Seismic Retrofitting for Non-Seismic Designed Reinforced Concrete Bridges in Low Seismic Zone

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SUMMARY:
The efficiency of bearing system replacement and steel jacketing of bride's column in improving the seismic performance of the non-seismic designed elevated reinforced concrete bridges in low seismic zone are investigated in this study. The bearing system replacement results show that the transverse displacements moderately decrease for low- and medium-rise bridges and slightly decrease for high-rise bridge while the longitudinal displacements increase for all bridges. The steel jacketing of bridge's column shows more efficiency in reducing the displacement of all studied bridges in both transverse and longitudinal direction. The displacement maximum decreased about 70 percent when the column was jacketed by 25 mm. thickness steel shell. This study also found that the effect of retrofitting on base shear forces cannot be clearly concluded because the increasing or decreasing of base shear forces depend on both characteristic of structures and characteristic of ground motions.

Keywords: Bearing System Replacement, Column Steel Jacketing, Seismic Retrofitting.

1. INTRODUCTION

The highway bridges with single leg column are the risky structures under earthquake because the massive bridge's mass of superstructure stands on the top of the bridge's column. This configuration produces the large seismic induced force to the bridge's column together with large P-Δ effects and may lead to structural failure of bridges if the seismic effect was not considered or seismic induced force is moderately larger than the design one. These examples are clearly seen in failure of bridges with single leg column in Kobe earthquake in 1995. This bridge's configuration was widely used in Thailand without considered seismic effects. In 2009, The Department of Public Works and Town & Country Planning (DPT) has announced the seismic resistance design standard for Thailand (DPT, 2009). In this standard, the Bangkok area was classified to the low seismic zone. FHWA (2006) has announced the seismic retrofitting manual for highway structures. In this manual, there are several retrofitting method suggested in this manual. It can be simply categorized to seismic induced force reduction method and structural member's capacity enhancement method.

Therefore, the efficiencies of few seismic retrofitting methods for the non-seismic designed elevated reinforced concrete bridges, i.e. bearing system replacement and steel jacketing of bride's column, in low and moderate seismic zone are studied and compared in this paper. The seismic responses of the studied bridge are evaluated by Nonlinear Time History Analysis (NTHA) of full model. Three bridges of single leg column, i.e, low-, medium-, and high-rise bridges are studied.

2. CASE STUDY OF TYPICAL CONFIGURATION REINFORCED CONCRETE BRIDGES

2.1. Studied Bridges Configuration

The regular reinforced concrete bridges which used in the part of the expressway phase 1 since 1976 in Bangkok, Thailand, as show in Fig. 1, 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 Fig. 2 with 25 m. span length, are used to study the effect of column flexibility on the seismic performance of the bridges and to investigate the efficiency of evaluation methods in evaluating the seismic performance of the bridges.

Figure 1. Typical configuration of oldest expressway in Bangkok, Thailand

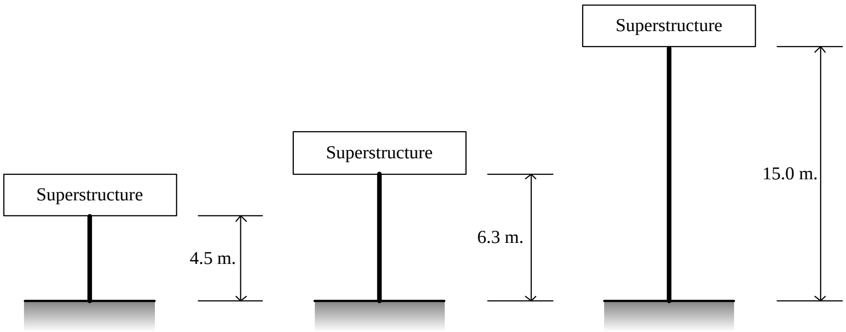


Figure 2. The case study of three different bridge's column heights

Superstructure of the studied bridges is the 18 cm. thickness reinforced concrete slab placed on the top of five pre-stressed concrete I-girders. 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 x 1.60 m as shown in Fig. 3. The connecting system between substructure and superstructure is bearing pads.

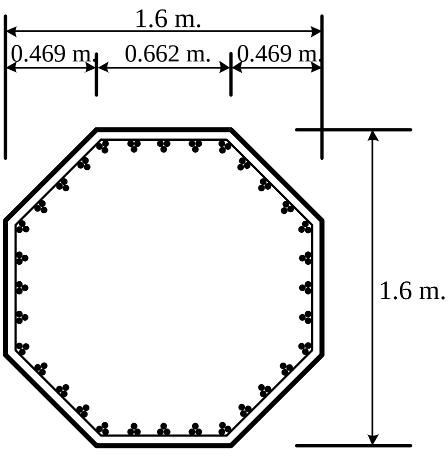


Figure 3. Column's cross-section of studied bridges

2.2. Analytical Model of Studied bridges

The analytical model of studied bridges is shown in Fig. 4. The superstructure is assumed to be elastic and modelled 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 beam-column element. Torsional mass, which affect to the dynamic properties of the bridges especially in transverse direction, is also calculated and defined to the nodes of elements.

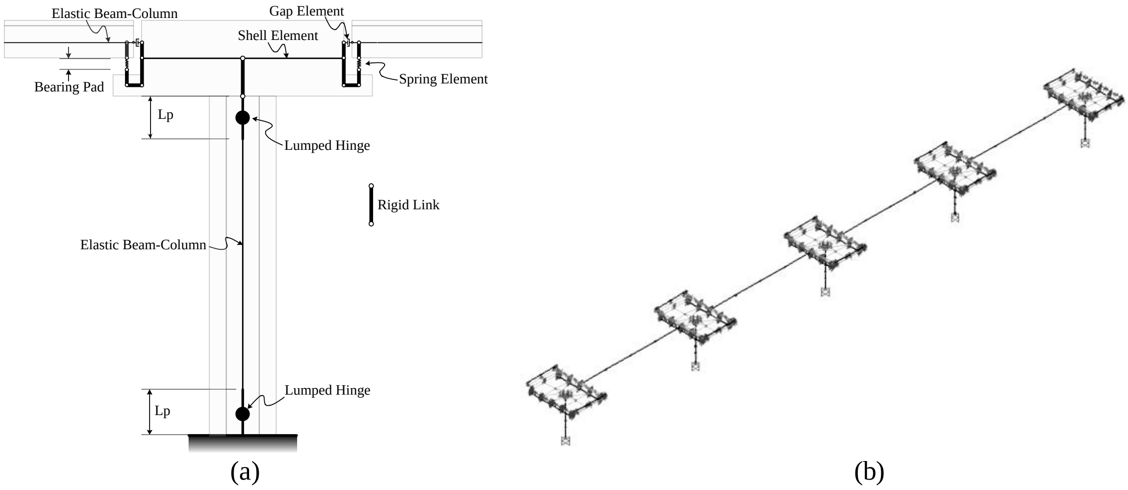


Figure 4. Analytical model of studied bridges: (a) Detail of each component modeling, and (b) Analytical Model

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 element as shown in Fig. 4. 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. Top of the column is rigidly connected to the 1.33 m. thickness cast-in-place reinforced concrete slab as shown in Fig.4. 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.

Bearing system of the studied bridges is modeled by elastic six degree-of-freedom spring element as shown in Fig. 5. This technique is similar as used by Akogul and Celik (2008). The stiffness of each degree of freedom is calculated by the beam theory (Yazdani, Eddy, and Cai, 2000).

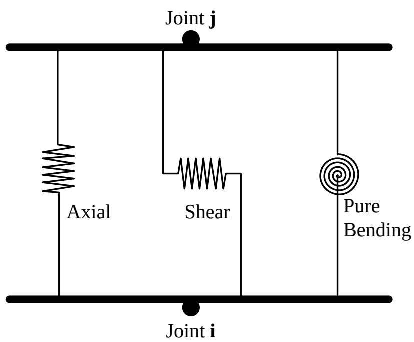


Figure 5. Three of the six degree-of-freedom spring element

The soil-structure interaction is neglected in this study. Then, boundary conditions at the bottom of the bridge's columns were assumed to be rigid supports.

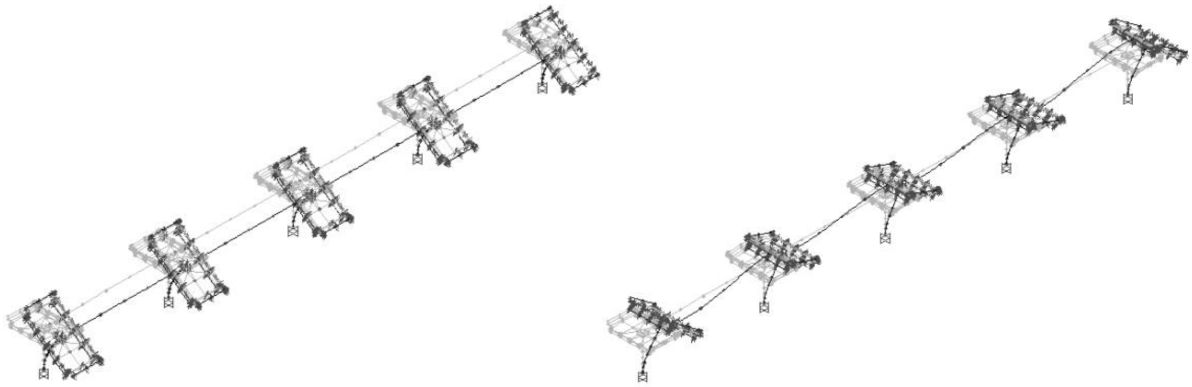
2.3. Dynamic Properties of the Studied Bridges

Dynamic properties of three different bridge's column heights are investigated in this study by modal analysis. The first transverse mode shape and first longitudinal mode shape of studied bridge are shown in Fig. 6(a) and Fig. 6(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 longitudinal direction is stiffer than transverse direction. The frequencies of the 6.3 m. column height were compared to the field test data. The frequency of the bridges in transverse direction and longitudinal direction from field test is 1.60-2.00 Hz and 2.00-2.80 Hz, respectively. It shows that the frequencies of the analytical model are in range of the field test data.

Table 1 Dynamic properties of three studied bridges

Column Height (m.)	Transverse Direction		Longitudinal Direction	
	Period (sec.)	Frequency (Hz)	Period (sec.)	Frequency (Hz)
4.5	0.450	2.224	0.272	3.679
6.3	0.610	1.640	0.358	2.796
15.0	1.746	0.573	0.980	1.020

According to the Seismic Retrofitting Manual for Highway Bridges published by the Federal Highway Administration (FHWA) in 2006, the invisible cracks in the structural member effect to the flexural rigidity of the members and should be considered in the seismic evaluation. This study also considered the effect of the cracked section in seismic performance evaluating process by applying FHWA manual (2006).



(a) (b)

Figure 6. Mode shape of the studied bridges in (a) Transverse direction, and (b) Longitudinal direction

3. CONSIDERED GROUND MOTION

The ground motion which uses in evaluating the seismic responses of the retrofitted bridges in this study is generated by a program for artificial motion generation (SIMQKE-1) proposed by Gasparini and Vanmarcke (1976) corresponding to the design spectrum for inner area of Bangkok, Thailand. This area was defined to be the low seismic zone but with high soil amplification of about 3.5. The generated ground motion was called simulated ground motion and shown in Fig. 7. The spectrum of the simulated ground motion is compared to the design spectrum and shown in Fig. 8.

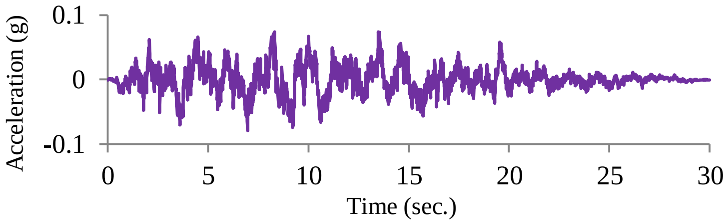


Figure 7. Artificial ground motions generated corresponding with the design spectrum for inner area of Bangkok

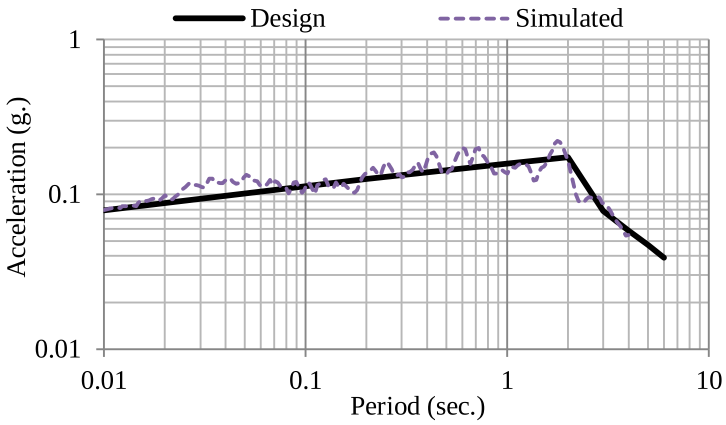


Figure 8. Comparison of spectrums of artificial ground motions and design spectrum

4. BEARING SYSTEM REPLACEMENT

4.1. Configuration of Bearing Pads and Mechanical Properties

The effect of bearing system replacement on the seismic performance of the studied bridges is investigated in this study. The bearing system which use in this study is the elastomeric bearing pad. Usually, the vertical load transferred from the superstructure to the sub-structure should be known for choosing the bearing pad's configuration. The transfer load for the studied bridges is about 58 tons. The bearing pad's configurations with four different thicknesses which use to replace in this study are shown in Fig. 9.

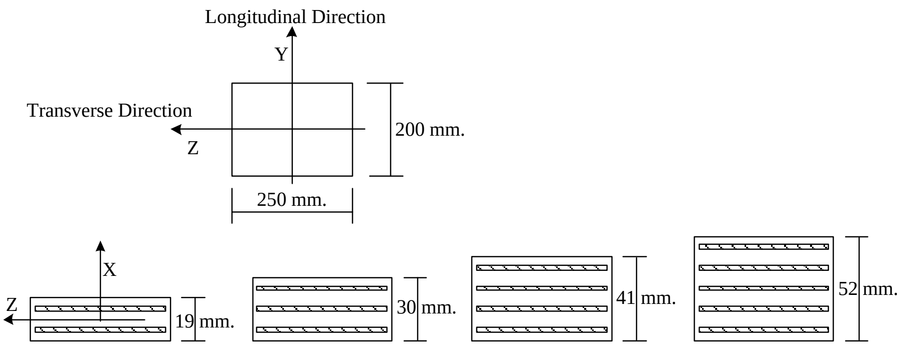


Figure 9. Bearing pad's configurations with four different thicknesses

The stiffness of the considered bearing pads were calculated by the beam theory (Yazdani, Eddy, and Cai, 2000). The shear modulus of the rubber, which used in calculating the stiffness of bearing pads, was accordance with AASHTO (2010). The summary of the stiffness of bearing pads in six degree of freedoms is shown in Table 2. It is shown that the stiffness of bearing pad decrease while the bearing pad's thickness increase.

Table 2 Six degree-of-freedom stiffness of four different height of bearing pads

Dimension (mm.)	K_X (kN/mm)	K_Y (kN/mm)	K_Z (kN/mm)	K_{RX} (kN-mm/rad.)	K_{RY} (kN-mm/rad.)	K_{RZ} (kN-mm/rad.)
200x250x19	1,533.98	3.46	3.46	23,686.3	7,989,466.7	5,113,258.7
200x250x30	789.70	2.14	2.14	14,662.95	4,113,032.7	2,632,340.9
200x250x41	531.72	1.55	1.55	10,618.00	2,769,358.9	1,772,389.7
200x250x52	400.79	1.22	1.22	8,322.21	2,087,424.7	1,335,951.8

4.2. Dynamic Properties of Three Studied Bridges with Replaced Bearing Pads

Modal analysis is performed to investigate the effect of bearing pad replacement on the dynamic properties of the studied bridges. The dynamic properties of the three studied bridges with replaced bearing pad are summarized in Table 3. It is shown that the bearing pad replacement significantly affect to the stiff structures as show in the period extension of the studied bridge which 4.5 m. column height. With 52 mm. bearing thickness, the maximum period shift was extended to 90% and 73% for stiff structure as transverse direction of bridge with 4.5 m. column height and longitudinal direction of all bridges, respectively. For the flexible structure as the transverse direction of bridge with 15 m. column height, the bearing pad replacement slightly affect to the dynamic properties that is extended to only about 6% when replaced by the bearing pads with 52 mm. thickness.

Table 3 Dynamic properties of three studied bridges with replaced by four different height of bearing pads

Column Height (m.)	Bearing Pad's Dimension (mm. x mm. x mm.)	Transverse Direction		Longitudinal Direction	
		Period (sec.)	Frequency (Hz)	Period (sec.)	Frequency (Hz)
4.5	Existing Bearing	0.526	1.901	0.273	3.660
	200x250x19	0.686	1.457	0.430	2.324
	200x250x30	0.804	1.243	0.453	2.207
	200x250x41	0.913	1.096	0.479	2.085
	200x250x52	1.010	0.990	0.471	2.124
6.3	Existing Bearing	0.722	1.385	0.383	2.610
	200x250x19	0.839	1.192	0.618	1.619
	200x250x30	0.926	1.080	0.634	1.578
	200x250x41	1.014	0.987	0.647	1.547
	200x250x52	1.096	0.912	0.660	1.515
15.0	Existing Bearing	2.098	0.477	1.132	0.883
	200x250x19	2.139	0.468	1.900	0.526
	200x250x30	2.166	0.462	1.952	0.512
	200x250x41	2.194	0.456	1.973	0.507
	200x250x52	2.222	0.450	1.985	0.504

4.3. Seismic Responses of Three Studied Bridges with Replaced Bearing Pads

Nonlinear time history analysis is performed to evaluate the seismic performance of the studied bridges with replaced the bearing pads in low seismic zone. The efficiency of the bearing replacement on the seismic responses reduction of the studied bridges can easily investigate by comparing the responses of replaced bearing system with the existing one as shown in Fig. 10 and 11.

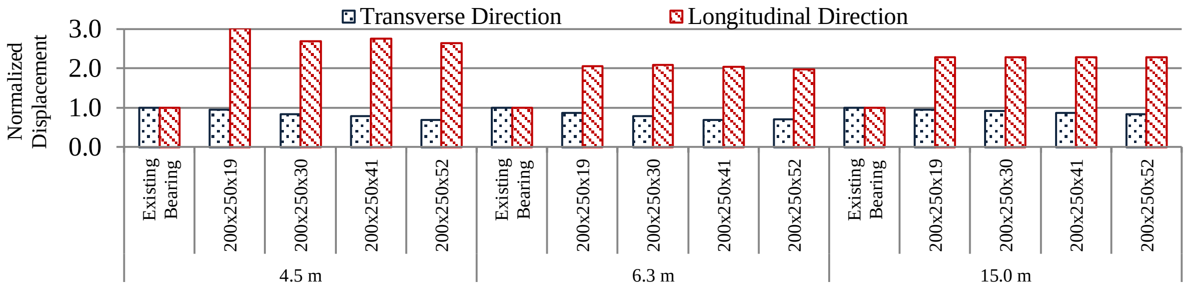


Figure 10. Normalized transverse and longitudinal displacements of three studied bridges with four different replaced bearing pads in low seismic zone

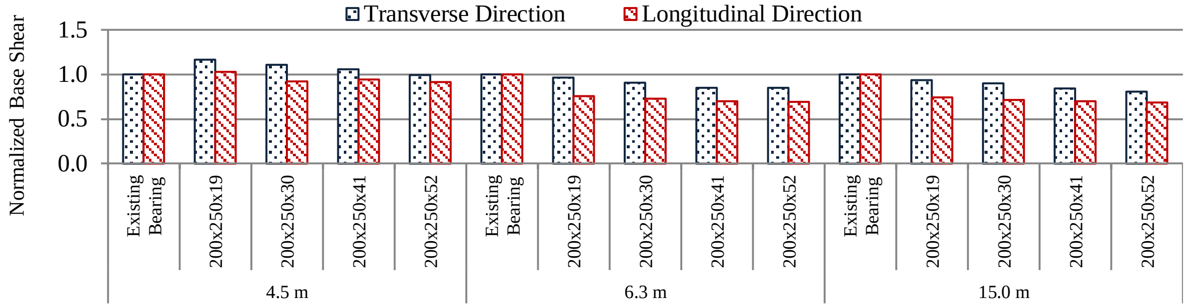


Figure 11. Normalized transverse and longitudinal base shear of three studied bridges with four different replaced bearing pads in low seismic zone

Fig. 10 shows that the longitudinal direction displacements of all studied bridges which replaced bearing system are increased because stiffness of the studied bridges in this direction softens after the bearing systems were replaced. The transverse direction displacements show the contrast results with the longitudinal direction, the displacements of the studied bridges decrease when the bearing systems were replaced. This result can be explained that the monitor point, which used for monitoring displacement, is at the top of column's top slab (top of substructure). Then, the displacements of substructure should decrease when the connecting systems between superstructure and substructure were softened.

Fig. 11 shows that for 6.3 m. and 15 m. high bridges, the bearing pads replacement can reduce the base shear force to about 25% - 30% and 5% - 20% for transverse and longitudinal direction, respectively, but it is not always reduce the seismic induced force. This can be clearly explained that the characteristic of design spectrum for Bangkok is the acceleration spectrum gradually increase with period up to 2 second, and then significantly decrease with period increase. Then, if the bearing pads replacement made the period extend but less than 2 second, it may lead to increase the seismic induced force to the bridges.

5. STEEL JACKETING OF BRIDGE'S COLUMNS

5.1. Configuration of Steel Jacketed Column

The steel jacketing is typically used for improving the strength and ductility of the reinforced concrete members. The construction and fabrication procedures typically used for steel jackets place constraints on their design. Limitations on handling stresses require that the shells have a minimum thickness of 10 mm (0.375 in), and restrictions on bending thick plates require a maximum thickness of 25 mm (1 in) (FHWA, 2006).

According to the suggestion of FHWA (2006), the details of retrofitted column of the studied bridges are shown in Fig. 12. The minimum gap between the existing column and steel shell is 2.5 cm. The strength of the grouted concrete was assumed to same as existing column. The 10 mm., 17 mm., and 25 mm. steel shell thickness were used in this study to investigate the effect of steel shell thickness.

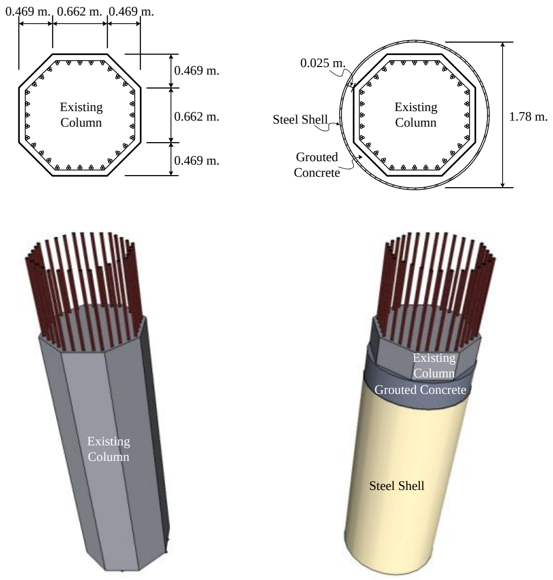


Figure 12. Details of the studied bridge's column retrofitted by steel jacketing

5.2. Strength and Ductility Behaviour of Studied Bridge's Column Retrofitted by Steel Jacketing

Moment-Curvature relationships of the retrofitted sections shown in Fig. 13 were calculated by the concept of fiber section analysis by SAP2000 (CSI, 2010). The results agree well with that by XTRACT used by Itani and Liao (2003). Fig. 13 shows that the steel jacketing significantly improves both strength and ductility of the column. Although the strength of the column jacketed by 25 mm. steel shell is significantly higher than the column jacketed by 10 mm. steel shell, the initial stiffness of three steel jacketed column bridges are not significantly different. This effect can be clearly explained while considering the dynamic properties of the retrofitted bridges.

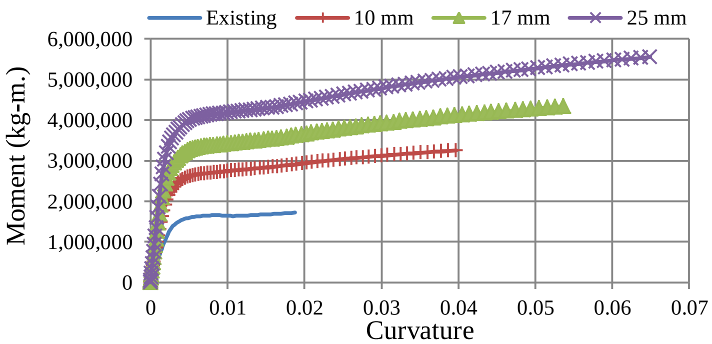


Figure 13. Moment-Curvature of three retrofitted studied bridge's columns

5.3. Dynamic Properties of Studied Bridges Retrofitted by Steel Jacketing

The generated moment-curvature relationships were defined to the analytical model. Then, modal analysis was performed to study the effect of retrofitting on the dynamic properties of the studied bridges. The dynamic properties of the retrofitted studied bridges are summarized in Table 4. It shows that: (1) with 10 mm. steel shell, natural periods of three bridges in transverse direction significantly decrease (31%-36%); (2) with 10 mm. steel shell, natural periods of three bridges in longitudinal direction are slightly (4%), moderately (13%), and largely (23%) decrease for the bridges with high, medium, and low legs, respectively; (3) the increasing of the thickness of steel shell from the minimum limitation (10 mm.) to maximum limitation (25 mm.) moderately and slightly increase in natural periods of three bridge systems in transverse and longitudinal direction, respectively; and (4) the increasing of natural period of three bridges in transverse direction is larger than that in longitudinal direction.

Table 4 Dynamic properties of three studied bridges retrofitted by three different thickness steel jacketing

Column Height (m.)	Steel Shell Thickness	Transverse Direction		Longitudinal Direction	
		Period (sec.)	Frequency (Hz)	Period (sec.)	Frequency (Hz)
4.5	Existing Column	0.526	1.901	0.273	3.660
	10 mm.	0.401	2.492	0.263	3.807
	17 mm.	0.374	2.674	0.252	3.970
	25 mm.	0.351	2.849	0.242	4.139
6.3	Existing Column	0.722	1.385	0.383	2.610
	10 mm.	0.537	1.864	0.341	2.935
	17 mm.	0.494	2.025	0.325	3.076
	25 mm.	0.456	2.193	0.310	3.223
15.0	Existing Column	2.098	0.477	1.132	0.883
	10 mm.	1.542	0.648	0.920	1.088
	17 mm.	1.411	0.709	0.868	1.152
	25 mm.	1.294	0.773	0.821	1.219

5.4. Seismic Responses of Studied Bridges Retrofitted by Steel Jacketing

In addition to investigation of static and dynamic properties of the steel jacket retrofitting, NTHA under generated ground motion corresponding with design spectrum was performed to evaluate the seismic responses of the retrofitted bridges. The efficiency of the column steel jacketing on the seismic responses reduction of the studied bridges can easily investigate by comparing the responses and base shears of retrofitted column with the existing one as shown in Fig. 14 - Fig 15, respectively.

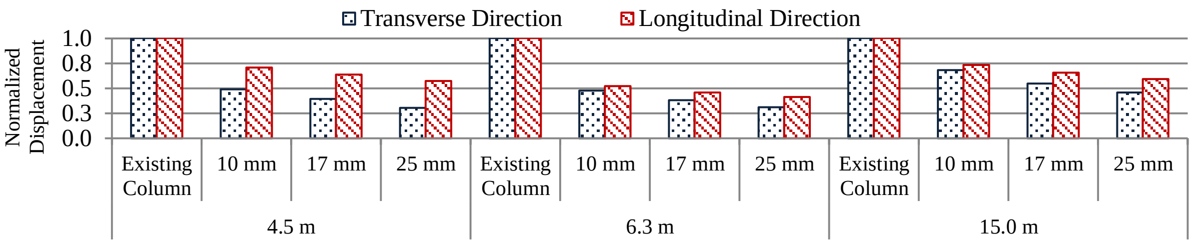


Figure 14. Normalized transverse and longitudinal displacements of three studied bridges with three different thickness steel jacketing on bridge's column in low seismic zone

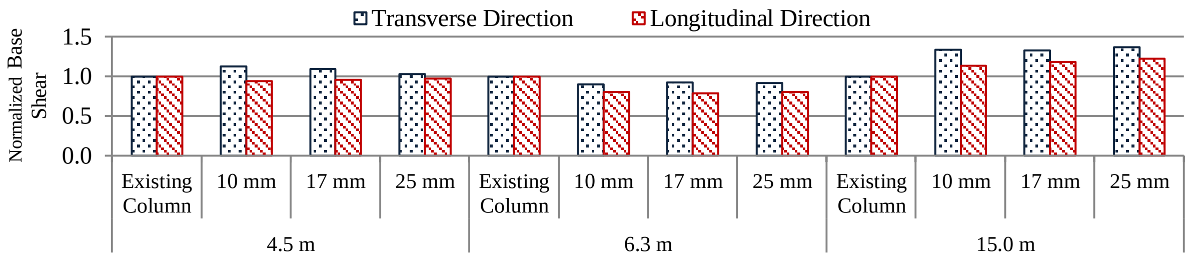


Figure 15. Normalized transverse and longitudinal base shear of three studied bridges with three different thickness steel jacketing on bridge's column in low seismic zone

Fig. 14 shows that the transverse displacement can be reduced to the maximum about 70 percent when the column of three bridges was jacketed by the 25 mm. thickness steel shell. It also shows that both transverse and longitudinal displacements decrease because the bridges systems stiffen after the bridge's columns were jacketed by steel shells.

Even if the displacements significantly decrease when the bridge's columns were jacketed by steel shells, the most of base shear forces slightly increase as shown in Fig. 15. This figure also shows that the base shear force is not always increase for all bridges because the jacketing steel shells to the bridge's columns made the dynamic properties of the retrofitted bridges change and may be possible changed to the position with higher or lower spectrum as same as the case of bearing pads replacement.

6. CONCLUSIONS

This study investigates the effects of two different seismic retrofitting methods for bridge's structures on the seismic responses of regular single column bridge with three different bridge's column heights situated in low seismic zone. The results lead to the following conclusions.

The bearing pads replacements make the studied bridge structures soften and lead to increment of displacements in longitudinal direction. Contrast to longitudinal direction, the displacement in transverse direction decreases because the connecting systems between superstructures and substructures soften. Even if the transverse displacements were reduced by bearing pads replacement, it slightly decreases and the variation of bearing pads heights slightly effect on the decreasing of the displacements especially in the bridge with high column.

The column steel jacketing made the structural system of the bridges stiffen. The displacements in both transverse and longitudinal largely decrease because the stiffness of the bridges in both directions increases. The variation of thickness of steel shells significantly effect on the decreasing of the displacements.

The effect of both retrofitting methods on base shear cannot be clearly concluded because, sometime, fundamental period was shifted to the higher acceleration position, and then lead to increase seismic induced force to the bridge but sometime fundamental period was shifted to the lower acceleration position, and then lead to decrease seismic induced force to the bridge. Therefore, the variation of base shear force should be checked after the bridge's structures were retrofitted.

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