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Technical Note

# Estimating the Loading Pattern Factor of Modal Pushover Analysis (MPA) for Integrated Bridges Using IDA Responses

**Yaser Nasiri**[1*] **and Panam Zarfam**[2]

1. M.Sc. Student in Earthquake Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran
2. Assistant Professor, Science and Research Branch, Islamic Azad University, Tehran, Iran,
* Corresponding Author; email: zarfam@srbiau.ac.ir

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## ABSTRACT

*In this paper, a new applied relationship is introduced for the analysis of integrated bridges where no expansion joint embedded on the deck. It can be used to investigate the seismic behavior and actual performance of integrated bridges under earthquake force and, in spite of its simplicity, its accuracy is acceptable. In fact, this relationship can be considered as a combination of incremental dynamic analysis and modal pushover analysis, benefiting from the advantages of both approaches, i.e. an appropriate loading pattern factor of Modal Pushover Analysis can be obtained by using Incremental Dynamic approach. To this end, the average acceleration - displacement and average acceleration - shear base of 120 earthquake records applied on the bridge are calculated and then the obtained incremental dynamic curve is plotted in the coordinates of displacement and shear base. For the obtained modal pushover curve, the sum of the first three SRSS modes is selected. The literature shows no record of the study conducted on the comparison of the two curves. In this paper, the aforementioned comparison was made using Incremental Dynamic Approach through examining six regular and irregular integrated bridges and applying 120 earthquake records in 10 acceleration levels. It was observed that the accuracy of the proposed relationship in predicting the bridge displacements and shear forces of columns' piers was high, and the calculation output showed negligible differences with dynamic analyze results. In this study, the soil-structure interaction is ignored.*

**Keywords:**
Loading pattern factor; Integrated bridges; Modal pushover analysis; Incremental dynamic analysis

## 1. Introduction

Numerous advanced pushover methods have been introduced to evaluate the seismic behavior of structures; however, since these methods have mainly been proposed for building structures and with regard to the existing fundamental differences between the structural performance of bridges and buildings, the application of pushover methods on bridge structures still lack the required accuracy and is accompanied with uncertainties. Therefore, a modal pushover analysis (MPA) has been presented in this paper to assess the seismic behavior of integrated bridges where the effects of higher modes are considered. The incremental dynamic analysis (IDA) used so far for validation of the studies is sufficiently accurate, although requiring highly time-consuming computational complexity. For this purpose, a method of low computational complexity with enough accuracy is needed; it should be simple and practical, leading to satisfactory results.

For this purpose, we have proposed a procedure in this paper that is an applied method for analysis of the seismic behavior and actual performance of integrated bridges under earthquake force; despite of its simplicity, this method produces accurate results. After extracting (MPA) and (IDA) curves, the capacity curves of these two analyses were compared.

Several methods to evaluate the seismic behavior of integrated bridges have been used by researchers including Isakovic and Fischinger [1], Maalek et al [2], and Pinho et al [3]. In all cases, the researchers compared two (MPA) and (IDA) curves by expressing the modal pushover analysis curve in coordinates of damage measurement (DM) and intensity measurement (IM), which are chosen for incremental dynamic analysis. However, in this study, in order to achieve the proposed relationship, the (IDA) curve has been plotted in coordinates of displacement and base shear selected for the modal pushover analysis.

## 2. Computational Approach

The multiple approximations and simplifications in nonlinear static methods, despite accelerating the expansion of their use, would reduce the accuracy of the results. In order to validate the static nonlinear methods, the IDA method is used. In the proposed relationship, efforts have been made to improve some weaknesses of the MPA Analysis including its validation through providing an appropriate loading pattern factor for modal pushover analysis using incremental dynamic analysis to assess the parameters influencing the regularity and irregularity of bridges. In order to meet the desired objectives in this study, a computer model in the Opensees software is developed and its outputs include the base shear force response and displacement of the bridge elements, modal characteristics, the curve changes of the seismic capacity at different stages of modal pushover analysis and incremental dynamic analysis. In this regard, average acceleration - displacement and average acceleration - shear base of 120 earthquake records applied on the bridge are calculated, and then the obtained incremental dynamic curve is plotted in the coordinates of displacement and shear base. For the obtained modal pushover curve, the sum of the first three SRSS modes is selected. Then, to obtain loading pattern factor of the proposed model according to the Equation (1) in the same displacement of both MPA and IDA, the MPA base shear is divided by the IDA base shear and the mean of the obtained values is calculated. The resulting number is then multiplied by 1/2. Now, if the numbers of the initial loading pattern in the MPA method is divided by the resulting number, the loading pattern with new numbers is obtained. By pushing over the bridge with loading pattern, the obtained curve approaches the (IDA) curve:

$$\text{Proposed relationship} = \frac{\text{Initial loading pattern}}{\left[ \text{Average}\left( \dfrac{\text{BASE SHEAR}_{MPA}}{\text{BASE SHEAR}_{IDA}} \right)_{disp} \right] \times 1.2} \qquad (1)$$

However, in this study, in incremental dynamic analysis, 120 records in 10 intensity levels are scaled and applied on the bridges. Surely, if the number of levels was higher than the intensity scale in the IDA analysis, the curve of the proposed relationship would be more accurate and closer to the IDA curve. This relationship in other integrated bridges like the models introduced in this study, in addition to saving the analysis time, would have an acceptable accuracy.

## 3. The General Specifications of the under Study Bridge

The analysis presented includes six integrated four-span bridges with spans of 45 meters. Bridge deck has multicellular thin wall sections and there is no expansion joint over the bridge. The deck junction to piers and abutments is rigid (integrated) with no supports. Piers are of two column frame type with circular cross-sections. Abutments are of short type. The design of dimensions and cross-sections of various elements of the bridge is carried out according to the AASHTO standards and rules for bridges [4], the Caltrans seismic design criteria for bridges [5] as well as recommendations and relationships in reference books for seismic analysis of bridges such as Miles and Moore [6] and Priestley et al [7]. In the geometry of bridges, three heights

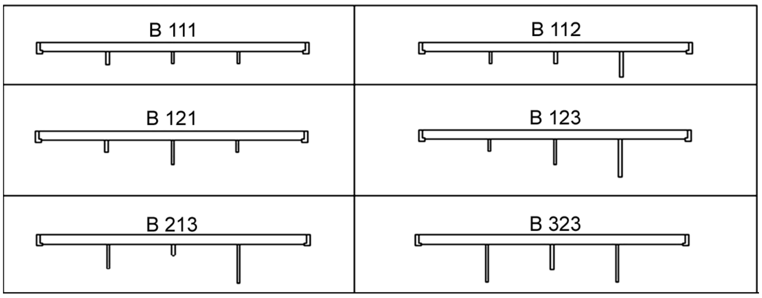

**Figure 1.** Geometry of bridges [1].

of 6, 12 and 18 meters are intended for the visible length of a pier. For simplicity, bridges have been labeled with the standard shown in Figure (1) so that the results of the analysis could be more easily provided and evaluated. In such a labeling, number 1 represents the 6 meter pier, number 2 represents the 12 meter pier, and number 3 represents the 18 meter pier in the bridge.

The stress-strain relationship of concrete is modeled by the Mander et al's model [8]. This model clearly shows the effect of concrete confinement on its maximum stress and strain. Concrete compressive strength is 35 MPa, shear modulus is 12 GPa, elastic modulus is 28 GPa, and its specific weight is 25 kN per cubic meter. Concrete02 is used to define this type of concrete in the OpenSees software. Moreover, rebars of cross-sections are of reinforced concrete type AIII with a yield stress equal to 450 MPa and a modulus equal to 200 GPa. The stress-strain relationship of rebars is modeled with the Menegotto-Pinto's model [9]. Steel02 is also used to define the profile of stress - strain of rebars in the OpenSees software.

Vertical load on the bridge is widely considered uniform over the deck. In calculating the load, the weights of road pavement and half piers are considered. Vertical loads on bridges, due to different heights of piers on six studied bridges, vary between 50100 kN and 50800 kN; thus, a wide-load with an intensity of 278 kN/m to 282 kN/m is considered along the bridges [1].

### *3.1. Modeling Different Elements of the Bridge*

The bridge has a width of 13 meters and a depth of 2.3 meters. The bridge deck is modeled by elements of the nonlinear beam-column with a length of 5 m and mass of each element is separately and equally divided between its two end nodes. The beam-column has an elastic section and the features of an uncracked cross-section are used for its rigidity; to this end, EI is reduced by 50% and GJ by 80% of the elastic values. The uncracked cross-section of the deck is equal to 9.86 cm and moment of inertia around y and z axes is equal to 10.12 $m^4$ and 214.56 $m^4$, respectively (Figure 2).

The piers are made of two circle columns with a diameter of 1.5 m, which are joined at the top by a very hard beam. Normally in integrated bridges, the bridge deck is completely filled with concrete in the place of piers so that the deck itself can play the role of the beam connecting the columns. Moreover, here filling is considered to be 2.5 meters throughout

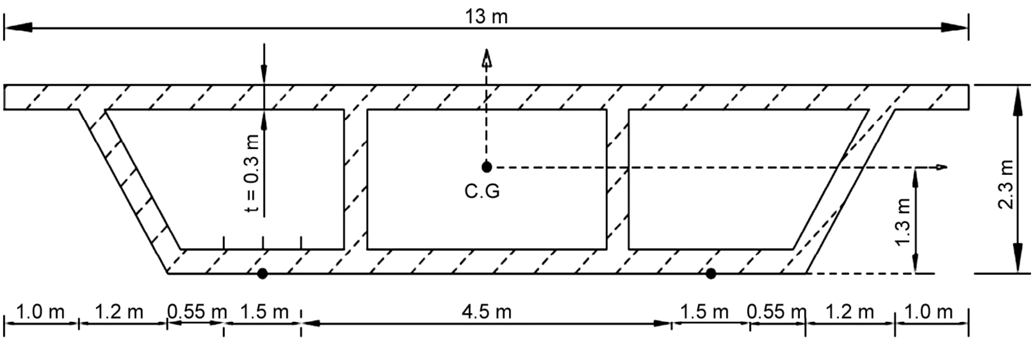

**Figure 2.** Cross section of the bridge deck [1].

the deck so that the optimal integration of piers with the deck is also provided in the longitudinal direction of the bridge. In addition, a rigid length is created at the top of the column that is the space between the underside of the deck (the column top node) and the geometric center of the section of the deck (deck node). The rigid length for bridges discussed in this study, is about one meter, taking into account the effect of the strain phenomenon. In computer modeling, the length is modeled with a rigid element between the column top node and the deck node. The section of columns is shown in Figure (3). The total areas of longitudinal and latitudinal rebars of the section are 1 percent and 0.97 percent of the area of column section. The rebar coating is also intended to be 50 mm.

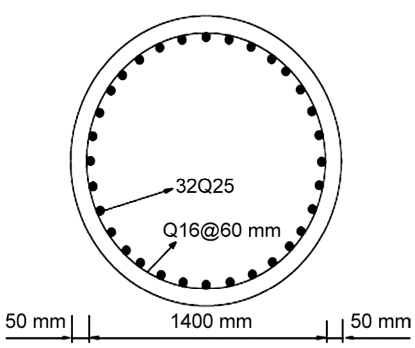

**Figure 3.** Cross-section of bridge columns [1].

In Figure (4), the width of the abutment is equal to the width of the deck that is 13 meters. The height of the abutment is also considered to be 4 meters according to the depth of the pavement and its thickness is 1.5 meters. The abutment relies on the levee from behind. Further, the deck section is assumed to be filled with concrete from the location of abutment to a distance of 1.25 meters along the length of the bridge so that the abutment integrity with the deck is optimally provided.

A three-dimensional computer model of the bridge (B123) in the OpenSees Software with all its elements is shown in Figure (5).

After structural modeling and analyzing it with the proposed method, the responses were interpreted, and accuracy and robustness of the proposed method was assessed. Here, the following quantities are considered as response parameters.

1. Lateral displacement of the deck
2. Shearing force of columns' foot

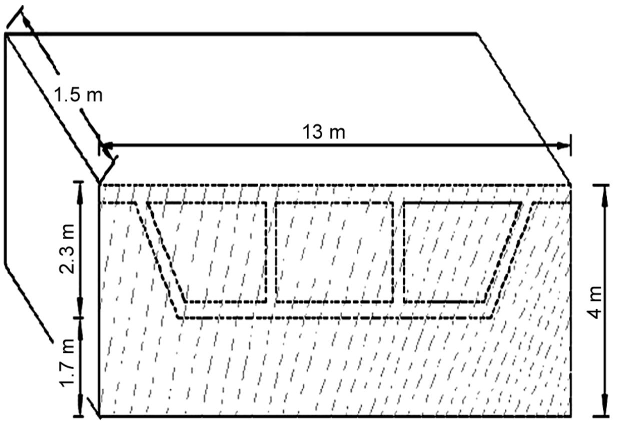

**Figure 4.** Details of the bridge abutment [1].

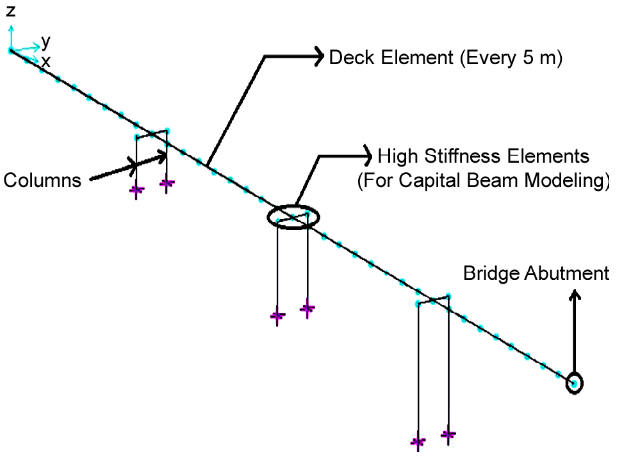

**Figure 5.** The three-dimensional model of the bridge (B123) in the OpenSees Software.

## 4. Comparing the IDA and MPA Curves with the Curve Obtained from the Proposed Approach

According to the results of three MPA, IDA, and the proposed approach curves, it was observed that the accuracy of the proposed approach in estimating the bridge displacements and shear forces of columns is acceptable and IDA results were calculated with a small difference. The proposed relationship for low seismic potential levels of accelerograms in which the bridge is in the range of linear functions has a lot of similarities and consistencies with the IDA method. Using the proposed curve, it can be easily observed that, with increasing levels of earthquake, the bridge behavior changes from linear to non-linear mode and is ultimately unsustainable. In each of these steps, the bridge is placed in one of the functional levels (ability to be used continuously, life safety, collapse threshold), Figures (6) to (11).

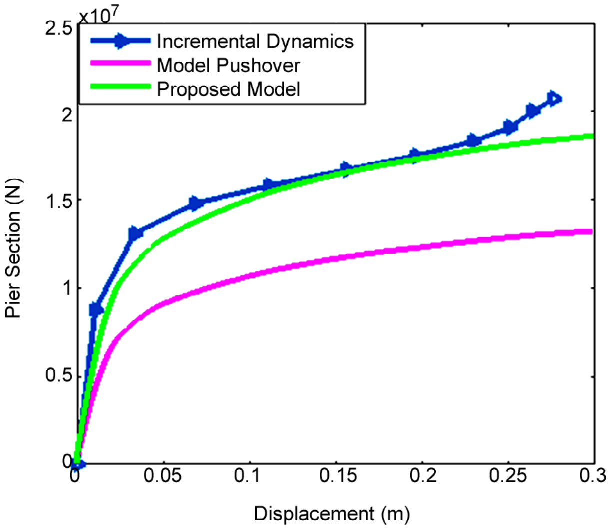

**Figure 6.** Comparison of different models in the bridge 111.

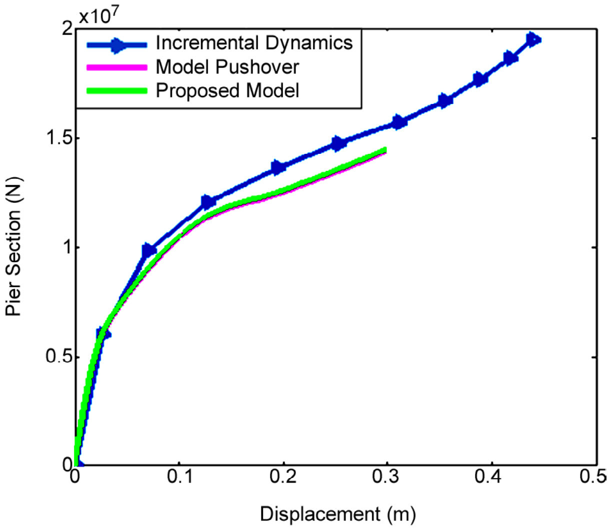

**Figure 9.** Comparison of different models in the bridge 123.

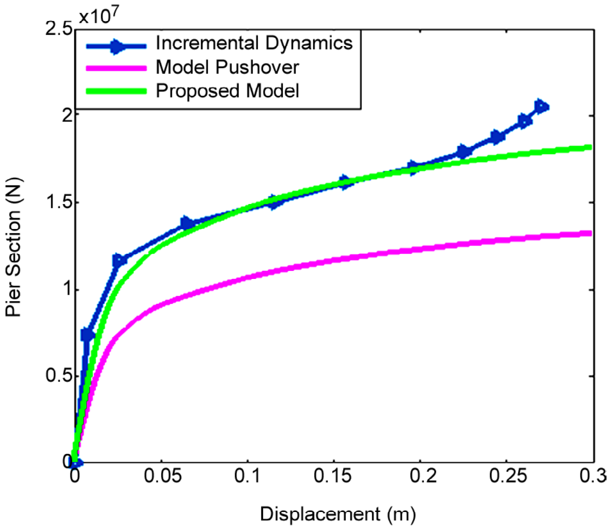

**Figure 7.** Comparison of different models in the bridge 112.

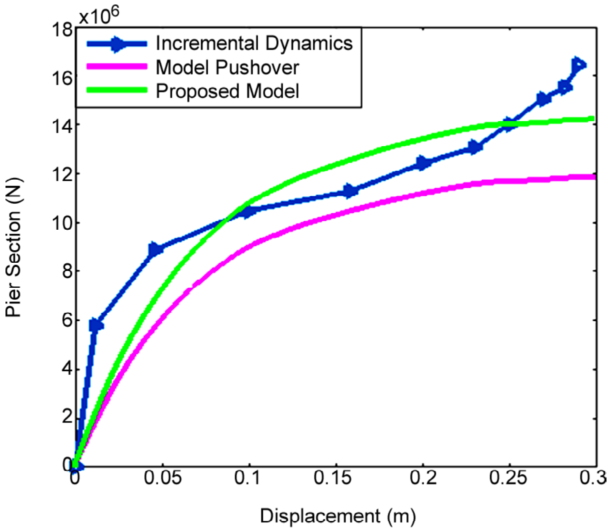

**Figure 10.** Comparison of different models in the bridge 213.

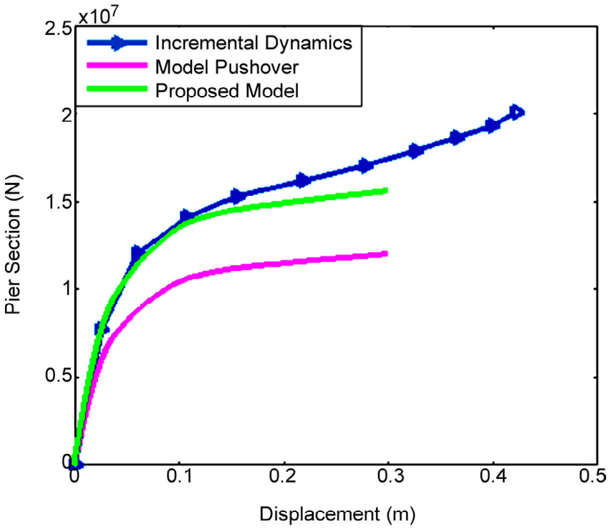

**Figure 8.** Comparison of different models in the bridge 121.

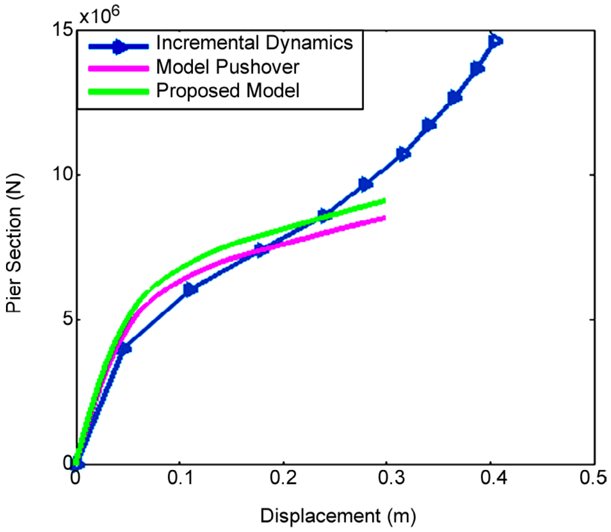

**Figure 11.** Comparison of different models in the bridge 323.

## 5. Conclusion

- Response of pushover methods is generally sensitive to the intensity of earthquakes and it moves from non-linear dynamic responses in high intensities; however, the proposed relationship in most suggested PGAs is moving consistent with the incremental dynamic response having the approximately equal distances. In addition, regularity or irregularity of the bridge has had no effect on the accuracy of the proposed relationship for different earthquake intensities and this accuracy is almost identical for all intensities.
- Most of the common incremental methods are sensitive to the irregularity of the bridge geometry. The accuracy of these methods is great in regular bridges; however, with a decrease in regularity, their error increases in a way that it is not acceptable for bridges with high irregularity. This model has been successful in this regard and could estimate seismic response of regular and irregular bridges with the same precision. This feature was observed for all response parameters and can be one of the strengths of the suggested index.
- The results of the analysis were presented for two parameters of displacement and shear force responses of columns. It is observed that the accuracy of this model in predicting the displacements of the bridge and shear forces of the columns is appropriate and IDA results are calculated with an ignorable difference.
- The proposed relationship for low seismic potential levels of accelerograms in which the bridge is in the range of linear behavior has a lot of similarities and consistencies with the IDA method.
- Investigation of the behavior and performance of the bridge under different applied earthquake levels, with increasing levels of earthquake showed that bridge behavior changes from linear to non-linear mode and is ultimately instable. In each of these steps, the bridge is placed in one of the functional levels (ability to be used continuously, life safety, collapse threshold). Suggested curve clarifies this point.
- By increasing the height of the pier, tangible loss is observed in the bridge capacity graph. This means reducing the seismic capacity or reducing the bridge power against the destructive effects of earthquake. Moreover, by increasing the pier height, the area under the curve which represents the maximum strain energy of the bridge during the incremental loading also declines. Moreover, with increasing the height of the bridge pier, functional levels displacements, continuous usability, life safety, and structural stability are also reduced, and this issue confirms the reduction of seismic capacity of the models.

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