Research Article

Influence of Lateral Load Patterns on the Seismic Performance 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 influence of a selection of two different lateral load patterns, i.e., 1^{st} 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 in order 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 influence the lateral capacity of the bridge especially when the rotational mass moment of inertia was considered. The different lateral capacities lead to different incremental dynamic analysis curves (IDA curves) and lead to differences in seismic performance. The IDA curves show that the ESDOF with lateral capacity from Unif gives a slightly stiffer seismic behavior than the nonlinear time history analysis of whole bridges while the ESDOF with lateral capacity from 1st gives significantly weaker IDA curves for the bridge with short column height. However, the effect of different lateral load patterns on the IDA curves decreases when the bridge's column height increases.

Keywords: Incremental dynamic analysis; lateral load pattern; rc bridge; seismic performance.

1. Introduction

The Incremental Dynamic Analysis (IDA) is a useful method for evaluating the seismic performance of the structures until collapse [1]. 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 yields an incremental dynamic analysis 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 computational time because analyzing the whole structures by the NTHA (Multi Degrees of Freedom system, MDOF) is time-consuming especially when highly nonlinear components were considered. To miligate this disadvantage and to make the IDA more practical, researchers have adopted the concept of Equivalent Single Degree of Freedom (ESDOF) [2, 3]. The basis of ESDOF originates from the concept of

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Nonlinear Static Analysis (NSA) [4]. It assumes that the considered point on 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 a nonlinear static analysis known as the Pushover Analysis (PA). The IDA by ESDOF covers a wide range of analysis techniques from basic to advance including a technique known as a modal incremental dynamic analysis [5-7].

Bridges are important structures and their seismic performance should be evaluated. How to use an IDA by ESDOF to evaluate the seismic performance of this kind of structures has not yet been 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 to the design spectrum for the inner area of Bangkok Thailand were considered. The column heights of three different bridges have also been considered in order to observe the effect of the flexibilities of the various substructures on the accuracy of the results obtained from the 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. Concept of Seismic Performance Evaluation by Incremental Dynamic Analysis

2.1 IDA of Multi-Degree of Freedom System

In conventional IDA, the NTHA of MDOF analytical model under the set of monotonically increasing ground motions were performed to investigate the seismic behavior of the structure under considered ground motion until collapse. The scalars that can be used to reflect the intensity of ground motion called Intensity Measure (IM) were collected at every step of scaling-up considered ground motion. The maximum response of the structure which can reflect the damage level of the structure called Damage Measure (DM) also were collected and observed at every result of NTHA of MDOF. IM was plotted together with DM as shown in Figure 1 and called the result an incremental dynamic analysis curve (IDA curve). It indicates the seismic behavior of the structure, from under the small considered ground motion to the largest considered ground motion that make the structure collapse. Even if the IDA of MDOF is a useful method, this method requires high performance computer, huge data storage and long computational time. There are the most important drawback of using this method for evaluating the seismic performance of the structures.

2.2 IDA by ESDOF based on Nonlinear Static Analysis

The concept of IDA based on nonlinear static analysis has been considered in order to reduce the computational price and time of IDA of MDOF [8]. The lateral behavior of the structure was generated by the nonlinear static analysis (NSA) under a suitable lateral load pattern. The cyclic nonlinear static analysis will be performed if the hysteresis behavior of the structures is required. Then, the generated lateral behavior was defined for the single degree of freedom system (SDOF) to be equivalent to that of the MDOF structure. The mass of SDOF was defined by a value that makes the fundamental dynamic properties of SDOF equal to the MDOF. An SDOF system that has lateral behavior equivalent to that of an MDOF system was used to perform the IDA. The concept of ESDOF is shown in Figure 2. By using this method, the computational time can be reduced.

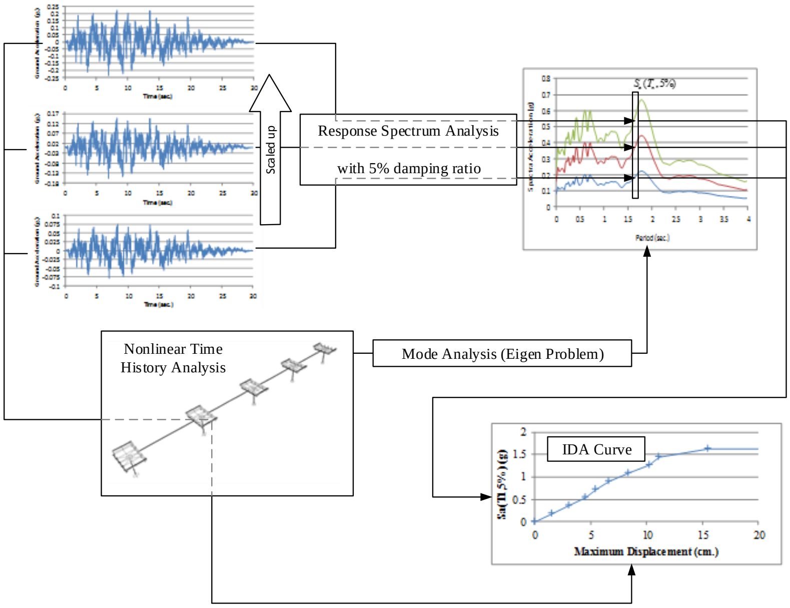


Fig.1. Concept of incremental dynamic analysis of single column bridges.

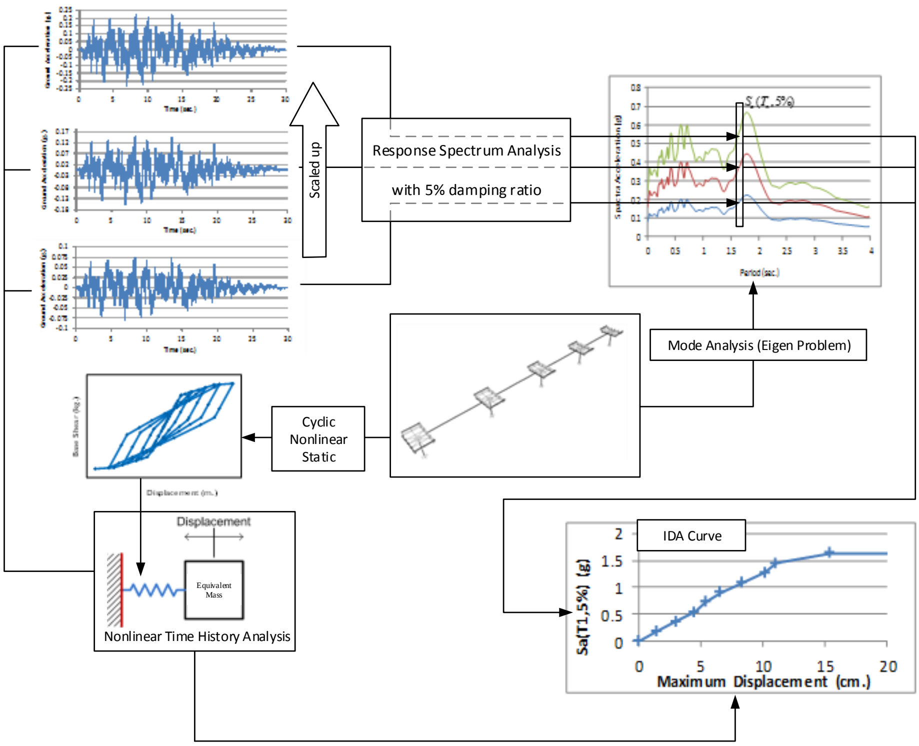


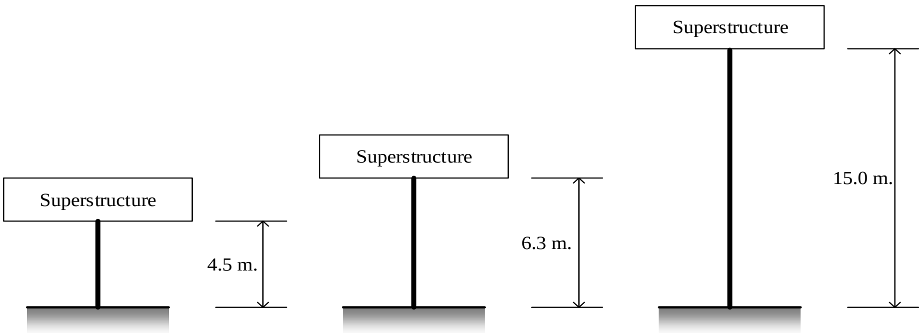
Fig.2. Concept of incremental dynamic analysis by ESDOF based on nonlinear static analysis.

3. General Configurations and Analytical Model of Single-column RC Bridge Structures

Bangkok, the capital city of Thailand, is situated in the middle of Thailand far from active faults. But in recent years, there are many earthquakes that have affected the capital city. In 2009, the Department of Public Work and Town & Country Planing (DPT) [9] has announced the seismic design standard for the seismic risk regions in Thailand. Bangkok is classified as a low-to-moderate seismic risk region. There are a lot of important structures that were built before the enforcement of this standard. Highway bridges are among these structures. Due to the lack of consideration for seismic induced effects, the single column bridge configuration is typically used as shown in Figure 3(a). Therefore, this study uses this type of structure as case studies both to assess their seismic behavior and to observe the application of a simplified method for evaluating the seismic behavior of this kind of structures at the same time. Because they are widely used, the bridges with three different column heights, as shown in Figure 3(b), were considered so that we can investigate their effects on the seismic behavior. Details of the studied bridges are described as follows.

The studied bridges are reinforced concrete single column bridge. A specification describing a bridge in detail is referred to as its as-built drawing. The design strength of concrete are 240 ksc. and 350 ksc. for in-situ reinforced concrete and precast prestressed concrete beam, respectively. A grade 40 deformed bar was used for reinforcement.

(a) Typical single column bridges in Bangkok, Thailand



(b) Bridges with three different column heights

Fig.3. General configurations of studied single-column reinforced concrete bridges.

3.1 Superstructure

The superstructure of the studied bridges is an 18-centimeter-thick reinforced concrete slab placed on the top of five pre-stressed concrete I-girders. It is assumed to be elastic and is modeled as lumped single elastic beam-column elements. According to the bridges modeling for nonlinear analysis proposed by Aviram [10], four elements per span are used in this study. The translational mass of the superstructure is automatically calculated and lumped to the nodes of beam-column element. Torsional mass, which affects the dynamic properties of the bridges especially in transverse direction, is also calculated and defined to the nodes of the elements.

3.2 Bearing System

The bearing system of the studied bridges is an elastomeric bearing pad system. It is modeled as an elastic spring element with six degrees of freedom. The stiffness in each degree of freedom is calculated according to the beam theory suggested by Yazdani et al. [11]. The shear modulus of the rubber depends on its hardness. A report by the Thammasat University Research and Consultancy Institute (TU-RAC) about an inspection of the bearing pads of an expressway in Bangkok shows that the hardness of the bearing pad's rubber is about 60 Shore A scale. AASHTO [12] suggest that an appropriate shear modulus of the rubber with 60 Shore A scale is 0.9 MPa. Although the effective compressive modulus of elasticity of the new bearing pads can be calculated directly from specified shear modulus according to the method in AASHTO [12], Yazdani et al. [11] have shown that aging and cold temperature elastomers may experience significant stiffening. The increase in stiffness may be as high as 50 times the original stiffness.

3.3 Substructure

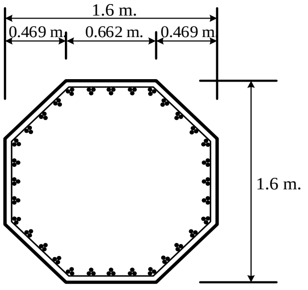
The substructure of the studied bridges is an octagon reinforced concrete column with a top slab. The cross-section of the column is 1.60 x 1.60 m as shown in Figure 4(a). The base of the bridge columns were modeled by the inelastic element in order to capture the inelastic behavior of the bridge structures. For nonlinear static analysis, the inelastic behavior was modeled using the lumped hinge technique. The lumped axial-bidirectional moment interaction hinge (P-M-M) was used in this study. Moment-curvature of the specified column cross-section was evaluated and shown in the Figure 4(c). The column reaches the limit when the extreme fiber of the cross-section reaches the ultimate compression strain. When the column is subjected to an axial load, the moment-curvature was adjusted automatically by considering the interaction diagram shown in Figure 4(b).

Due to a limitation of SAP2000, the plastic hinge length element with lumped hinge should be replaced by a nonlinear spring element to model the inelastic behavior of the bridges for nonlinear time history analyses. The moment-curvature of the column cross-section was evaluated taking into account the axial load. It is defined to the nonlinear spring element in nonlinear time history analytical model. The fundamental dynamic properties of the nonlinear time history analytical model were compared to those of the nonlinear static analytical model to make sure that the dynamic properties of both models are the same.

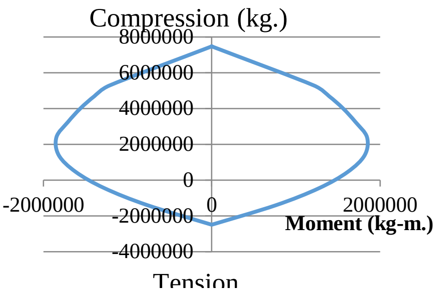
The top of the column is rigidly connected to the 1.33-meter-thick cast-in-place reinforced concrete slab. It is modeled as an elastic thick shell element. This element is used to realistically model the mass distribution of the slab. Because of the high thickness-to-width ratio of the slab, a thick element was used to account for the influence of shear deformation.

A gap element is used to model the gap between the superstructure and the substructure. The initial gap was set to 2 centimeters which is the same as the details shown in the as-built drawing. The stiffness of the gap element is set to about 100 times the axial stiffness of the superstructure in order to avoid rounded errors.

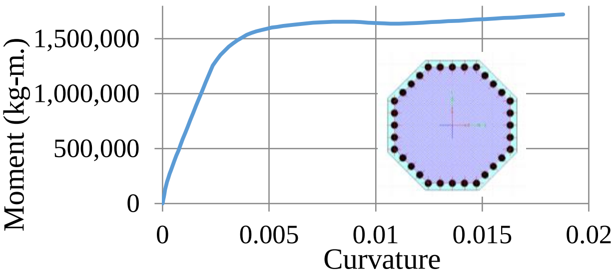
According to the modeling concepts described above, the inelastic analytical model of the bridges is shown in Figure 5(a). Figure 5(b) shows the analytical model of the studied bridges in the computer program.



(a) Bridge column cross-section

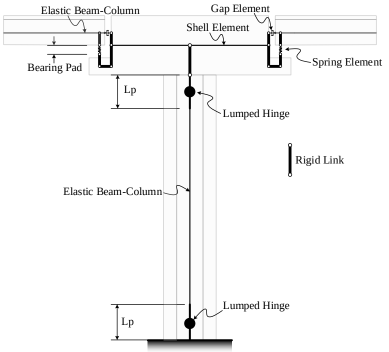


(b) Interaction Diagram

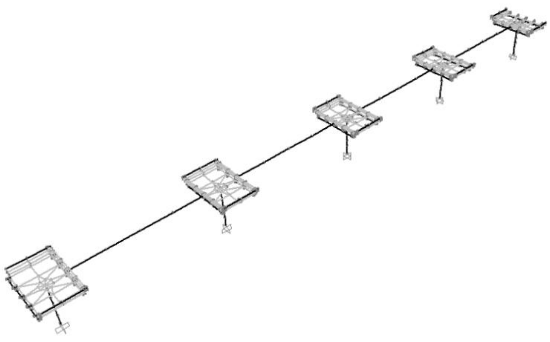


(c) Moment-curvature of bridge column

Fig.4. Details of substructure properties.



(a) Detail of each component modeling



(b) Analytical Model in the computer program

Fig.5. Analytical model of studied bridges.

4. Dynamic Properties of Studied Bridges

The dynamic properties of the studied bridges are assessed via the method of vibration mode finding analysis. An Eigen-problem analysis of the provided analytical model of the bridges is performed to evaluate the mode shapes and frequencies of all studied bridges.

The results show that the fundamental mode of vibration of the single column bridge is the oscillation of the structure in a direction perpendicular to the traffic direction called the transverse direction. The shape of the fundamental mode of vibration of the bridge in the transverse and longitudinal directions was shown in Figure 6(a) and 6(b), respectively. The dynamic properties of both directions of vibration were concluded in Table 1.

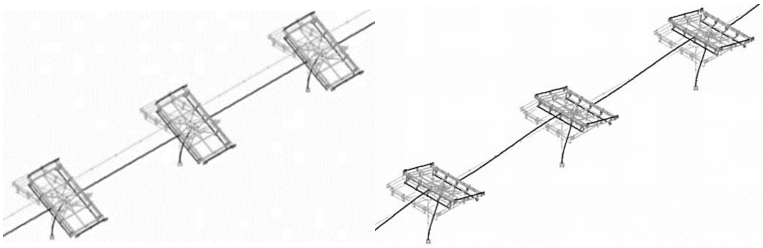
To validate the analytical model and to calculate dynamic properties of the bridges, we compared the calculated frequencies of a bridge with 6.3 meter column height to those from field tests. The frequencies of the bridges in the transverse and the longitudinal directions of the field test were 1.60-2.00 Hz and 2.00-2.80 Hz, respectively. These numbers show that the calculated frequencies are in the range of the field test data, and the analytical model can be used to reliably evaluate the seismic performance.

The mass participation ratios of all bridges were also shown in Table 1. These results show that the vibration of a bridge with tall columns is dominated by the fundamental mode. Also, higher modes may be more influential when the bridge column height decreases.

According to the Seismic Retrofitting Manual for Highway Bridges published by the Federal Highway Administration (FHWA) in 2006, the invisible crack in the structural member may affect the flexural rigidity of the members and should be considered in the seismic evaluation. This study also considered the effect of cracked sections in the seismic performance evaluation process. Then, the flexural rigidity of the reinforced concrete column of all studied bridges was reduced to half of that of the gross-section (0.5EcIg) [13].

5. Artificial Ground Motions

In evaluating the seismic performance of bridge structures, the ground motion should be selected carefully because each ground motion from each earthquake has its own unique characteristic. According to the Seismic Retrofitting Manual for Highway Bridges published by the Federal Highway Administration [13], the maximum response of the three ground motions should be used for evaluating performance. This study uses the design spectrum for the inner area of Bangkok, Thailand [9] as the target spectrum as shown in Figure 7(b). The ground motions were generated by matching the response spectrum with the target spectrum. Three artificial ground motions generated by SeismoArif and referred to as A1, A2, and A3 were shown in Figure 7(a). According to the concept of IDA, the generated ground motions will be scaled up until the DM of the structures show collapse.

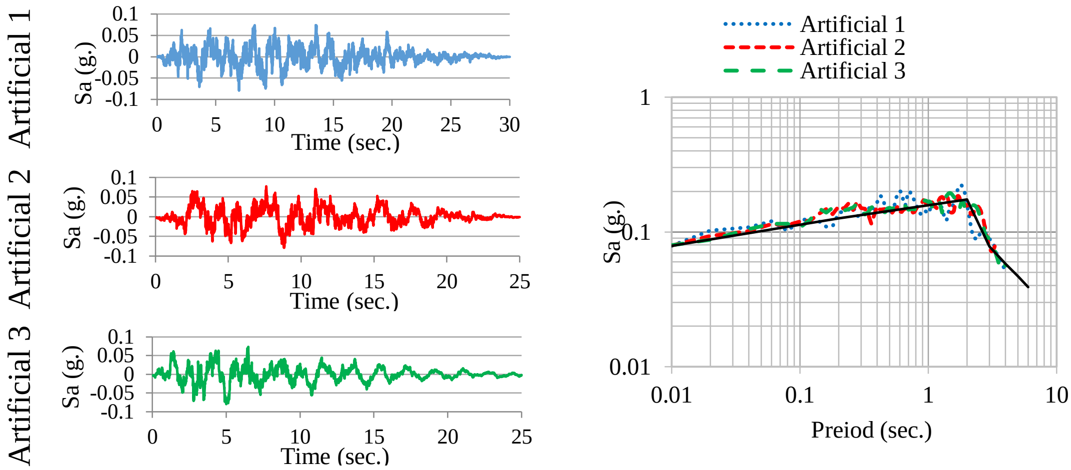


(a) Transverse mode shape (b) Longitudinal mode shape

Fig.6. Fundamental mode of vibration of the studied bridges in transverse and longitudinal directions

Table1. 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



(a) Three artificial ground motions

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

Fig.7. Artificial ground motions generated according to the design spectrum for the inner area of Bangkok.

6. Lateral Behavior of the Studied Bridges according to Nonlinear Static Analyses

Nonlinear static analyses of the studied bridges were performed to generate its lateral behaviors. An important parameter that strongly affects the lateral behavior of the structures, is the lateral load pattern [14].

6.1 Lateral load pattern

In evaluating the seismic behavior of structures using methods based on the NSA, international standards, such as FEMA 356, suggest that at least two lateral load patterns should be considered. One of the load patterns can be selected from the following two categories.

The first category is the modal pattern. The distribution of vertical load can be selected from one of the following: The distribution proportional to the shape of the fundamental mode in the direction under consideration, and the distribution proportional to the story shear distribution calculated by combining modal responses from a response spectrum analysis of the building, including sufficient modes to capture at least 90% of the total building mass, and using the appropriate ground motion spectrum.

For the second pattern, the distribution can be selected from one of following: uniform distribution consisting of lateral forces at each level proportional to the total mass at each level (or uniform acceleration load distribution), and adaptive load distribution that changes as the structure is displaced.

This study uses two lateral load patterns selected from the two categories above in order to investigate the effects of different lateral load patterns on the seismic behavior of single-column RC bridges as evaluated using the concept of ESDOF IDA. The first load pattern distributes the load proportionally to the fundamental mode in the transversal direction. We refer to this load pattern as “First mode load pattern (1st)”. The second load pattern is the uniform distribution consisting of lateral forces at each level proportional to the total mass at each level. We refer to this load pattern as “Uniform acceleration load pattern (Unif)”.

6.2 Effect of Lateral Load Pattern on the Lateral Capacity of the Bridges

The lateral behavior of the studied bridge with 4.5, 6.3, and 15 meter column heights from three selected lateral load patterns was shown in Figure 8.

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

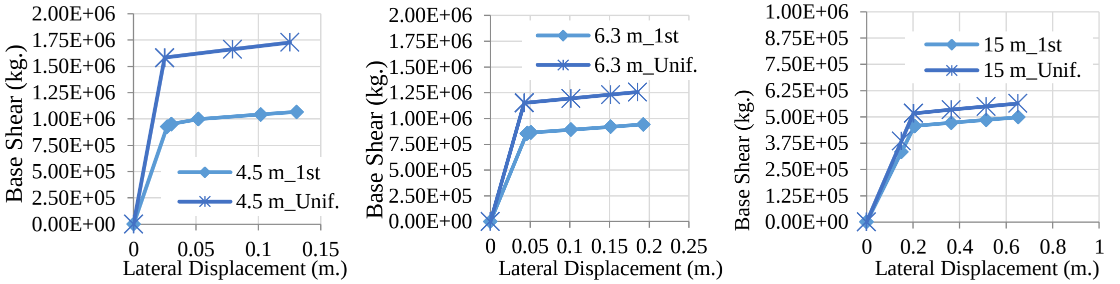
The results show that different lateral load patterns lead to dramatically different lateral capacities of the bridge structures, especially the bridge with the least modal participating mass ratio in the considered direction. The difference in lateral capacities of the bridges decrease when the modal participating mass ratio increases. These results were due to the effects of the higher mode.

7. Effect of Lateral Load Pattern on IDA Curves of Studied Bridges Obtained by ESDOF

The IDA of ESDOFs were performed in order to investigate the effects of different lateral load patterns on the IDA curves obtained by the ESDOF. The IDA curves of ESODF were compared to the IDA curves of the MDOF and shown in Figure 9. The IDA curves obtained from the ESDOF with lateral capacity from 1st and Unif are referred to ESDOF_PT1 and ESDOF_PTU respectively. The hysteresis behavior of the ESDOF is the pivot hysteresis rule [15].

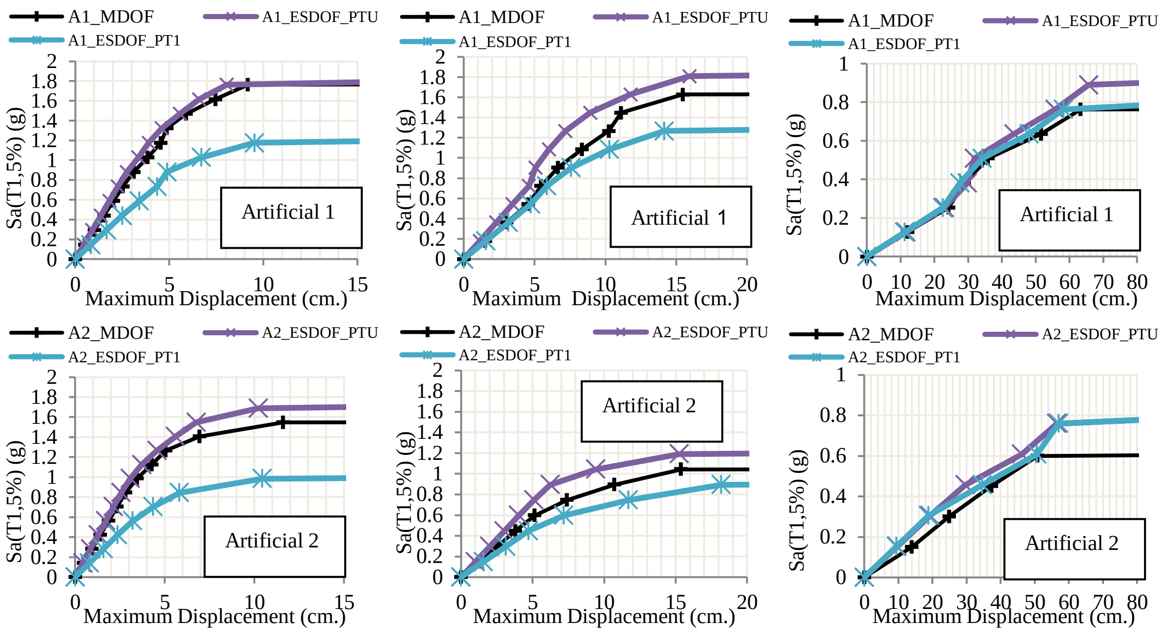
Figure 9 shows that The ESDOF_PTU shows slightly stiffer seismic behavior than the NTHA of MDOF while the ESDOF_PT1 shows much weaker seismic behavior than the NTHA of MDOF for the short column bridge. For the medium column bridge, the ESDOF_PTU gives moderately stiffer IDA curves while the ESDOF_PT1 shows moderately weaker one than NTHA. The different lateral load patterns insignificantly affected the IDA curve of the tall column bridge.

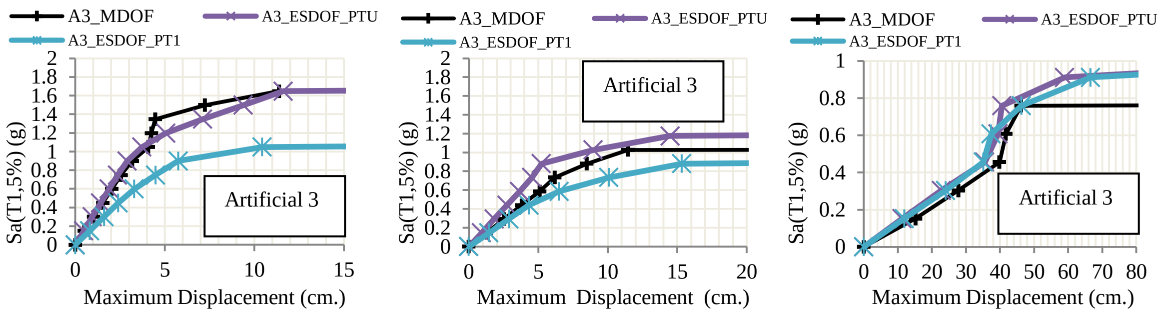
The results show that lateral load patterns strongly affect the seismic behavior of the bridge structure, especially for bridges with low modal participating mass ratios in the fundamental mode as well as bridges with short columns. This effect decreases when the bridge column height increases. It may be concluded that this is result of higher mode effect.



(a) 4.5 meters column height (b) 6.3 meters column height (c) 15.0 meters column height

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





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

Fig.9. Comparison of IDA curves of short column, medium column and tall column bridges under three artificial ground motions obtained from NTHA of MDOF and ESDOF with three different lateral capacities in transverse direction.

8. Conclusions

This study investigated the effects of different lateral load patterns on the seismic behavior of the three studied bridges under three artificial ground motions by the mean of IDA by ESDOF. We arrived at the following conclusions.

The use of the concept of ESDOF for evaluating the seismic performance of the studied bridges by the mean of IDA can reduce the computational time from 60 minutes per load case for MDOF to 4 minutes per load case for ESDOF (a reduction of about 93%).

The seismic performance of the studied bridges with the participating mass ratio less than 80% of the total mass (4.5 meters and 6.3 meters column heights in this study) can be evaluated by the ESDOF with the load patterns in accordance with FEMA 356. However, the ESDOF with the first mode load pattern leads to an overestimate of the seismic responses while the uniform acceleration results in an underestimate of the seismic responses.

The effect of different lateral load patterns on the seismic behavior of the studied bridges decreases when the bridge column height increases. Therefore, either the first mode or the uniform acceleration lateral load patterns based on FEMA 356 can be used effectively in applying the concept of ESDOF for evaluating the seismic performance of the studied bridges that is dominated by the fundamental mode (participating mass ratio higher than 80% of the total mass as is the case for the 15-meters column height in this study).

9. Acknowledgments

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