EFFECTS OF LATERAL LOAD PATTERNS ON THE SEISMIC BEHAVIOR OF RC BRIDGES BY INCREMENTAL DYNAMIC ANALYSIS

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ABSTRACT

The incremental dynamic analysis (IDA) by the concept of equivalent single degree of freedom (ESDOF) is applied to the bridge structures in this study to observe the effects of two different lateral load pattern, i.e., 1st model load pattern (1st) and Uniform acceleration load pattern (Unif), on the seismic behavior of the RC bridges under three ground motions generated corresponding with the design spectrum for the inner area of Bangkok, Thailand. Three different bridge's column heights were considered to investigate the effect of the different substructure flexibilities on the accuracy of using IDA by ESDOF to evaluate the seismic behavior of the bridges. The results show that the different lateral load patterns influences on the different lateral capacity of the bridge especially when the rotational mass moment of inertia was considered. The different lateral capacity leads to different incremental dynamic analysis curve (IDA curve). The IDA curves show that the ESDOF with lateral capacity from Unif give slightly stiffer seismic behavior than the nonlinear time history analysis of whole bridges while the ESDOF with lateral capacity from 1st give significantly weaker for the bridge with short column height. However, the effect of different lateral load pattern on the IDA curves decreases when the bridge's column height increases.

Keywords: Incremental Dynamic Analysis, ESDOF, Load Pattern, RC Bridge, Seismic Behavior.

1. INTRODUCTION

The incremental Dynamic Analysis (IDA) is the useful method for evaluating the seismic performance of the structures until collapse (Vamvastikos and Cornell 2005). Nonlinear Time History Analyses (NTHA) of the structures under monotonic scaled considered ground motions were performed to evaluate the Damage Measurement (DM). Plotting between Intensity Measurement (IM) of the scaled ground motions and DMs called incremental dynamic analysis

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curve (IDA curve). It gives an overview of the seismic behavior of the structures under earthquake until collapse. However, one disadvantage of this approach is the computation-time because the analyzing of whole structures by the NTHA is the time consumed especially when the highly nonlinear components were considered. To reduce this disadvantage and make the IDA more practical, the concept of Equivalent Single Degree of Freedom (ESDOF) was adopted (FEMA P440A 2009; Kalkan and Chopra 2010). The basis of ESDOF originates from the concept of Nonlinear Static Analysis (NSA) approach (ATC-40 1996). It assumes that the considered point of the structure behaves as one directional lateral displacement under lateral excitation such as seismic induced force. The lateral displacement of the structures can be evaluated by the nonlinear static analysis or known as Pushover Analysis (PA). It is not only the basic IDA by ESDOF but also the advance of the IDA based on the ESDOF, such as modal incremental dynamic analysis, is also investigated and used to evaluate the seismic performance of the buildings (Han and Chopra 2006, Zarfam and Mofid 2011).

The bridge is one of the important structures which should be evaluated for the seismic performance. The using of IDA by ESDOF for evaluating the seismic performance of this kind of structures has not yet clearly explained. This paper applies the concept of IDA by ESDOF to evaluate the seismic behavior of the reinforced concrete bridges. Three ground motions generated corresponding with the design spectrum for the inner area of Bangkok Thailand were considered. Three different bridge's column heights also consider to observe the effect of the different substructure flexibilities on the accuracy of using IDA by ESDOF to evaluate the seismic performance of the bridges. The effects of two different lateral load patterns used in generating the lateral behavior of ESDOF on the accuracy of IDA by ESDOF for the studied bridges are the mainly focus of this study.

2. SINGLE LEG REINFORCED CONCRETE BRIDGES

The regular octagonal single column reinforced concrete bridges which have used in the part of the expressway phase 1 since 1976 in Bangkok, Thailand, as show in Figure 1(a), were chosen to be the case studies in this study. Three different bridge's column heights, i.e., 4.5 m., 6.3 m., and 15.0 m. as shown in Figure 1(c) with 25 m. span length, 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. The fundamental frequency of the bridges is also shown in Figure 1 (c).

The superstructure of the studied bridges is the 18 cm. thickness reinforced concrete slab placed on the top of five pre-stressed concrete I-girders. The substructure of the studied bridges is the octagon reinforced concrete column with 1.33 m. thickness top slab. The cross-section of the column is 1.60 × 1.60 m as shown in Figure 1(b). The connecting system between substructure and superstructure is bearing pads.

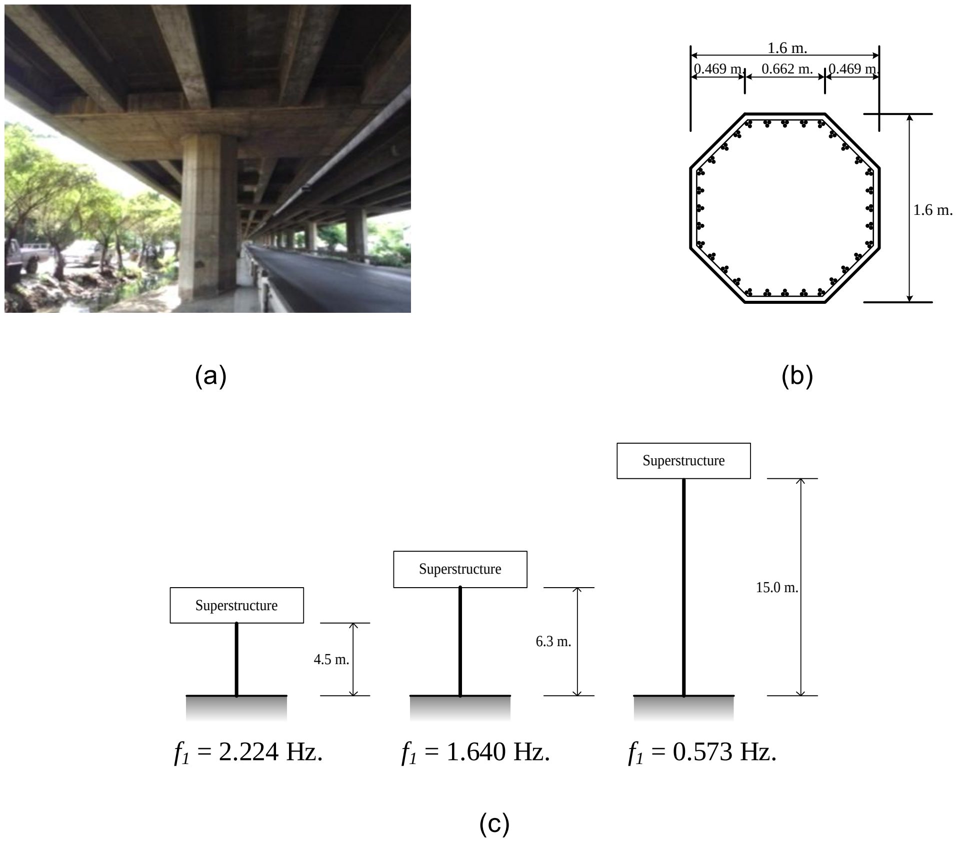


Figure 1: Case studies of single leg column RC bridge, (a) typical configuration of oldest expressway in Bangkok, Thailand, (b) octagonal cross-section of bridge's column, and (c) bridges with three different column heights and fundamental frequencies in transverse direction.

2.1. Analytical model of studied bridges

The analytical model of studied bridges is shown in Figue 2. 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 lumped superstructure elements (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. The inelastic behavior of the plastic length member is lumped to a point at the center of an element as shown in Figure 2(a). The inelastic behavior which should be defined to the lumped plastic hinges is the Moment-Curvature ($M-\phi$) relationship of the cross-section of bridge's column. Top of the column is rigidly connected to the 1.33 m. thickness cast-in-place reinforced concrete slab as shown in Figure 2. It is modeled by elastic shell element. Mass of 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.

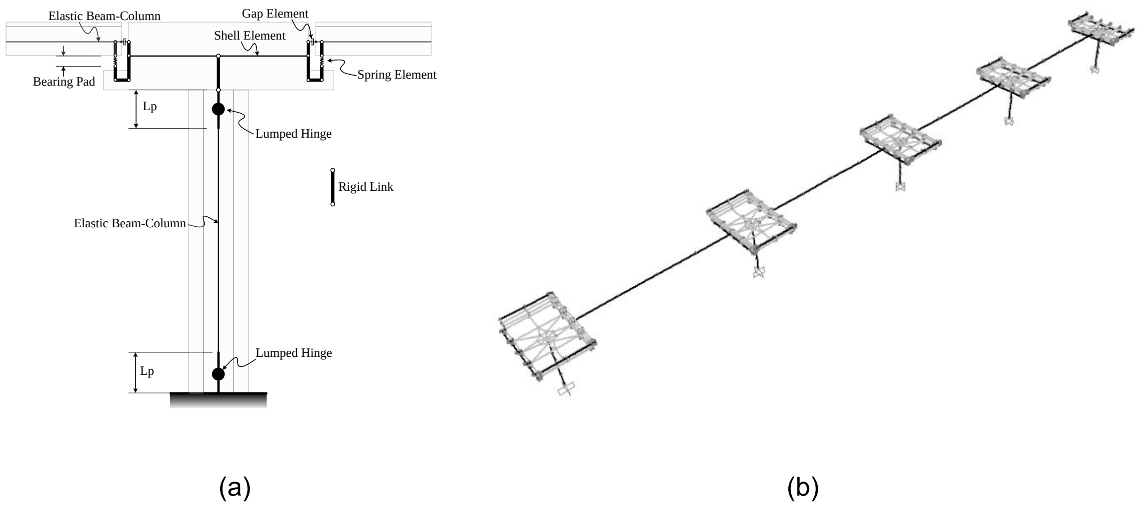


Figure: 2. Analytical model of the studied bridges: (a) Detail of each component modeling, and (b) Analytical Model.

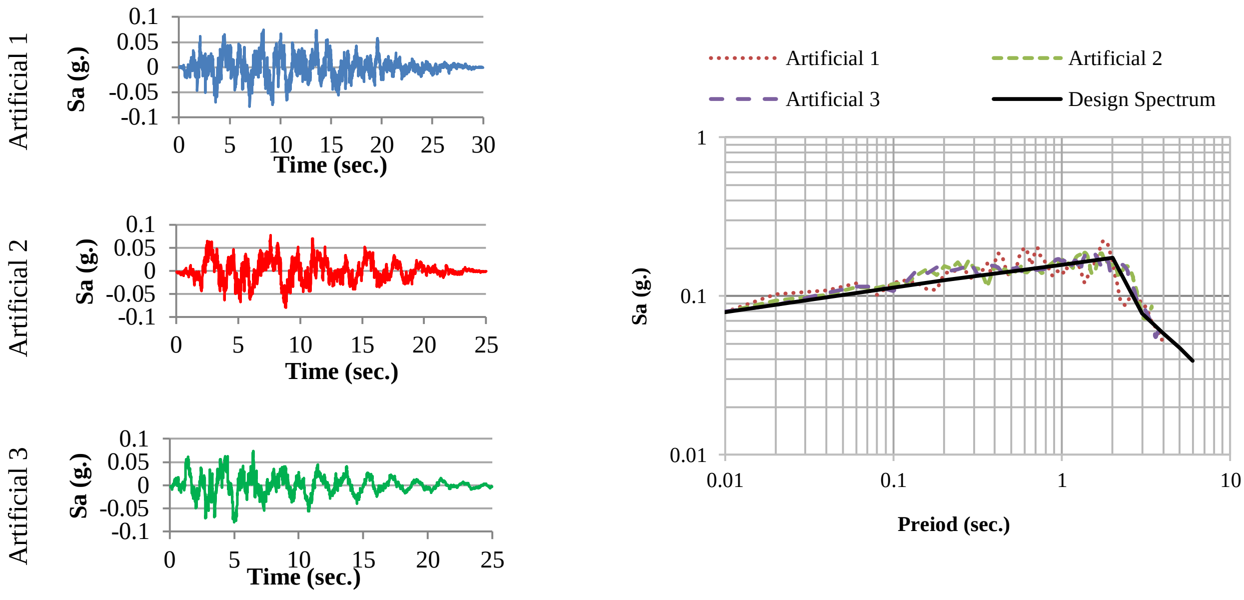
Bearing system of the studied bridges is modeled by an elastic six degree-of-freedom spring element. The stiffness of each degree of freedom is calculated by the beam theory (Yazdani et al. 2000). The boundary conditions at the bottom of the bridge's columns were assumed to be fixed supports.

2.2. Artificial ground motions

FHWA (2006) suggests that the maximum response of the three ground motions should be used for evaluating performance. This study uses three artificial ground motions, Figure 3(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 Figure 3(b). The response spectrums of the artificial ground motions were generated and compared to the design spectrum as shown in Figure 3(b).

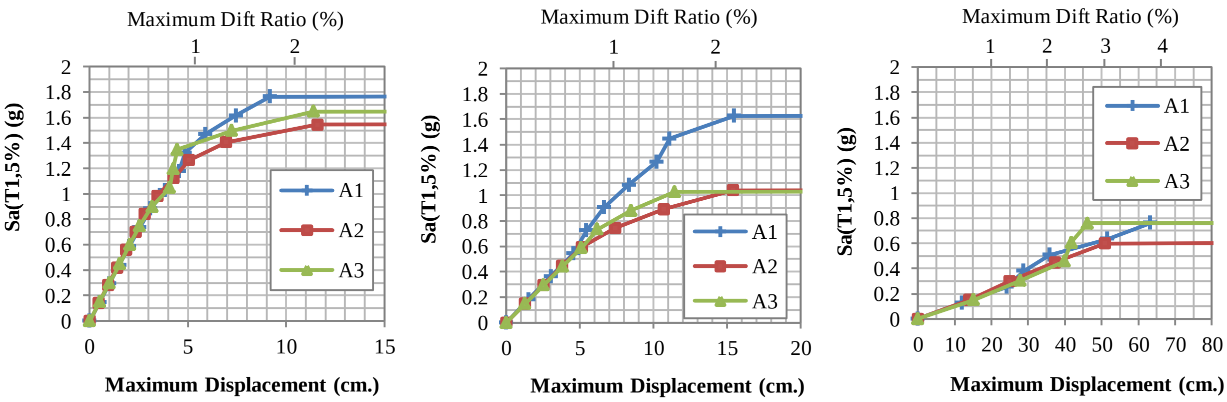
3. INCREMENTAL DYNAMIC ANALYSIS BY NTHA OF WHOLE BRIDGE MODEL

Nonlinear dynamic analyses of the studied bridges under various scaled intensity of three considered ground motions, called Incremental Dynamic Analysis (IDA), were achieved by SAP2000 program. Selected intensity measurement (IM) of this study is the spectrum acceleration at the fundamental mode of the structures with 5% damping ratio. The IM is scaled up and plotted 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 Figure 4.



(a) (b)

Figure 3: Artificial ground motions generated corresponding with the design spectrum for the inner area of Bangkok: (a) Three generated artificial ground motions, and (b) Comparison of response spectrum of generated ground motions with the design spectrum



(a) (b) (c)

Figure 4: IDA curves of three studied bridges in transverse direction (a) 4.5 meter column height, (b) 6.3meter column height, and (c) 15 meter column height

4. INCREMENTAL DYNAMIC ANALYSIS BY NTHA OF ESDOF

4.1. Effects of lateral load patterns on the lateral capacity

The NTHA of the ESDOF were performed to generate the IDA curves of the studied bridges. The ESDOF is the mass-spring system. The mass is used to represent the mass of the bridges. The spring is used to represent the lateral behavior of the bridges. The lateral behavior of the bridges obtained from NSA until the bridge collapse called lateral capacity curve. Using the NSA to evaluate the lateral capacity of the structures, choosing the lateral load pattern directly affects to the lateral capacity curve (Pinho 2007). This study uses two built-in lateral load patterns in SAP2000, i.e. 1st mode load pattern (1st) and uniform acceleration load pattern (Unif), to study the effect of load patterns on the accuracy of IDA by ESDOF compared to NTHA.

The 1st is the elastic first mode lateral load pattern. The lateral force at any degree-of-freedom is proportional to the product of the amplitude of the elastic first mode and the mass at that node. The lateral load pattern can be calculated as follows:

$$F_i = \frac{m_i \phi_i}{\sum m_i \phi_i} \quad (1)$$

where F_i is lateral force at i degree-of-freedom, m_i is mass of i degree-of-freedom, and ϕ_i is amplitude of elastic first mode at i degree-of-freedom.

For the uniform acceleration load pattern, after defining the considered acceleration direction, the unit acceleration was automatically defined to all degree-of-freedom. The pattern of force which is the product of mass and unit acceleration is used to be the Unif (CSI 2011).

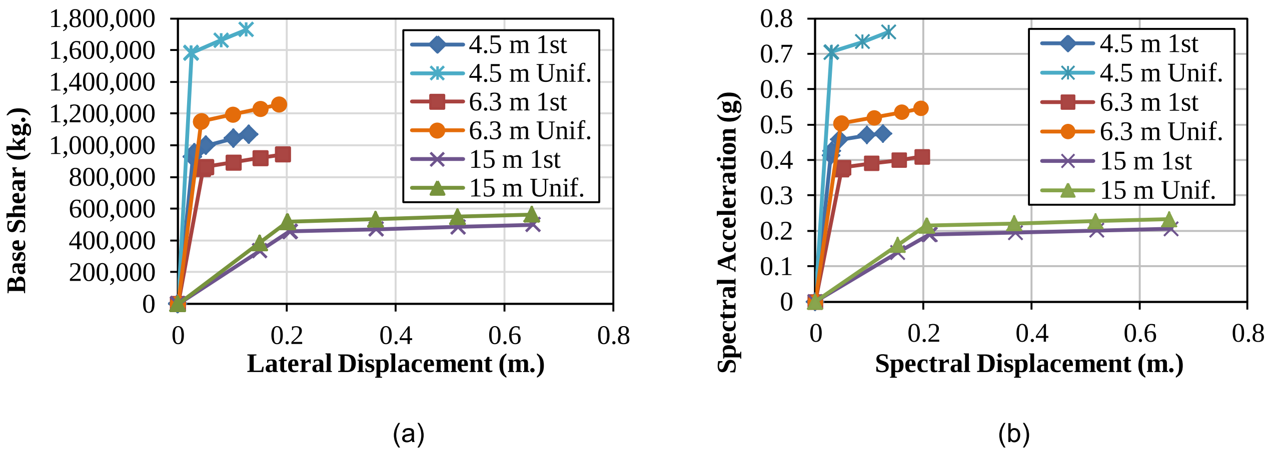


Figure 5: Lateral capacity of three studied bridges in transverse direction (a) pushover curves, and (b) capacity diagrams

The NSA of all studied bridges was carried out by SAP2000. The results are shown in Figure 5. It shows that the different lateral load patterns strongly influences on the different lateral capacity of the bridge with short column because the rotational mass moment of inertia was accounted in the 1st. The accounting of rotational mass moment of inertia in NSA leads to weak lateral capacity than without considered. When the column height increase, the effect of rotational mass moment of inertia decrease as seen in the Figure 5 for the bridge with tall column. However, the lateral capacity obtained from the 1st always shows the less capacity than the one obtained by the Unif.

4.2. Comparison of IDA curves obtained by whole bridge model and ESDOF

The lateral capacity of the studied bridges obtained from NSA were defined to the ESDOF and perform the IDA of the system. The ESDOF system which the lateral capacity obtained from the 1st is referred as ESDOF_PT1 while the system which the lateral capacity obtained from the Unif is referred as ESDOF_PTU. The hysteresis behavior of the ESDOF is the pivot hysteresis rule (CSI 2011). The IDA curves of three different bridge's column heights and under three different considered ground motion were compared to the NTHA as shown in Figure 6.

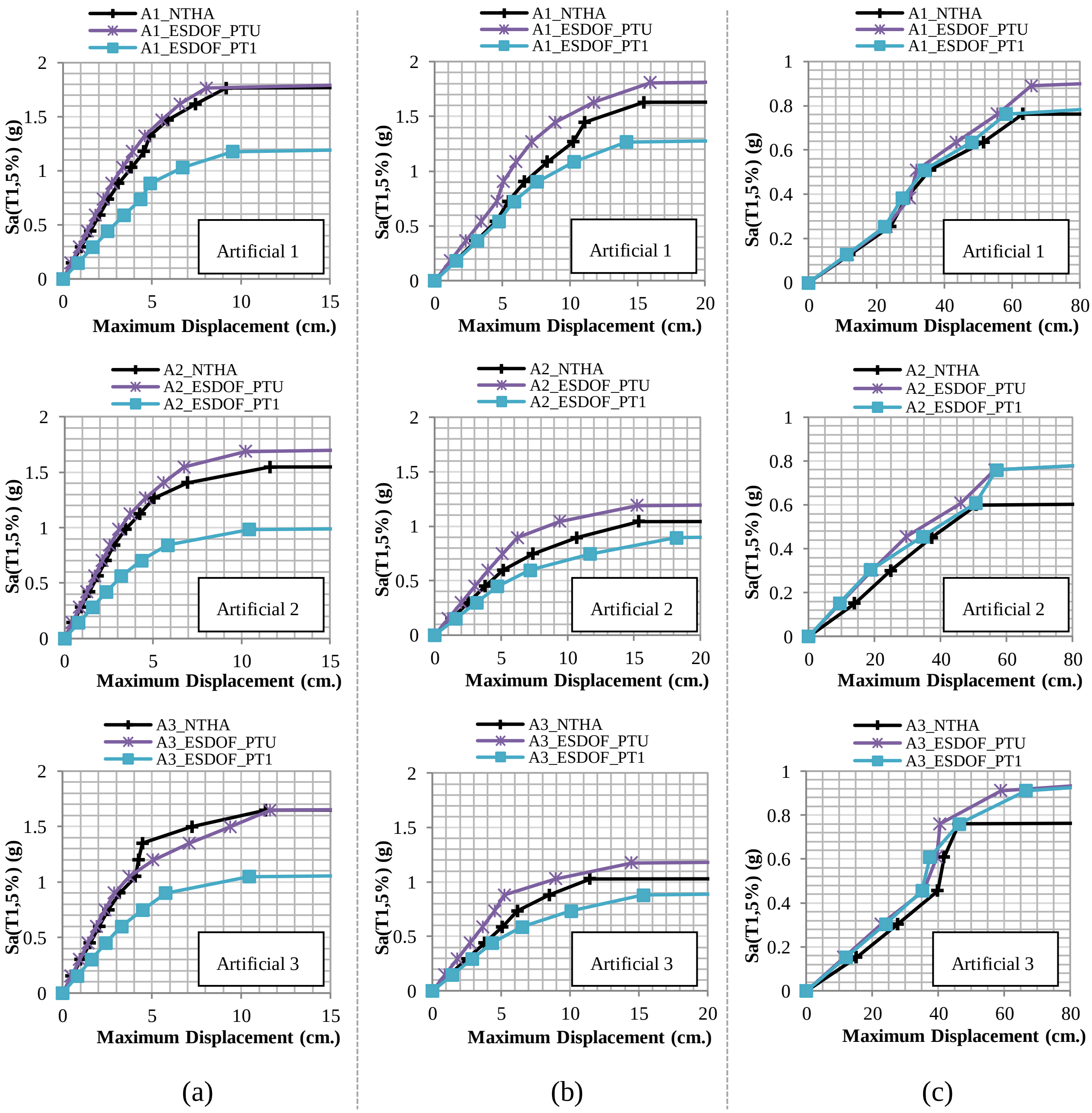


Figure 6: Comparison of IDA curves of three studied bridges in transverse direction obtained by ESDOF with two different lateral patterns and whole bridge model under three artificial ground motions (a) 4.5 meter column height, (b) 6.3 meter column height, and (c) 15 meter column height

Figure 6 shows that using different lateral load pattern lead to different IDA curve. The different lateral load pattern strongly affects to the IDA curve of the bridge with short column. The ESDOF_PTU shows slightly stiffer seismic behavior than the NTHA of whole bridges when the ESDOF_PT1 gives strongly weaker for the bridge with short column height. For the bridge with medium column hight, the ESDOF_PTU gives moderately stiffer while the ESDOF_PT1 shows moderately weaker than NTHA. The different lateral load pattern insignificantly affects to the IDA curve of the bridge with tall column.

5. CONCLUSIONS

This study focus on the effects of using different lateral load patterns on the seismic behavior of the bridge structures in form of IDA curve. The results lead to the conclusion that using different lateral load pattern strongly affects to the IDA curve of the bridge with short column. The effect of using different lateral load pattern on the IDA curves decreases when the bridge's column height increases.

Even if the ESDOF_PTU shows more accurately IDA curve compared with NTHA of the whole bridge model, the ESDOF_PT1 can be used to evaluate the seismic performance of the bridges with medium to heigh column height in the sense of conservative aspect.

6. ACKNOWLEDGMENTS

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