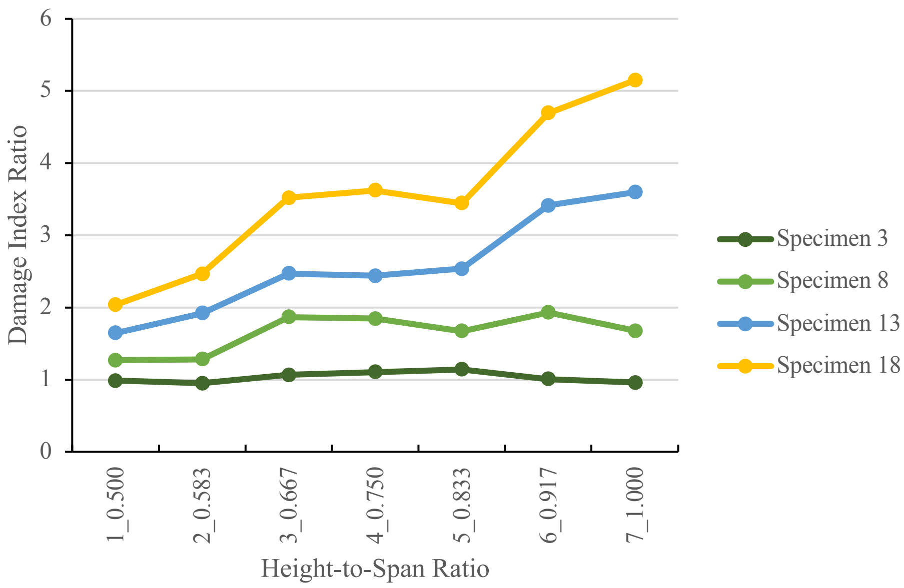


FIGURE 9. Overall relationship of height-to-span ratio to the damage index ratio value for all specimen

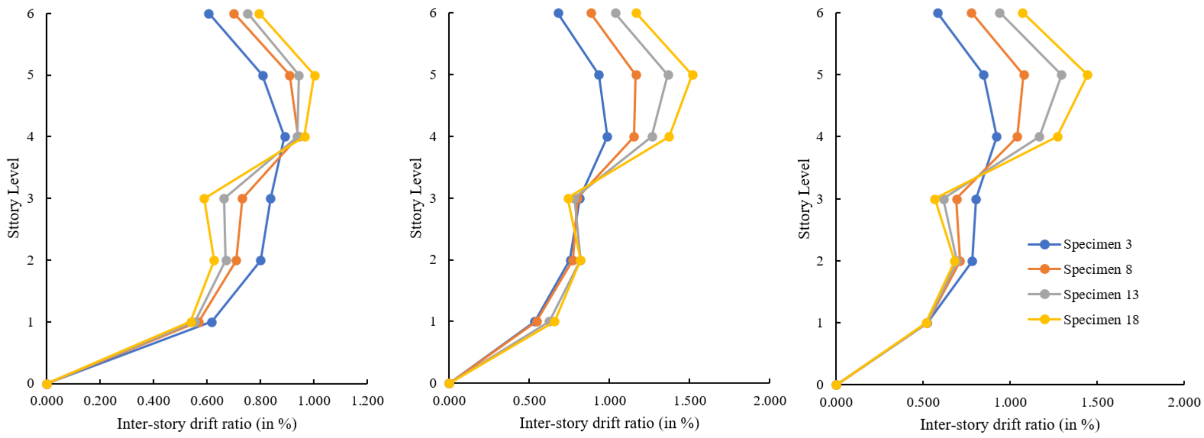


FIGURE 10. Effect of height-to-span ratio to the inter-story drifts value for all specimen

CONCLUSION

To sum up, the influence of the span-to-height ratio to the seismic response and damage distribution is observed. Four specimens of 2D frame building were subjected to three earthquake motions and the inter-story drift ratio and damage index ratio response are examined under seven different span-to height ratios.

The main first noticeable differences were in the natural period of the first mode. The higher span-to-height ratio were followed by the higher natural period. Although the higher span-to-height ratio were made for the specimens, the final definition state of damage index ratio for three specimens were similar, which the tower part suffered the damage distribution more than the lower part, indicated by the damage index ratio is larger than one. For the inter-story drift response, the consistent pattern was obtained, where the inter-story drift was larger together with the increase of span-to-height ratio.

The proposal of damage index ratio which only considering the irregularities indices is useful for the early predictions, however, accurate damage index ratio can be retrieved by considering the value of span-to-height ratio.

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DECLARATION OF COMPETING INTEREST

None

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