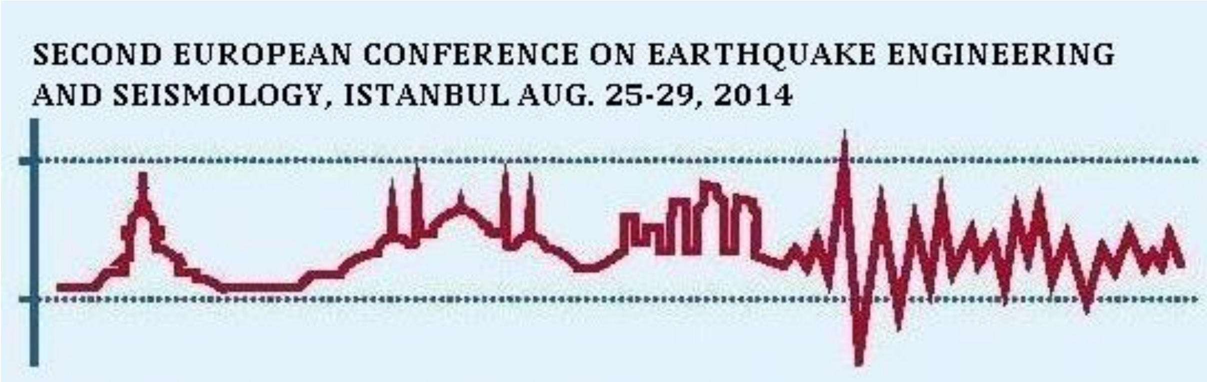

EFFICIENCY OF EXTENDED CAPACITY SPECTRUM METHOD FOR EVALUATING SEISMIC BEHAVIOR OF SINGLE COLUMN RC BRIDGES

Prakit CHOMCHUEN [1] and Virote BOONYAPINYO [2]

ABSTRACT

This study aimed to investigate the efficientcy of the extended conventional capacity spectrum method in evaluating the seismic behavior of the regular single column reinforced concrete bridges, which were widely used in Thailand. The incremental dynamic analysis called incremental capacity spectrum method (ICSM) was proposed and applied in this study. The three artificial ground motions generated corresponding with the design spectrum for the inner-area of Bangkok, Thailand, were scaled to be the series of considered ground motions. The seismic responses of the bridges with three different column heights under the series of considered ground motions were evaluated by the concept of the capacity spectrum method, i.e., method B proposed by ATC-40. The results were shown in form of the comparison between incremental dynamic analysis curve obtained from nonlinear time history of multi-degree-of-freedom model and from ICSM.

The results show that the extended incremental capacity spectrum method can be used to evaluate the acceptable seismic behavior of the regular single column bridges, which dominated by fundamental mode, compared with nonlinear time history analysis. For the less fundamental modal participating mass ratio studied bridges, this method can also be applied to evaluate the seismic behavior by the conservative aspect.

INTRODUCTION

The Incremental Dynamic Analysis (IDA) has been proposed since 2002 (Vamvatsikos and Cornell 2002) as the tool for evaluating the seismic behaviour of the structures. The result of this method called “Incremental Dynamic Analysis Curve (IDA curve)”. It is the relationship between the maximum response of the structures and the corresponding intensity of considered ground motion. Because the maximum response of the structures obtained by the Nonlinear Time History Analysis (NTHA), the IDA is the time consumed method and require high computational price.

Bridges with single column are widely used in Bangkok, Thailand. It is the weak structure under the seismic induced force as seen from many past earthquake events. The seismic design standard has been announced in 2009, then, before that time, the structures may design and construct without considering the seismic effect. The seismic behaviour of these structures should be evaluated.

Several seismic response evaluation methods based on the Capacity Demand Method (CDM) have been proposed to reduce the computational price of NTHA. The popular method is the Capacity Spectrum Method (CSM) proposed by ATC-40 (1996). The capacity of the structures obtained by

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Nonlinear Static Analysis (NSA) was compared with the demand under considered ground motion to evaluate the seismic response.

The IDA is widely used to assess the seismic behavior of the bridges. (Mander et al 2007, Tehrani and Mitchell 2012, Tehrani and Mitchell 2013 and Nazari and Bargi 2014). According to using the NTHA in generating the IDA curve, the computing cost and time still be the problem in using IDA practically. Then, the trend of adapting the nonlinear static analysis for generating IDA curves were interested by many researchers. Vamvatsikos and Cornell (2005) propose the empirical relationship between the standard pushover curve and IDA curve called SPO2IDA. FEMA (2009) publishes the results of performing the IDA of the equivalent single degree of freedom system (ESDOF). To account the higher mode effects in the IDA by ESDOF, Ferracuti et al. (2009) use the displacement-based adaptive pushover to evaluate the seismic responses of the structures by the mean of IDA. Han et al. (2010) apply the MPA to estimate probability of collapse of the structures from the aspect of IDA. Zarfam and Mofid (2011) adapted the modal incremental dynamic analysis (MIDA) to investigate the seismic performance of the RC frames. Jing et al. (2011) propose the method to directly calculate the seismic intensity from the points on the capacity curve by the modified capacity spectrum method.

This study aimed to investigate the extended conventional capacity spectrum method in evaluating the seismic behavior of the regular single column reinforced concrete bridges by the concept of the incremental dynamic analysis called "Incremental Capacity Spectrum Method (ICSM)". The typical configuration of bridges in Bangkok with three different column heights, such as short, medium, and tall, were selected to be the case study. The three artificial ground motions generated corresponding with the design spectrum for Bangkok, Thailand, were scaled to be the series of considered ground motions. The seismic responses of the studied bridges under the series of considered ground motions were evaluated by the concept of the CSM method-B in ATC-40.

CONVENTIONAL CAPACITY SPECTRUM METHOD

The nonlinear static analysis (NSA) is the powerful tool for evaluating the lateral response of the structures. The selected lateral load pattern was applied to the structures. The magnitude of the load starts from zero and increases monotonically until reaching the target. The target can be either target magnitude of the load or failure criteria (instability or collapse of the structures). The Capacity Demand Method (CDM) applies the advantage of the NSA for evaluating the seismic performance of the structures by comparing the lateral capacity with the demand diagram. The demand diagram is the converted version of the response spectrum of single degree of freedom under considered ground motion to the same unit with the lateral capacity diagram. The intersection between the lateral capacity diagram and demand diagram in the elastic range of the capacity is the seismic performance of the structure under the considered ground motion. If the demand diagram intersects the lateral capacity diagram beyond elastic, there are several capacity demand based methods for evaluating the seismic performance but the attractive one is the Capacity Spectrum Method (CSM) proposed by ATC-40 (1996) because it has a step-by-step procedure which can be easily programmed and acceptable result (Chomchuen and Boonyapinyo 2012).

The capacity spectrum method used in this study is the procedure B of ATC-40 (ATC-40 1996). The evaluation of seismic performance of structures is necessary to determine the ductility and total viscous damping from the capacity curve generated by NSA. Typically, the capacity curve will intersect the demand curves corresponding to several viscous damping ratios. Each point on the capacity curve can be associated with an equivalent viscous damping ratio and natural period. The point at which the capacity curve intersects a demand curve associated with the same viscous damping ratio is the performance point which is the seismic response of the monitor point under the considered ground motion.

INCREMENTAL CAPACITY SPECTRUM METHOD

The Incremental Capacity Spectrum Method (ICSM) is the combining of the concept of CSM and IDA. The maximum response under each scaled considered ground motion was evaluated by the mean of CSM to be the Damage Measure (DM). The DMs under the series of scaled considered ground motion will be plotted together with corresponding Intensity Measure (IM) to be the IDA curve. The concept of ICSM was concluded and shown in Fig.1.

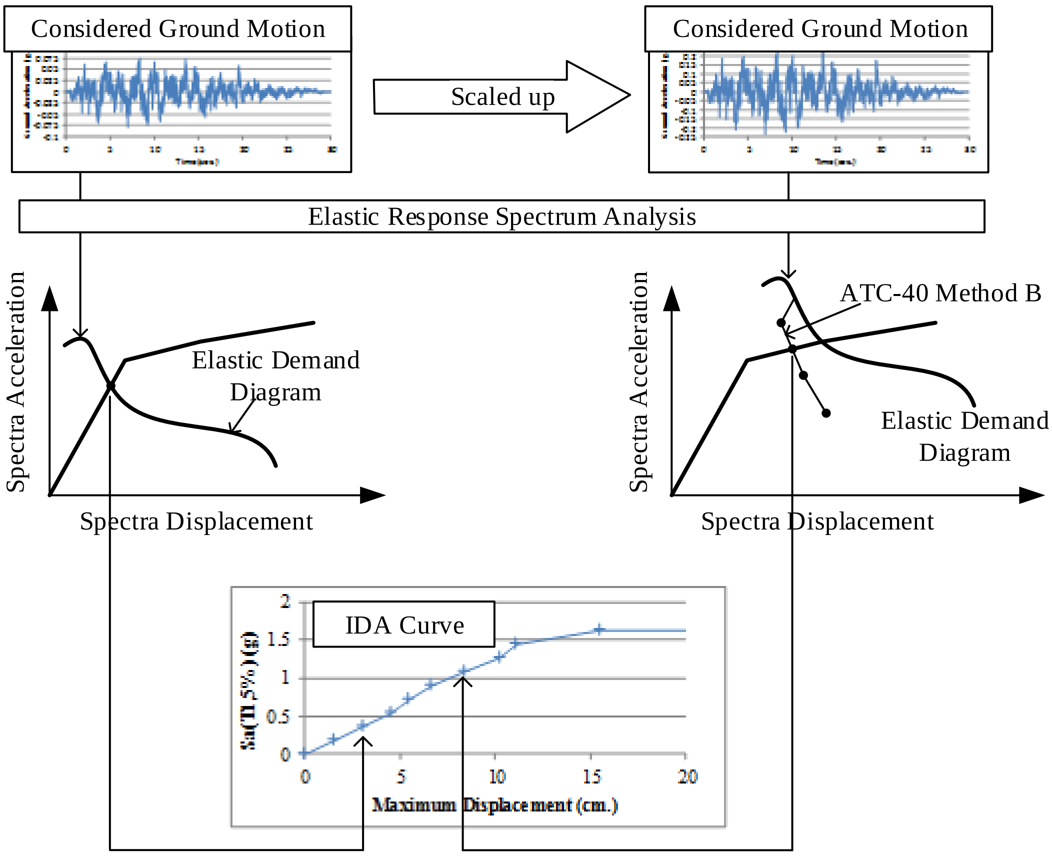


Figure 1. Concept of Incremental Capacity Spectrum Method (ICSM)

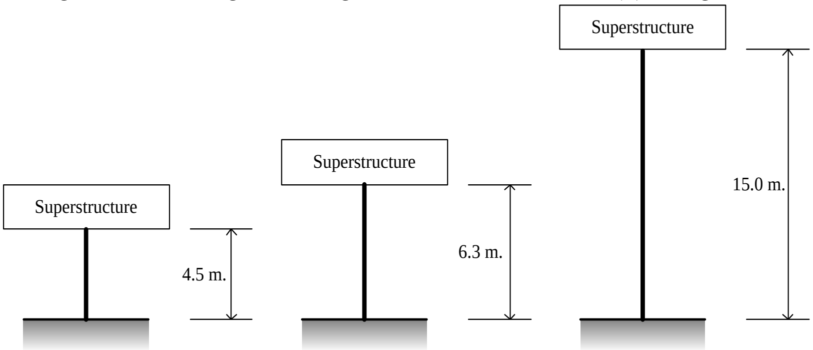
CASE STUDIES OF SINGLE-COLUMN REINFORCED CONCRETE BRIDGES

The single column reinforced concrete bridges were widely used in Thailand. The typical configuration of the bridges is shown in Fig.2(a). This figure also shows that this bridge type was used with various column heights depend on the required function. Therefore, three different column heights with same all other configurations were used to be the case studies in this paper.

Details of Studied Bridges

Structural system of the bridges consists of the superstructure, reinforced concrete top-slab, and single octagon reinforced concrete column (Fig.2(b)). Three different bridge's column heights, i.e., 4.5 m., 6.3 m., and 15.0 m., as shown in Fig.2(c), are used to investigate the effect of column flexibility on the seismic performance of the bridges and efficiency of evaluation methods in evaluating the seismic performance of the bridges with different column flexibilities.

(a) Typical single column bridges in Bangkok, Thailand (b) Bridge column cross-section



(c) Bridges with three different column heights

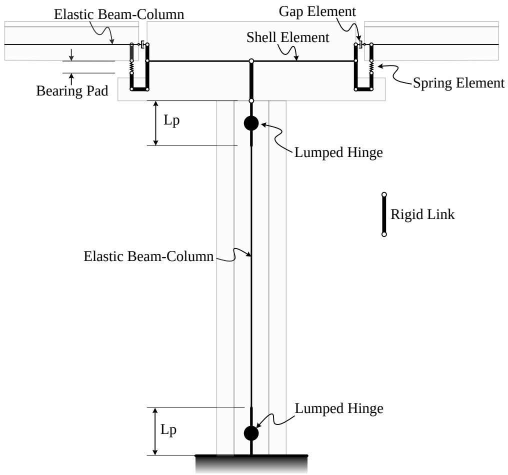
Figure 2. General configurations of studied single column reinforced concrete bridges

Analytical Model of Studied Bridges

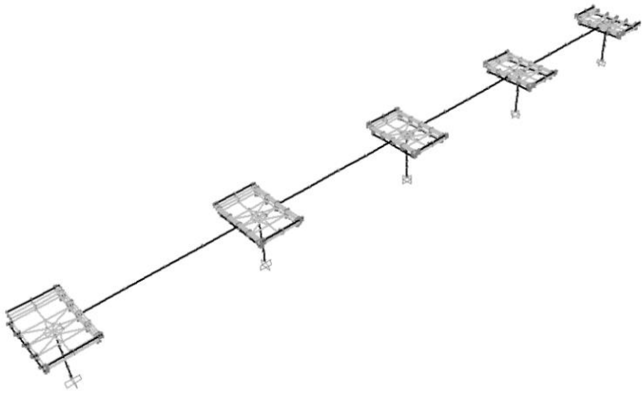
The concept of the analytical model of studied bridges is concluded and shown in Fig.3. The superstructure is assumed to be elastic and modeled by lumped single elastic beam-column elements. Four elements per span are used in this study. The translational mass of the superstructure is automatically calculated and lumped to the nodes of the beam-column element. Rotational mass moment of inertia, which affect to the dynamic properties of the bridges, especially in transverse direction, is also calculated and defined to the nodes of the superstructure elements accordance with Aviram et al. (2008).

The substructure is also modeled by the elastic beam-column element. Inelastic behavior of the studied bridges is modeled by the lumped plastic hinge technique for nonlinear static analysis. The inelastic behavior of the plastic length member is lumped to a point at the center of the element as shown in Fig.3(a). The inelastic behavior which should be defined to the lumped plastic hinge is the Moment-Curvature ($M-\phi$) relationship of the cross-section of bridge's column. For nonlinear dynamic analysis, the non-linear spring is used to model the inelastic behavior of the plastic hinge length instead. Top of the column is rigidly connected to the 1.33 m. thickness cast-in-place reinforced concrete slab as shown in Fig.3(a). It is modeled by elastic shell element. Mass of the top-slab is automatically lumped to the nodes. Because the nodes are distributed along the slab area, the translational mass may produce the torsional rotation of the top slab already. Then, torsional mass is not defined to the top slab.

Bearing system of the studied bridges is modeled by the elastic six degree-of-freedom spring element. The stiffness of each degree of freedom is calculated from the beam theory (Yazdani et al. 2000). The boundary conditions at the bottom of the bridge's columns were assumed to be fixed supports. The analytical model in the computer program is shown in Fig.3(b).



(a) Details of bridge component modeling

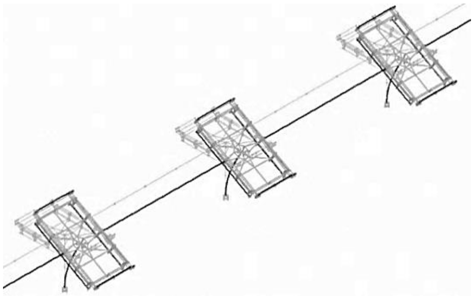


(b) Analytical model of the bridge in computer program

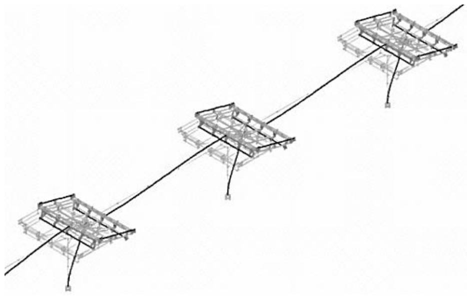
Figure 3. Details of the analytical model of the studied bridges

Dynamic properties of the studied bridges

Dynamic properties of three different bridge's column heights are investigated in this study. The first transverse mode shape and first longitudinal mode shape of studied bridges are shown in Fig.4(a) and Fig.4(b), respectively. The periods and frequencies of all bridges are shown in Table 1. The dynamic properties show that the shorter bridge's column is stiffer than the longer bridge's column and the bridge's behavior in the longitudinal direction is stiffer than transverse direction. The frequencies of the bridge with 6.3 m. column height were compared to the field test data. The frequency of the bridges in the transverse direction and longitudinal direction of field tests is 1.60-2.00 Hz and 2.00-2.80 Hz, respectively. It shows that the frequencies of the analytical model are in the range of the field test data.



(a) Transverse mode shape



(b) Longitudinal mode shape

Figure 4. Fundamental mode of vibration of the studied bridges in transverse and longitudinal direction

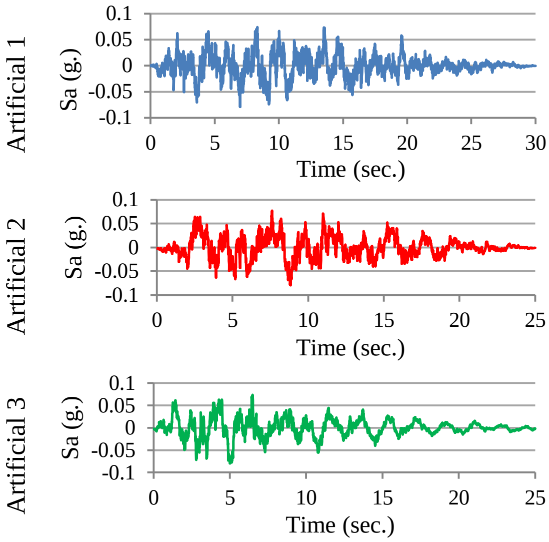
Table 1. Fundamental dynamic properties of vibration of three studied bridges

Column Height (m.)	Transverse Direction			Longitudinal Direction		
	Period (sec.)	Frequency (Hz.)	Modal Participating Mass Ratio (%)	Period (sec.)	Frequency (Hz.)	Modal Participating Mass Ratio (%)
4.5	0.450	2.224	53.3	0.272	3.679	66.2
6.3	0.610	1.640	68.3	0.358	2.796	87.1
15.0	1.746	0.573	86.6	0.980	1.020	92.8

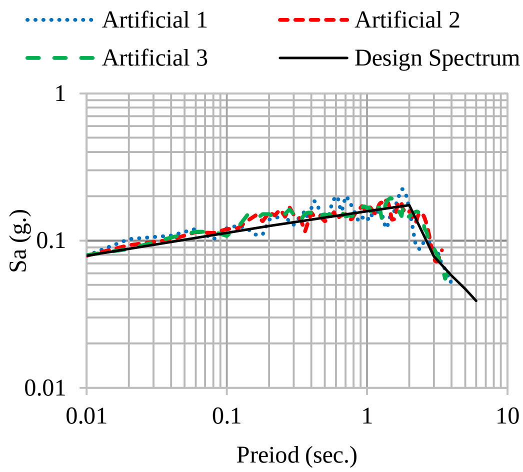
Table.1 also contains the modal participating mass ratios of the studied bridges. Considering the transverse direction which is the weakest direction, the fundamental mode dominates about 86% of total mass for the studied bridge with tall column. The influence of the domination of fundamental mode of vibration decreases when the bridge's height decreases. It should be noted that the bridge with short column (stiff bridge) should consider the higher mode effect.

ARTIFICIAL GROUND MOTİONS

FHWA (2006) suggests that the maximum response of the three ground motions should be used for evaluating the seismic performance of the bridges. This study uses three artificial ground motions, Fig.5(a), generated corresponding to the design spectrum for the inner area of Bangkok specified in the seismic resistance design standard of Thailand (DPT) (2009) in evaluating seismic performance of the studied bridges. The design spectrum for Bangkok area is shown in Fig.5(b). The response spectrums of the artificial ground motions were compared to the design spectrum as shown in Fig.5(a).



(a) Three artificial ground motions



(b) Comparison of response spectrum of generated ground motions with the design spectrum

Figure 5. Artificial ground motions generated corresponding with the design spectrum for the inner area of Bangkok

INCREMENTAL DYNAMIC ANALYSIS OF MDOF STUDIED BRIDGES

To verify the efficientcy of ICSM in evaluating the seismic performance of the studied bridges, the IDA of MDOF in this study was achieved by SAP2000 program. The concept of this method is shown in Fig.6. Selected intensity measurement (IM) of this study is the spectrum acceleration at the fundamental mode of the structures with 5% damping ratio. Each IM of scaled ground motions were plotted together with the corresponding maximum transversal displacement of the top of the middle column to be the incremental dynamic analysis curve (IDA curve) as shown in Fig.7.

Fig.7 shows that the bridge with shorter column has more seismic performance than the longer column height. On the other word, when considered only the flexural failure, the performance of the bridges decreases when the height of bridge's column increases.

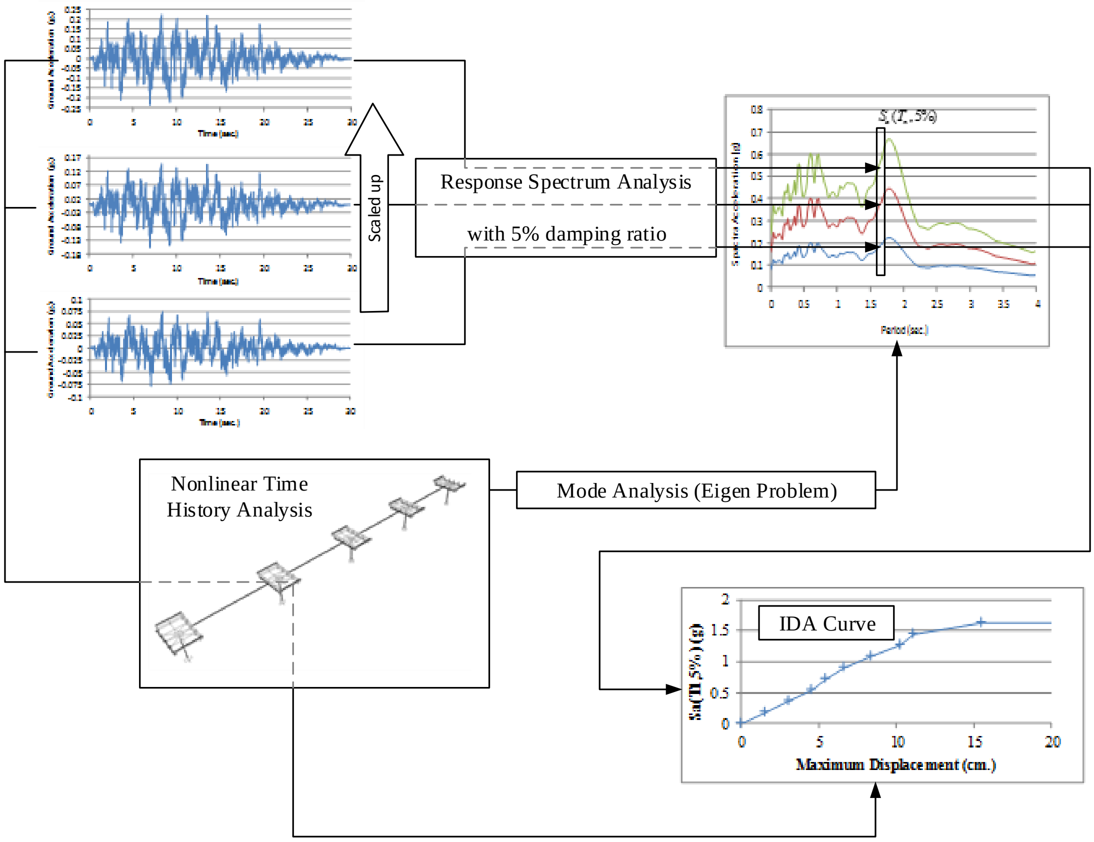
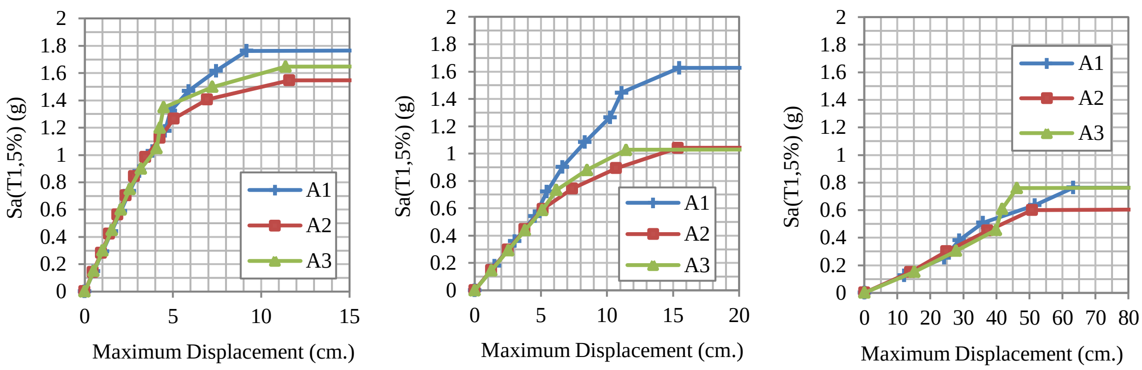


Figure 6. Concept of incremental dynamic analysis of MDOF model of the studied bridges



(a) 4.5 m. column height (b) 6.3 m. column height (c) 15.0 m. column height

Figure 7. IDA curves of three studied bridges under three artificial ground motions in transverse direction

NONLINEAR STATIC ANALYSIS OF STUDIED BRIDGES

Lateral Load Patterns

It is obviously that the lateral load pattern is an important factor that influences on the lateral capacity of the structures. FEMA 356 (2000) have suggested that at least two lateral load patterns should be considered. These two load patterns are selected from two groups separately. The first group includes an inverted triangle and the fundamental modal shape load pattern. The second group includes a lateral load pattern that is proportional to mass and adaptive loading pattern.

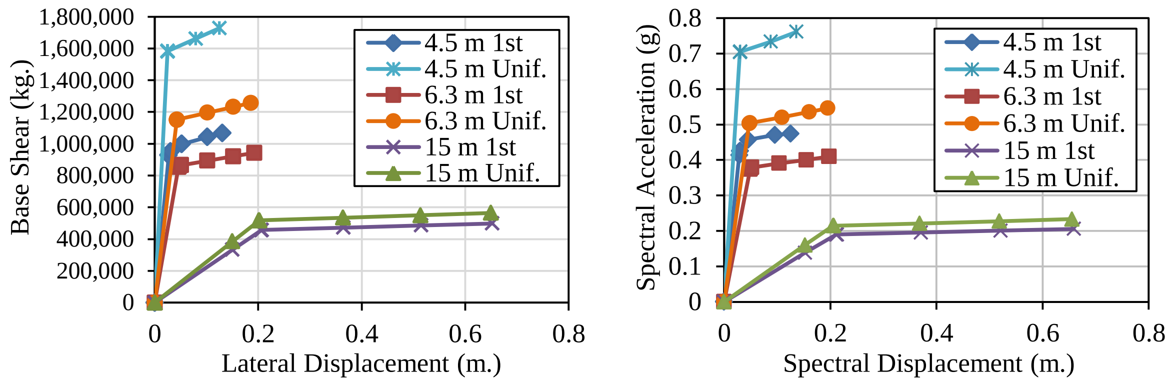
This study uses two built-in lateral load patterns in SAP2000, i.e. 1st mode load pattern (1st) to be the load pattern from the first group and uniform acceleration load pattern (Unif) to be the mass proportional load pattern, to study the effect of load patterns on the lateral capacity of the bridges.

The 1st is the fundamental mode lateral load pattern. The lateral force at any degree-of-freedom is proportional to the product of the amplitude of the fundamental mode and the mass at that node.

The pattern for the mass proportional load in this study is the Unif. The unit acceleration was automatically assigned to all degree-of-freedom corresponding to the defined direction (CSI 2011). The pattern of force which is the product of mass and unit acceleration (mass proportional distribution) is used to be the Unif.

Lateral Capacities of Studied Bridges

Applying two selected load patterns separately to the MDOF model of studied bridges, the NSA of all studied bridges was carried out by SAP2000. The relationship between the base-shear and lateral displacement of the top of the middle column of every load increments were plotting together to be the lateral capacity of the bridges. The results are shown in Fig.8(a). To evaluate the seismic performance of the bridges by the CSM, the lateral capacity curves should be transformed to the Acceleration-Displacement Response Spectrum (ADRS) format called lateral capacity diagrams, as shown in Fig.8(b).



(a) Lateral capacity curve (b) Lateral capacity diagram

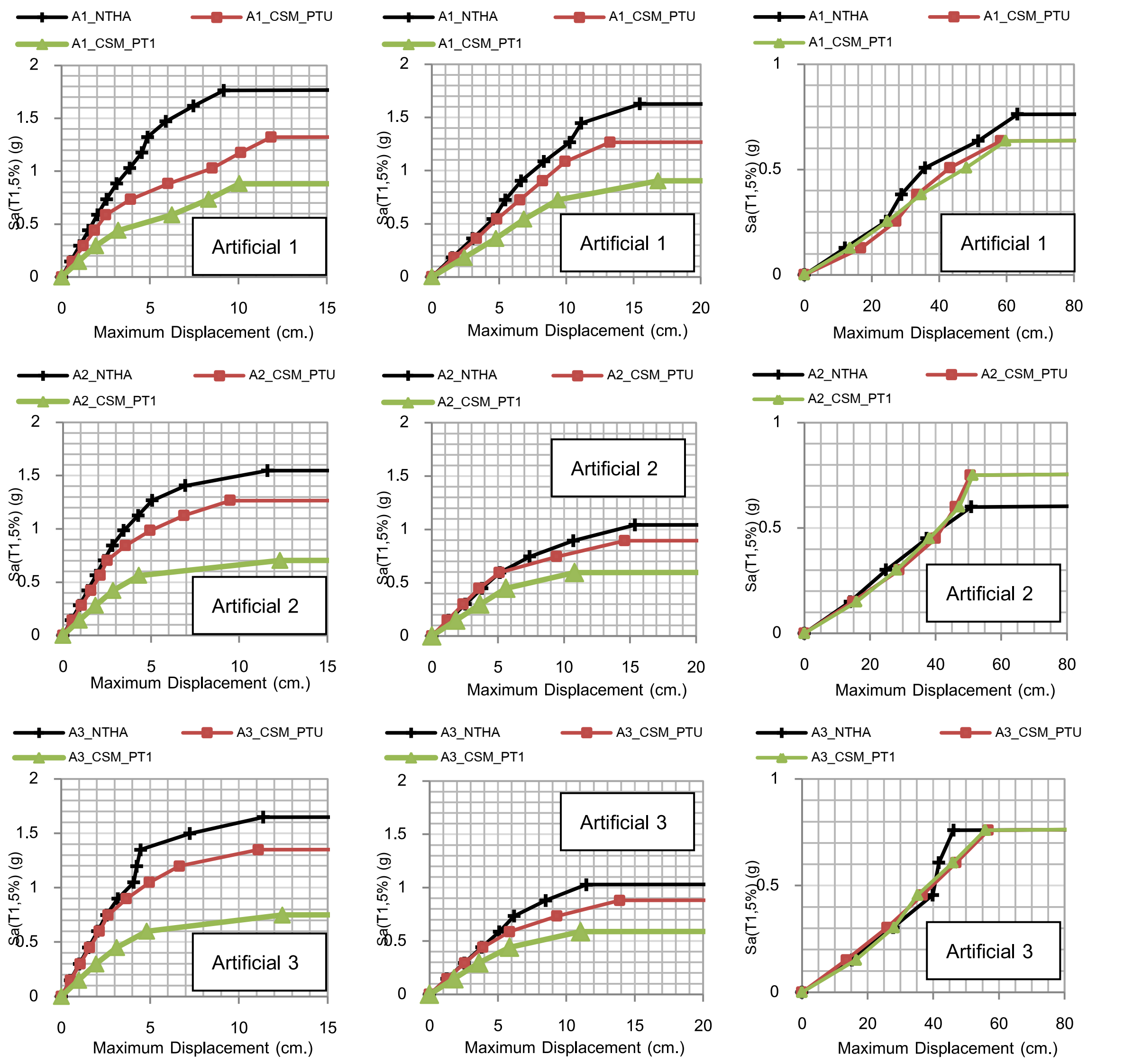
Figure 8. Lateral capacity of three studied bridges in transverse direction

The modal participating mass ratio of the bridge with short, medium, and tall column is 53.3, 68.3, and 86.6 percent, respectively. For all bridges, the maximum capacity obtained from Unif higher than those obtained from 1st. It is about 1.62, 1.33, and 1.13 times for the bridge with short, medium, and tall column respectively.

The results shown that different lateral load pattern leads to the highly different lateral capacity of the bridge structures, especially the bridge with least modal participating mass ratio in the considered direction. The differentiation of the lateral capacity of the bridges decrease when the modal participating mass ratio increases. It is the results of higher mode effect.

INCREMENTAL CAPACITY SPECTRUM METHOD OF STUDIED BRIDGES

The ICSM of three studied bridges under three considered ground motions were carried out in this study. The results are shown in the Fig. 10. The IDA curve obtained by ICSM with the lateral capacity generated from the 1st is referred as CSM_PT1 while IDA curve obtained by ICSM with the lateral capacity generated from the Unif is referred as CSM_PTU.



(a) 4.5 m. column height (b) 6.3 m. column height (c) 15.0 m. column height

Figure 10. Comparison of IDA curve in transverse direction obtained from ICSM and NTHA of MDOF of three studied bridges under three artificial ground motions

EFFICIENTCY OF ICSM IN EVALUATING SEISMIC BEHAVIOUR OF STUDIED BRIDGES

The efficiency of ICSM in evaluating the seismic performance can be investigated by comparing the IDA curve obtained from ICSM with one obtained from NTHA of MDOF as shown in Fig. 10. The IDA curves of the short bridge column from ICSM show the weaker strength under earthquake than the NTHA especially when the lateral capacity from 1st is considered as shown in Fig.10(a). Figs.10(b)-(c) show that the accuracy of ICSM increase when the height of bridge column increase.

For the bridges with short and medium column height, Figs.10(a)-(b) also shows that the IDA curves by ICSM with lateral capacity obtained from uniform acceleration load pattern (CSM_PTU) agree well with elastic responses with NTHA while the IDA curves by ICSM with lateral capacity obtained from 1st mode load pattern (CSM_PT1) give the underestimated capacity for every point. Even if the CSM_PTU agrees well with NTHA in the elastic range, it results in the underestimated capacity after the bridge's structure yield. Unlike Figs.10(a)-(b), Fig.10(c) shows that both CSM_PTU and CSM_PT1 give the corresponding well results with NTHA.

CONCLUSIONS

For attractiveness of the CSM in evaluating the seismic response, it was used to evaluate the seismic response of three different column heights studied bridges under the scaled series of three considered ground motions in this study. The results were shown in form of IDA curves. It were compared to the IDA curves obtained from the NTHA of MDOF of the studied bridges to investigate the efficiency of the ICSM in evaluating the seismic behaviour of the regular single column bridges. The study leads to following conclusion.

The ICSM can be used efficiently for the bridge with dominated by the first mode of vibration. In other words, the ICSM can be used to evaluate the seismic behavior of the single column RC bridges by the conservative aspect.

The suitable lateral load pattern should be seriously concerned if the ICSM was selected to use for evaluating the seismic behavior of the single column bridges, especially for the bridge which is affected from the higher mode contribution.

ACKNOWLEDGMENTS

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