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Assessment of nonlinear static and incremental dynamic analyses for RC structures

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Abstract. In this study, seismic behaviour of reinforced concrete buildings using the pushover and incremental dynamic analysis method was investigated. A numerical study was performed for a reinforced concrete frame building. Pushover analysis according to uniform and triangular load shapes and incremental dynamic analyses were performed for selected building. For the nonlinear analysis, three ground motion records were selected to ensure compatibility with the design spectrum defined in the Turkish Seismic Code. The maximum response, dynamic pushover curve, capacity curves, interstorey drifts and moment rotation curves for various element ends of the selected building were obtained. Results were compared each other and good correlation was obtained between the dynamic analyses envelope with static pushover curves for the building.

Keywords: incremental dynamic analysis; pushover analysis; distributed plastic hinge

1. Introduction

Earthquakes, affected the many people, are the one of the most destructive natural hazards. Last ground motions such as Kocaeli (1999), Indian Ocean earthquake (2004), Kashmir earthquake (2005), Sichuan earthquake (2008), Haiti earthquake (2010), Van earthquakes (2011), Gorkha earthquake (2015) caused many loss of lives together heavy collapses and damages. In addition to earthquakes, blast-induced ground vibrations affect buildings (Mahmoud 2014; Öncü *et al*. 2015).

To provide specified performances criteria for the buildings existed current seismic codes is the base of the Performance based earthquake engineering. These criteria depend on the functionality of the buildings. The seismic codes require any damages for structural and non-structural elements for low intensity earthquakes, limit the damages for structural and non-structural elements for medium intensity earthquakes and aim to prevent the overall or partial collapse of buildings for high-intensity earthquakes in order to avoid the loss of life.

Evaluation of the nonlinear response of a building requires a method shows the behavior of building from linear elastic region to yielding stage and until it collapses. For multi degree of freedom systems, determination of nonlinear behaviors can be difficult due to effect of higher

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modes. Incremental Dynamic Analysis (IDA) is generally used to accurate estimation of the nonlinear behavior of buildings. In this method, a set of ground motion records are selected and each record is scaled into multiple intensity levels to cover the entire range of structural response from elastic behavior all the way from linear elastic response to global dynamic instability (Vamvatsikos and Cornell (2002); Dolsek and Fajfar (2005); Han and Chopra (2006); Whan and Chopra (2006); Amirahmad, (2013); Onat *et al*. (2015); Onat *et al*. (2016)).

Also, the other method used for estimation of performance of building is the static pushover analysis. This method is a practical procedure for estimating the structural capacity of buildings in the post-elastic range. Capacity curve of a building shows the relationship between the base shear force and the roof displacement. To obtain the capacity curves, lateral forces are increased monotonically until a certain level of deformation at the top of building is reached. (Chan and Zou (2004); İnel and Özmen (2006); Eslami and Ronagh (2012); Yön and Calayır (2014); Brunesi *et al*. (2015). Louzai and Abed (2015).

In this paper, to evaluate the nonlinear static and incremental dynamic analyses for reinforced concrete buildings a numerical study was carried out for a reinforced concrete frame building. Pushover analysis according to uniform and triangular lateral load shapes and incremental dynamic analyses were performed for selected building. For the nonlinear analysis, three ground motion records were selected to ensure compatibility with the design spectrum defined in the Turkish Seismic Code (TSC). The capacity curves, interstorey drifts, maximum response, dynamic pushover curve and moment rotation curves for various element ends of the selected building were obtained. To more accuracy estimation of nonlinear behavior of structural system distributed plastic hinge approach was used.

2. Distributed plastic hinge model

This approach has been used many researchers (Mwafy and Elnashai (2001); Jeong and Elnashai (2005); Kwon and Kim (2010); Duan and Hueste (2012); Carvalho *et al.* (2013); Yön and Calayır (2015) and Yön *et al.* (2015).

In this model, distributed plasticity accounts the structural element. The structural element is divided in three types of fibers: some fibers are used for modeling of longitudinal steel reinforcing bars; some of fibers are used to define nonlinear behavior of confined concrete which consists of core concrete; and other fibers are defined for unconfined concrete which includes cover concrete. For each fiber, the stress/strain field is determined by using $\sigma - \varepsilon$ constitutive laws according to defined materials.

3. Numerical application

In this study, seismic behaviour of reinforced concrete buildings using the pushover and incremental dynamic analysis method was investigated. For numerical study, a seven-storey and five bays reinforced concrete frame building selected. The total building height is 23.0 m and height of the 1st storey is 5.0 m while the upper ones are 3.0 m. The first, third and last bays are 6.0 m and the second and fourth bays are 5.0 m. The building is located in Z2 soil class and has building importance coefficient of 1.0. Incremental dynamic analyses increased from 0.1g to 0.5g PGA were performed for three various earthquakes. Selected ground motion records were adjusted

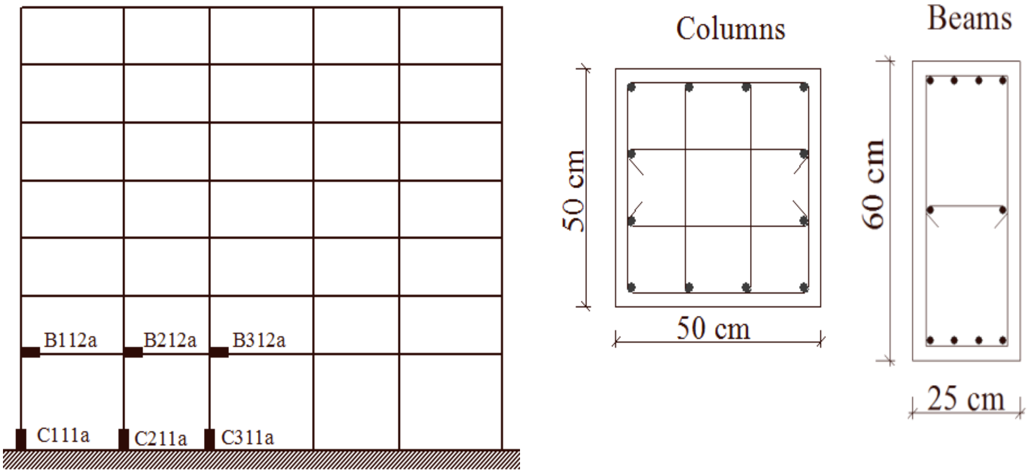
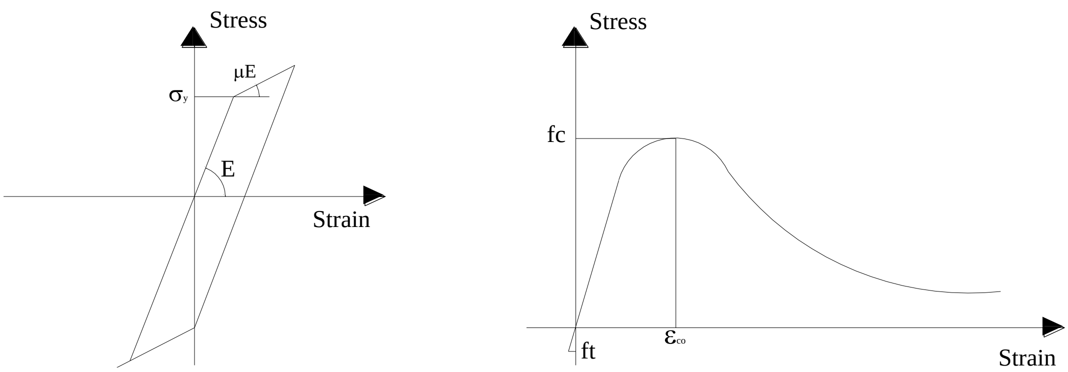


Fig.1 The elevation view of the building and typical element details

Table 1 Confinement parameters of the selected building

	Element Dimensions (cm)	Transverse reinforcement spacing (cm)	Length of confinement zone (cm)	Confinement Factors
Confinement zone of column	50/50	10	50	1.292
Central zone of column		15		1.180
Longitudinal reinforcement of column		12Ø 16		
Confinement zone of beam	25/60	10	120	1.129
Central zone of beam		20		1.029
Longitudinal reinforcement of beam		4Ø 12/4Ø 12		
Web reinforcement		2Ø 12		
Diameter of Transverse reinforcement/reinforcement		Ø 8/S420		



a) Steel b) Concrete

Fig. 2 Material models for steel and concrete

Table 2 Selected earthquake acceleration records for dynamic analysis

Earthquakes	Station	Direction	Date	Magnitude	PGA (g)
Imperial Valley	El Centro Array	E-W	May 19, 1940	7.0	0.313
Kobe	Kjm	E-W	January 16, 1995	6.9	0.821
Kocaeli	Düzce	N-S	August 17, 1999	7.4	0.358

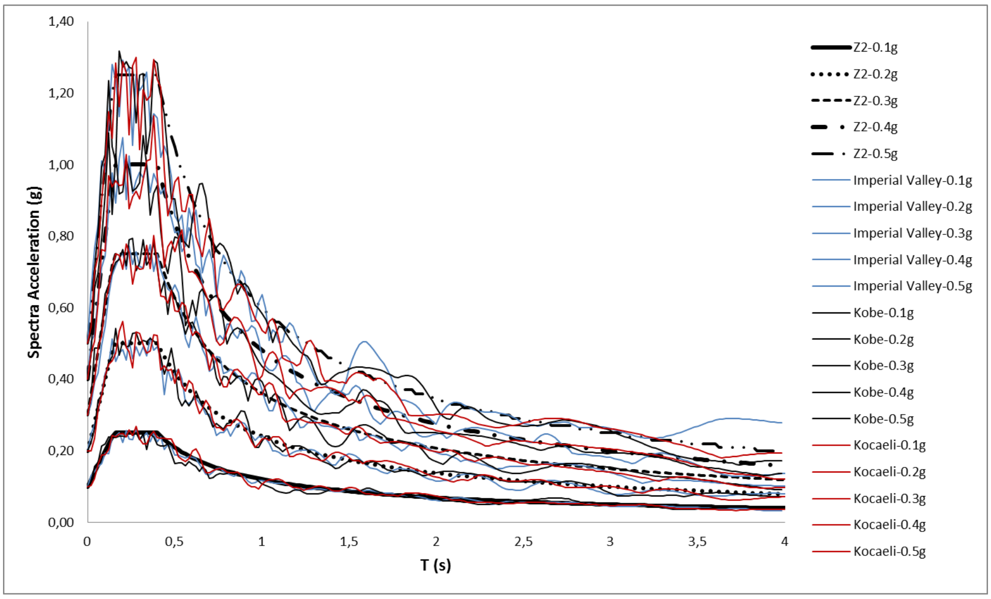


Fig. 3 Response spectra of the earthquake acceleration records scaled according to the elastic design spectrum for Z2 soil class and different ground accelerations

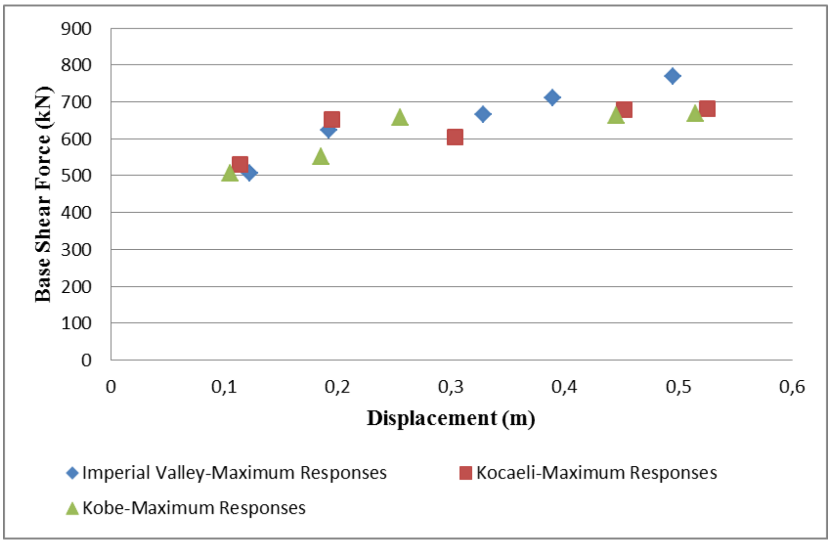
with the design spectrum defined in the TSC. The base of the building was assumed to be rigidly fixed, and the soil compliance and damping properties were not taken into account.The elevation view of the building and typical element details are presented in Fig. 1.

Table 1 shows structural elements dimensions, transverse and longitudinal reinforcements and confinement factors. Fig. 2 shows material models used in nonlinear analyses for steel and concrete. The bilinear elastic–plastic material model with kinematic strain-hardening is used for the steel. The concrete material is defined by the uniaxial confinement concrete model. The confinement effect was calculated using the Mander model (Mander *et al.* 1988).

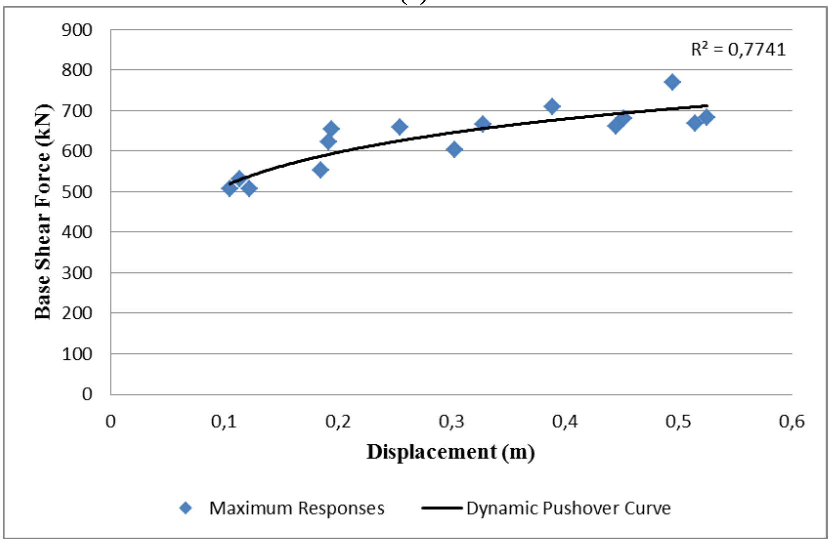
3.1 Earthquake parameters and local site conditions

Selected earthquake accelerations properties are given in Table 2. The seismic records have been provided from the PEER Strong Motion Database and these records have been scaled in frequency content in order to be compatible with the target design spectrum.

The selected earthquake records were scaled according to the elastic design spectrum for Z2 soil class defined in Turkish Seismic Code (TSC). Design spectra obtained from multiplication of elastic spectrum with five ground accelerations from 0.1g to 0.5g are given in Fig. 3. Dynamic effect has been taken into consideration in this way.



(a)



(b)

Fig. 4 (a) Maximum responses for various scaled earthquake records and (b) dynamic pushover curve

Maximum responses obtained from scaled records and the incremental dynamic analysis (IDA) curve was fitted to the maximum responses are presented in Fig. 4(a)-(b). Maximum displacement does not necessarily coincide with the peak base shear in the dynamic analysis. Antoniou and Pinho (2004), suggested a procedure to extract these parameters from the dynamic analysis results. According to this suggestion, the dynamic analysis envelopes consist of the locus of maximum displacement versus corresponding base shear (i.e., peak base shear within a ±0.5 s interval of the instant of maximum displacement occurrence). For 0.1g ground acceleration, the base shear forces occur 500 kN and 0.1m displacemet for all scaled records. The base shears occur 550-650 kN for 0.2 m displacement. For 0.3g ground motions the base shear for Kobe, Kocaeli and Imperial Valley

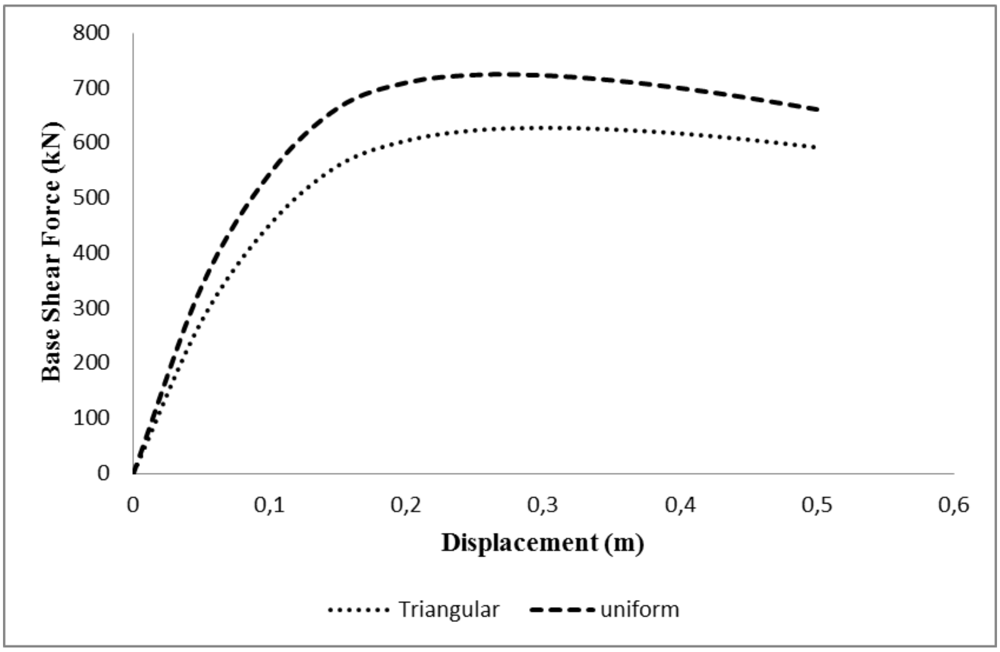


Fig. 5 Capacity curves of the building according to various load shapes

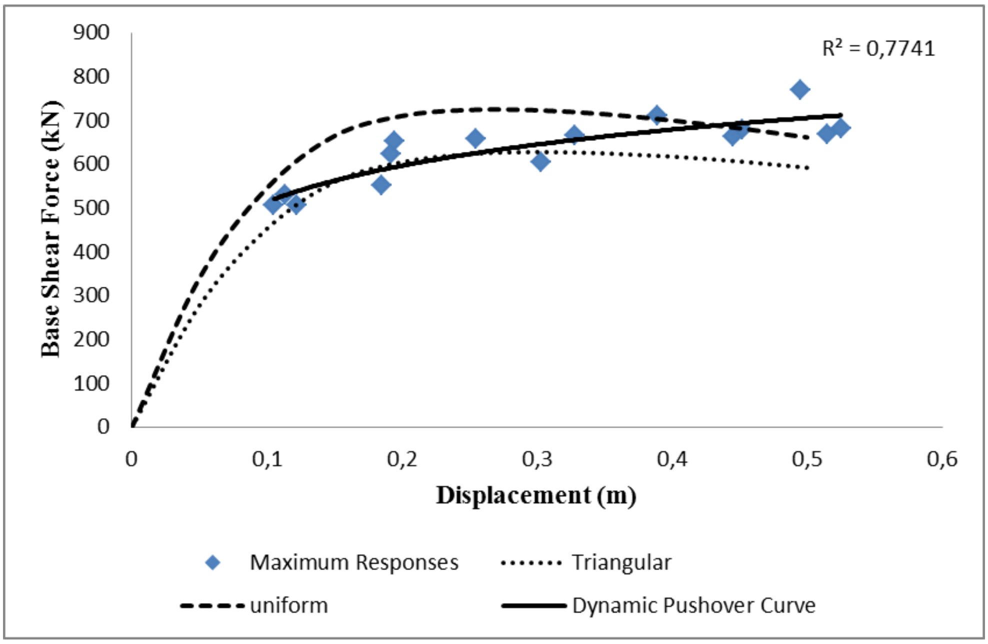
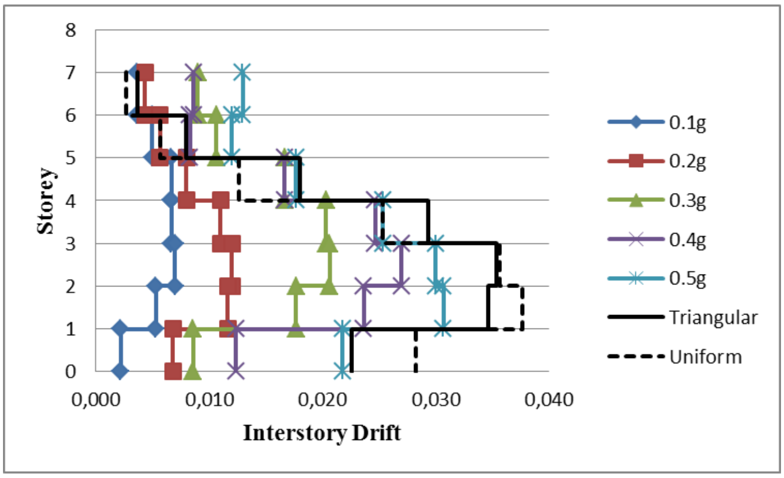
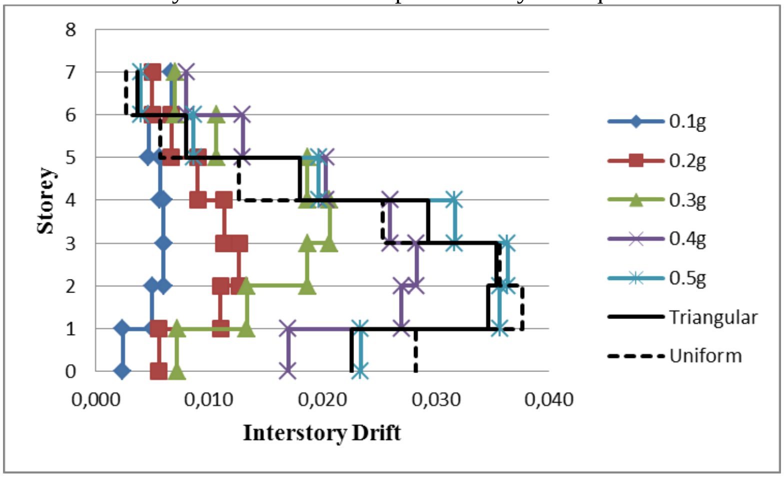


Fig. 6 Comparison of pushover curves obtained various load shapes and dynamic pushover curves

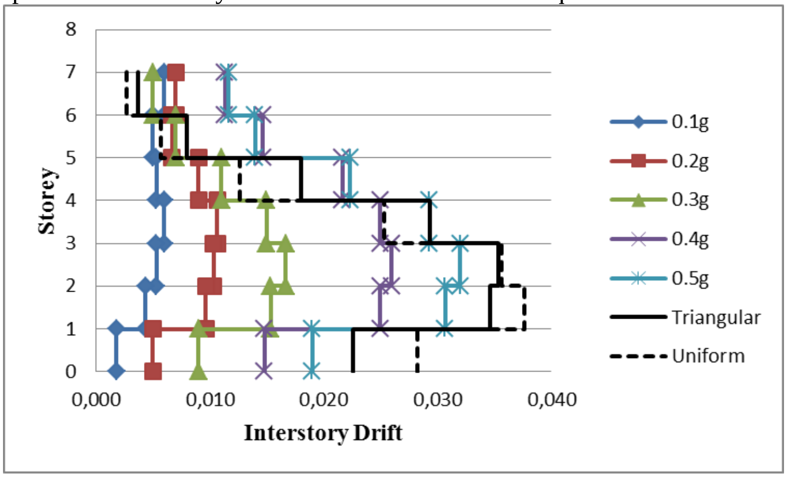
earthquakes occurs approximatly 650 kN, 600 kN and 670 kN, respectively. For this ground motion the displacements are around 0.3 m, approximatly. For 0.4g, the base shears are around 700 kN and the displacements are around 0.4 m. In addition to this, base shear force for Imperial



(a) Comparison of interstory drifts for scaled Imperial Valley earthquake and lateral static loads

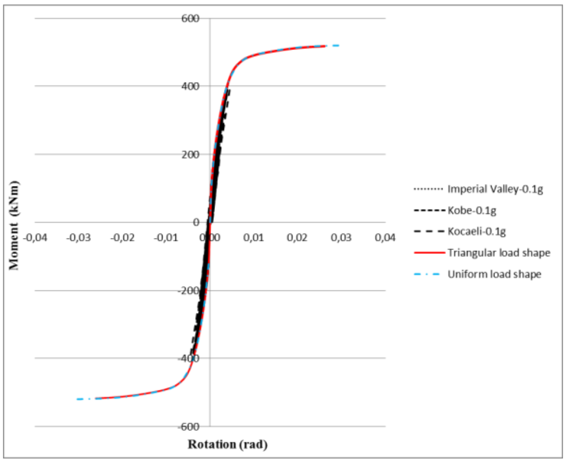


(b) Comparison of interstory drifts for scaled Kocaeli earthquake and lateral static loads

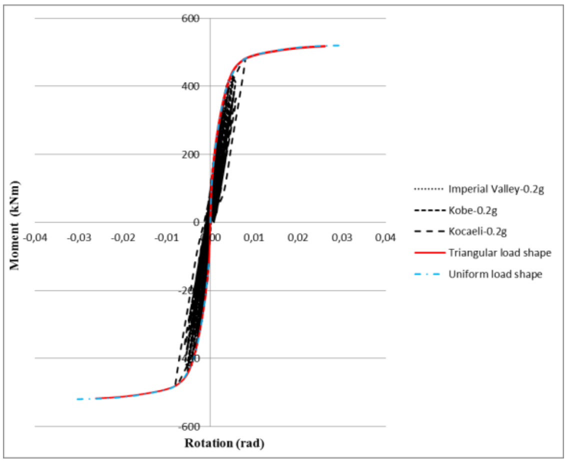


(c) Comparison of interstory drifts for scaled Kobe earthquake and lateral static loads

Fig. 7 Comparison of interstory drifts obtained scaled earthquake records and various lateral static load shapes



(a)



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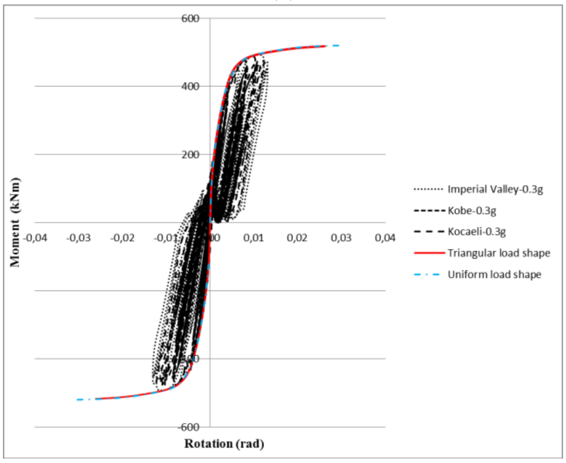

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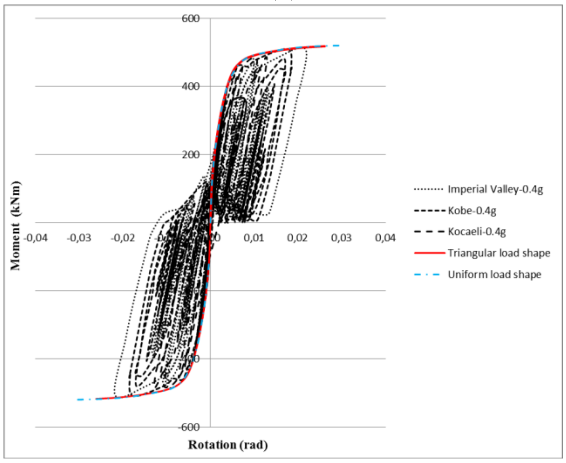

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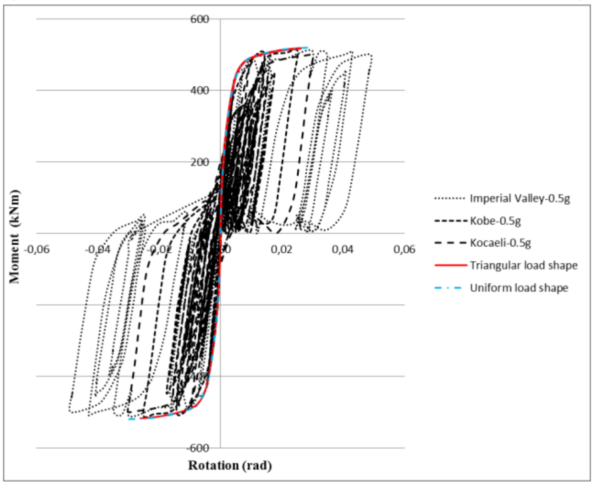


(e)

Fig. 8 Moment-rotation curves of lower end of C111a column under nonlinear static and dynamic loads

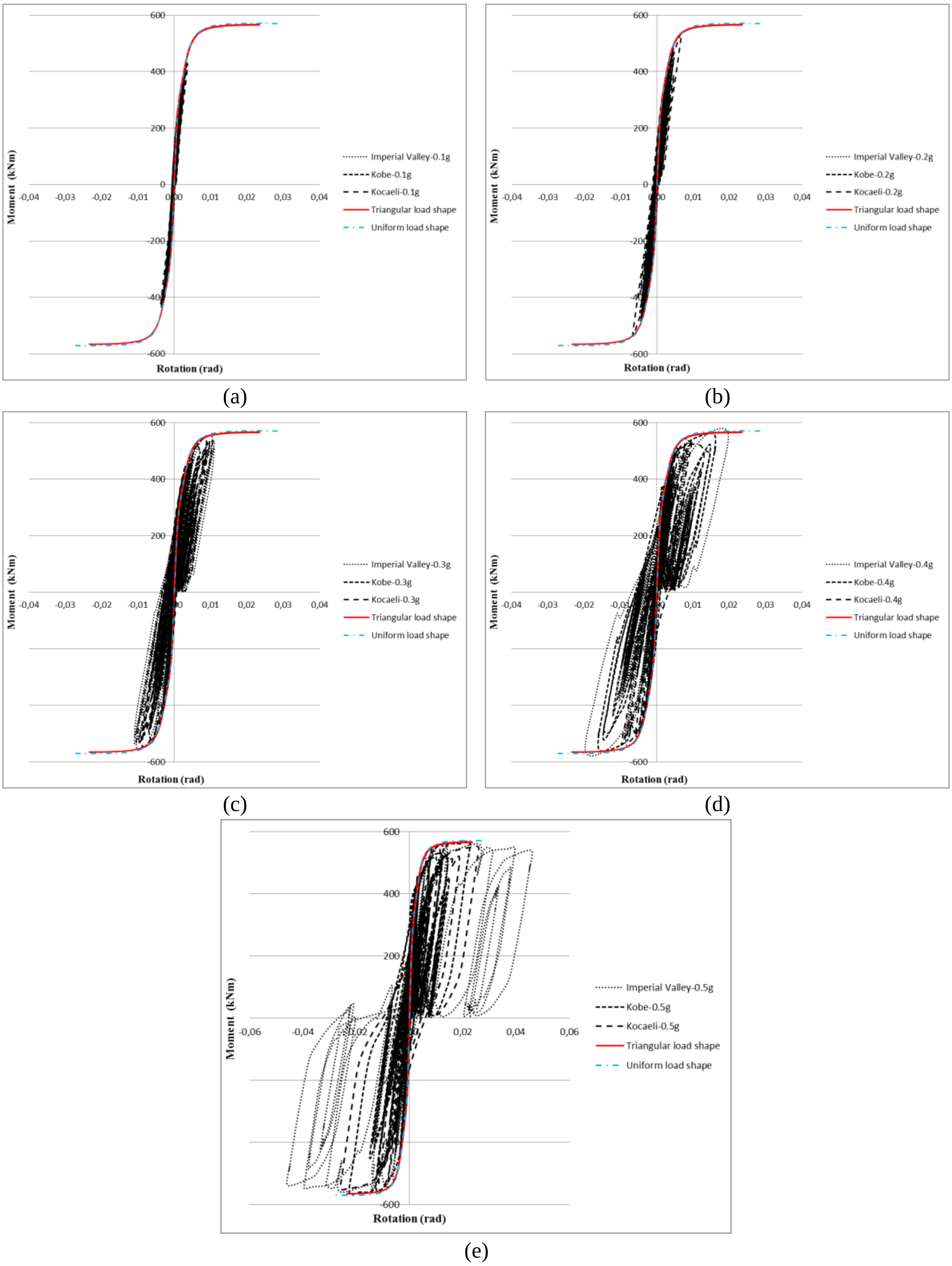


Fig. 9 Moment-rotation curves of lower end of C211a column under nonlinear static and dynamic loads

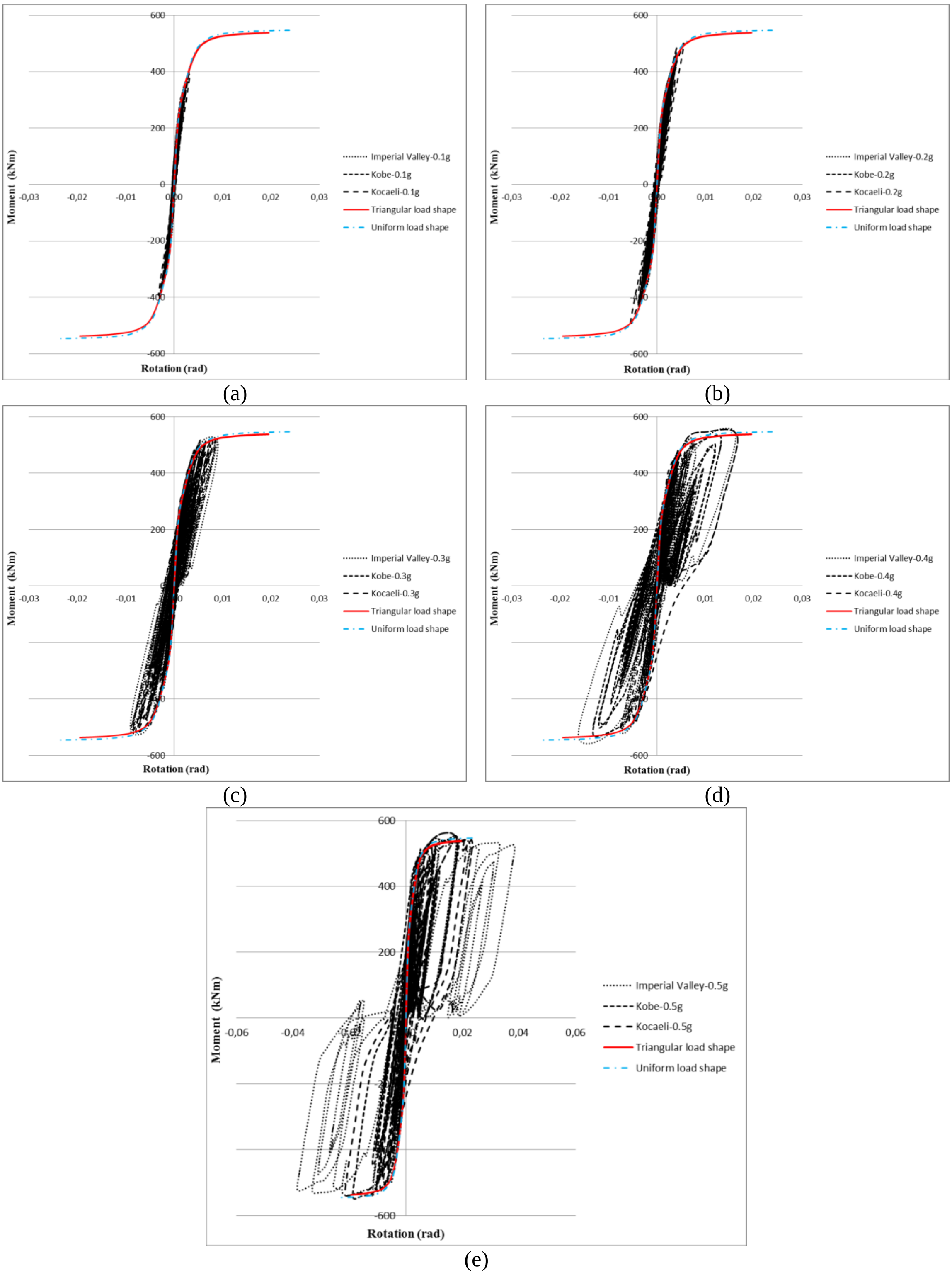
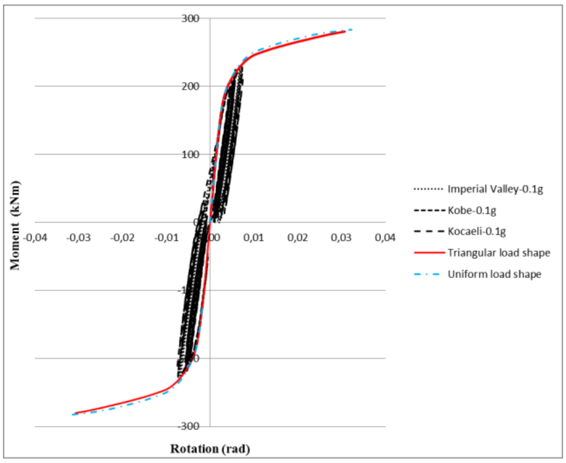
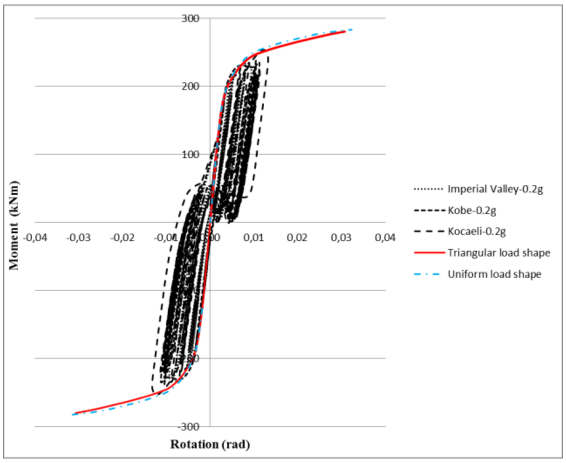


Fig. 10 Moment-rotation curves of lower end of C311a column under nonlinear static and dynamic loads



(a)



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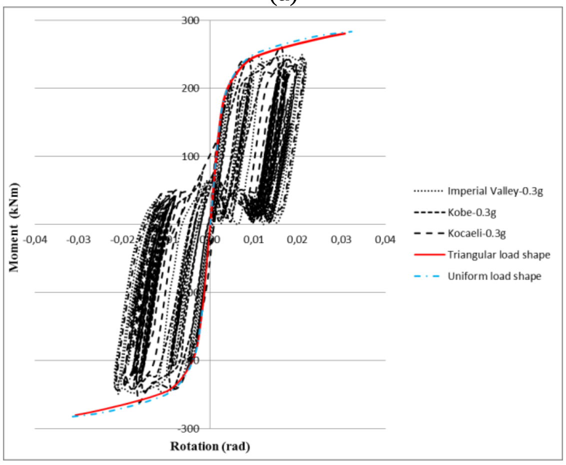

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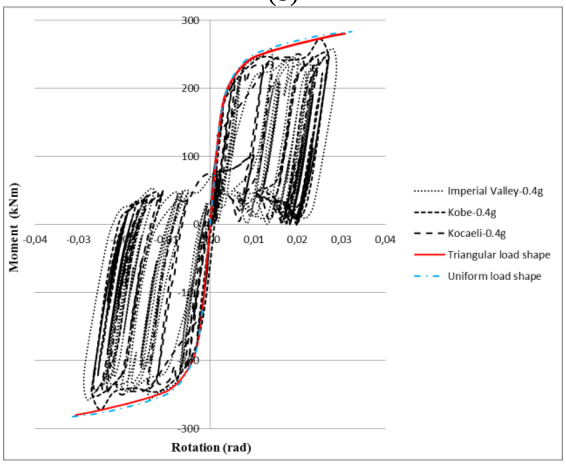

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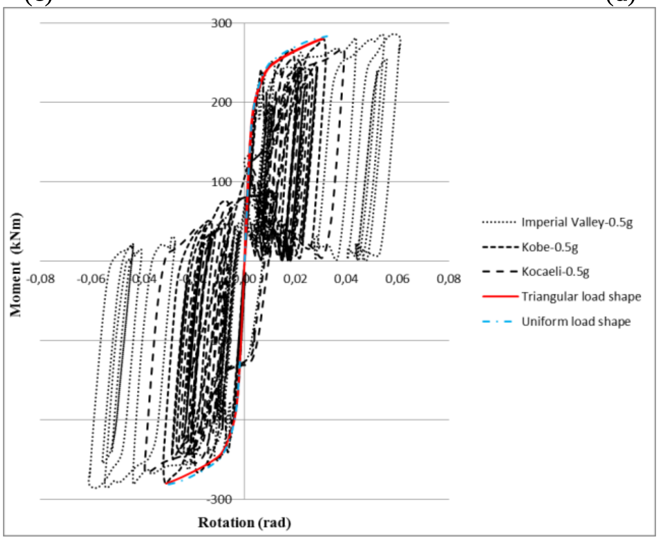
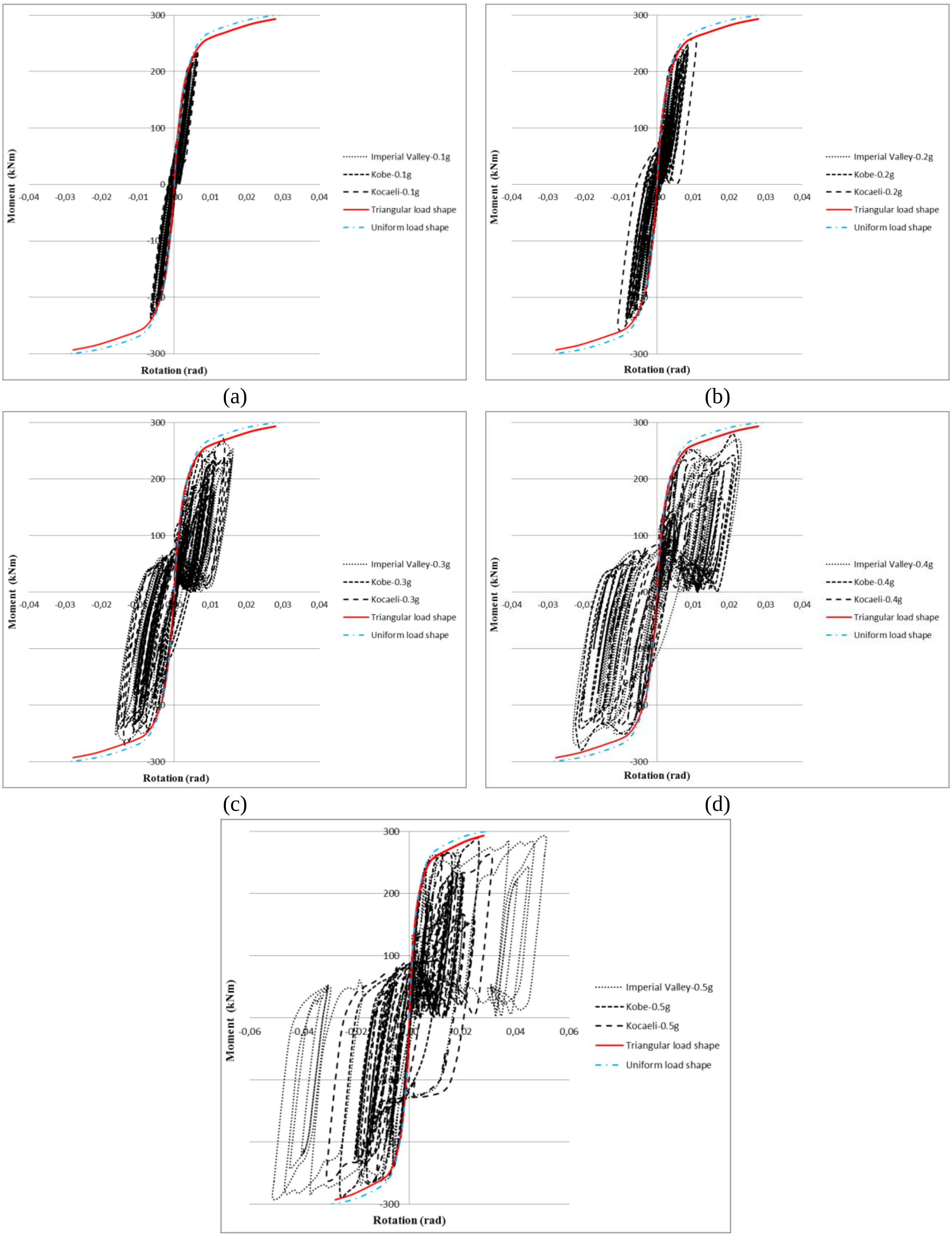


(e)

Fig. 11 Moment-rotation curves of left end of B112a beam under nonlinear static and dynamic loads



(e)

Fig. 12 Moment-rotation curves of left end of B212a beam under nonlinear static and dynamic loads

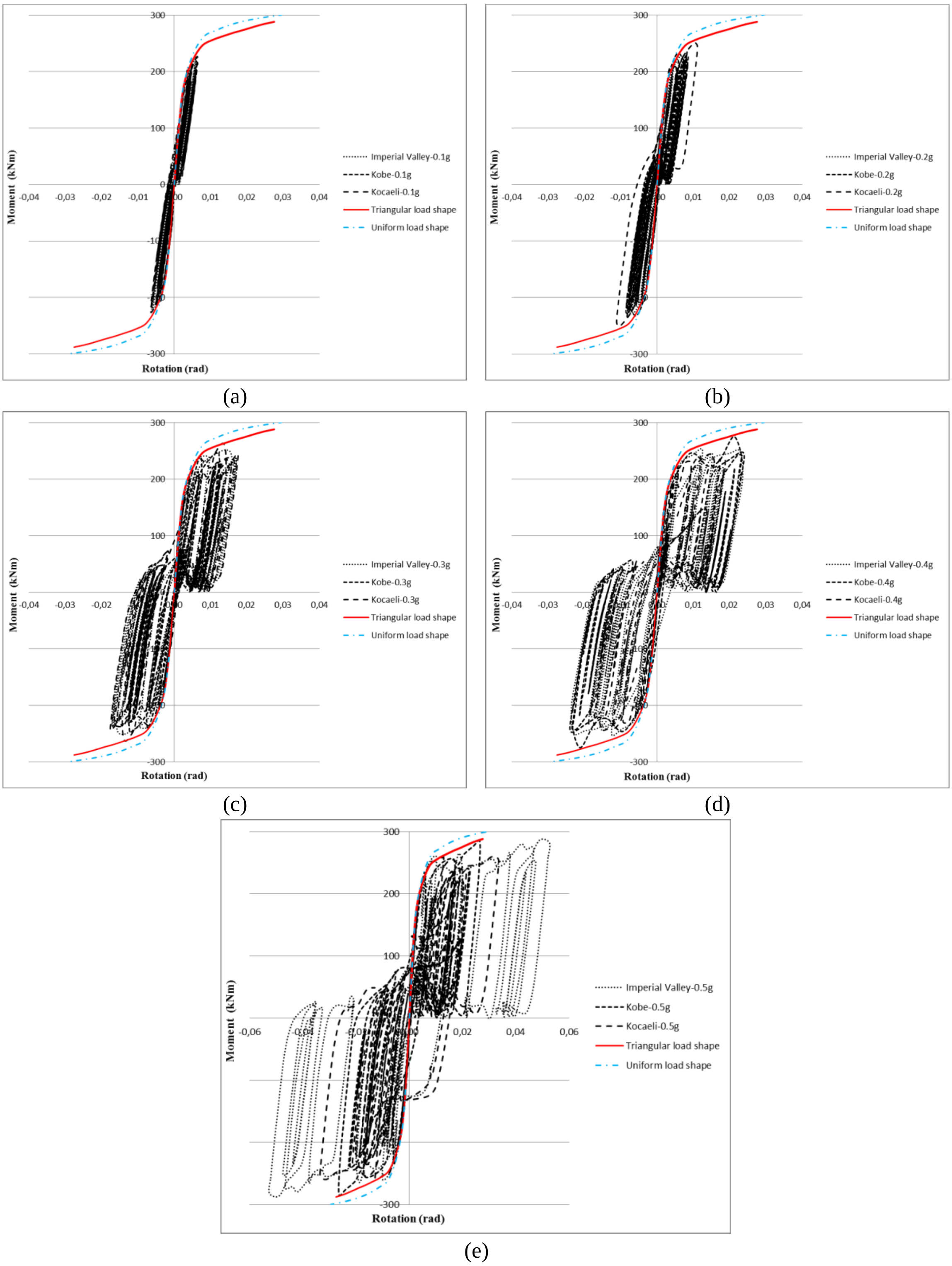


Fig. 13 Moment-rotation curves of left end of B312a beam under nonlinear static and dynamic loads

Valley is close to 800 kN while these forces are around 700 kN for the other earthquakes. It is seen from these figures, base shear forces and displacement increases depend on the increasing of ground acceleration.

Two load shapes are used for the pushover analysis. The first load shape is in a uniform distribution, representing lateral forces that are proportional with the mass. The other one is the triangular distribution shows the first mode shape. Obtained capacity curves of the building for triangular and uniform load shapes are shown in Fig. 5. The uniform load shape yields higher initial stiffness and base shear capacity as regards triangular load shape. Put another way, the uniform load shape gives a better estimation of the ultimate strength of buildings affected by higher modes according to triangular load shape.

A comparison of the capacity curves of the selected building and the maximum response of the incremental dynamic analysis with dynamic pushover curve is presented in Fig. 6. However, the responses low peak ground accelerations are too close or under for the triangular capacity curve of the building. In addition to this, the maximum responses are under the uniform pushover curve. Only the values obtained from 0.5g ground acceleration exceeds the curve. Seismic actions follow the same trend and shape of the pushover curves. The dynamic curve is above the triangular pushover curve for 0.4g and 0.5g while this curve exceeds the uniform pushover curve for 0.5g. The uniform pushover curve gives good result for the nonlinear behavior until 0.5g.

Interstory drifts obtained from Imperial Valley, Kocaeli and Kobe which scaled from 0.1g to 0.5g, triangular and uniform load shapes are given in Fig. 7, respectively. According to the figures, the uniform load shape yields higher interstory drifts at lower stories while this load shape gives less interstory drifts at upper stories according to the triangular load shape. This indicates the lower stories usually have the potential to act large displacement under significant lateral demands for the uniform load shape.

It is seen from this figure, the interstory drifts increase depend on increasing of peak ground accelerations. However, for upper stories the interstory drifts obtained from scaled Imperial Valley and Kobe earthquakes exceed interstory drifts of the triangular and uniform load shapes. But, at lower stories, interstory drifts obtained from these earthquakes are under the interstory drifts of the lateral static load shapes. However, this situation is not seen for Kocaeli earthquake. Interstory drifts obtained from 0.5g peak ground acceleration are exceed the interstory drifts obtained from various lateral static loads except at first and second stories for uniform load shapes.

Moment-rotation curves obtained from IDA and pushover analyses of selected ends of columns and beams named as C111a, C211a, C311a, B112a, B212a and B312a (see Fig. 1) for the building are shown in Figs. 8-13 at the same roof displacement case. These curves are drawn according to peak ground acceleration and same load shapes.

As seen from Figs. 8-10, rotations at the ends of the ground floor column increases according to increasing peak ground accelerations. However, moments are same for triangular and uniform load shape while rotations obtained from uniform load shape are larger than triangular load shape. It is seen that these figures, the moments and rotations for 0.1g, 0.2g, 0.3g and 0.4g obtained from IDA are under the moments and rotations of various lateral static loads. But for 0.5g occurred rotations exceed the rotations of triangular and uniform load shapes.

Figs.11-13 shows moments-rotation curves obtained from scaled earthquakes and various lateral load shapes for beam ends of first floor. As seen these figures, moments and rotations for uniform load shape are larger than triangular load shape. The moments and rotations for 0.1g, 0.2g, 0.3g and 0.4g obtained from IDA are under the moments and rotations of various lateral static loads similarly ends of columns. But for 0.5g occurred rotations exceed the rotations of triangular and uniform load shapes.

4. Conclusions

It is presented to seismic behaviour of reinforced concrete buildings using the pushover and incremental dynamic analysis method, in this study. A numerical application was performed for a sample reinforced concrete frame building. Pushover analysis according to uniform and triangular load shapes and incremental dynamic analyses were performed for the building. The maximum responses, dynamic pushover curve, capacity curves, interstorey drifts and moment rotation curves for various element ends were obtained. According to results;

• Base shear forces and displacement increases depend on the increasing of ground acceleration. Minimum base shears and displacements occur at 0.1g ground accelerations while maximum values occur at 0.5g ground accelerations for all earthquakes.

• The uniform load shape yields higher initial stiffness and base shear capacity as regards triangular load shape. Put another way, the uniform load shape gives a better estimation of the ultimate strength of buildings affected by higher modes according to triangular load shape.

• The uniform load shape yields higher interstory drifts at lower stories while this load shape gives less interstory drifts at upper stories according to the triangular load shape. This indicates the lower stories usually have the potential to act large displacement under significant lateral demands for the uniform load shape. Also, the interstory drifts increases depend on increasing of peak ground accelerations. For upper stories the interstory drifts obtained from scaled Imperial Valley and Kobe earthquakes exceed interstory drifts of the triangular and uniform load shapes. But, at lower stories, interstory drifts obtained from these earthquakes are under the interstory drifts of the lateral static load shapes except Kocaeli earthquake.

• For column ends, rotations obtained from uniform load shape are larger than triangular load shape. But moments are same for triangular and uniform load shape. Moments and rotations for 0.1g, 0.2g, 0.3g and 0.4g ground accelerations are under the moments and rotations of various lateral static loads. But, for 0.5g occurred rotations exceed the rotations of triangular and uniform load shapes. For beam ends, moments and rotations for uniform load shape are larger than triangular load shape. The moments and rotations obtained from incremental dynamic analysis, except 0.5g, are under the moments and rotations of various lateral static loads.

According to the findings, the uniform lateral static loading shows dynamic behaviour of the selected building until 0.5g ground accelerations. To evaluate the accurate behaviour of reinforced concrete buildings, the dynamic pushover envelopes can be obtained and compared with static pushover curve for large intensity earthquakes.

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