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Influence of Longitudinal Constraints on Seismic Response of Cable-Stayed Bridges

R. Tuladhar[1], M.M. Elbadry[2] and W.H. Dilger[3]

ABSTRACT

The seismic response of cable-stayed bridges can be greatly affected by the type of longitudinal constraint provided to the deck by its connection to the towers. This is demonstrated in a parametric study on two cable-stayed bridges, each with different types of longitudinal constraints for the deck. Significantly enhanced response is obtained when the longitudinal constraints between the deck and the tower are changed from elastomeric bearing to fixed connections. It is also shown that using pinned or fixed deck-to-tower connections at both towers of a cable-stayed bridge causes the most unfavourable seismic response, particularly during cases of low velocity wave propagation.

INTRODUCTION

Cable-stayed bridges are innovative structures suitable for medium and long span crossings. Aesthetics, ease of construction and economic competitiveness have been the main reasons for the success of cable-stayed bridges. Considerable research on the static behaviour of these structures and on their response to wind effects has been done. However, the experience with the behaviour of these bridges in major earthquakes is limited. Only very few cases of earthquake induced damage of cable-stayed bridges have been reported (Filiatrault et al. 1993). The recent trend in bridge construction indicates a very favourable future for cable-stayed bridges and, therefore, many of these bridges can be expected to be built in zones of high seismic risk. This makes the seismic behaviour of these complicated structures an important topic of current research.

The seismic response of cable-stayed bridges is influenced by several factors related to the characteristics of seismic loading and to the physical characteristics of the bridge. One of the important physical characteristics which significantly affects the seismic response is the type of longitudinal constraints between the deck and the towers. The deck can be longitudinally constrained to the towers through fixed connections, pinned connections, rollers or elastomeric supports. The present paper discusses the results of a parametric study on the influence of these different types of longitudinal constraints on the seismic response of cable-stayed bridges. Two bridge examples are considered. The first is a conventional type cable-stayed bridge model derived from the Annacis Bridge in Vancouver, B.C. The second is a model derived from a multi-span bridge design developed and proposed (but not built) by SCI-Strait Crossing Inc. for the construction of a fixed link across the Northumberland Strait to connect Prince Edward Island to New Brunswick in Eastern Canada (Dilger et al. 1992). The study shows that longitudinal constraints between the deck and the towers of cable-stayed bridges significantly affect their seismic response. This effect is greatest, particularly during low velocity wave propagation, when pinned or fixed connections between the deck and the tower are used at both towers.

[I] Post-Doctoral Fellow, Dept. of Civil Engineering, The University of Calgary, Calgary, Canada, T2N 1N4
[II] Assistant Professor, Dept. of Civil Engineering, Concordia University, Montréal, Canada, H3G 1M8
[III] Professor, FRS, Dept. of Civil Engineering, The University of Calgary, Calgary, Canada, T2N 1N4.

INVESTIGATION ON A CONVENTIONAL TYPE CABLE-STAYED BRIDGE

Bridge geometry

This is a 465 m main span bridge derived from the Annacis Bridge in Vancouver, B.C. The bridge has a composite deck and concrete towers. The number of cables has been reduced to 16 from the original 48 per tower and correspondingly the inertia of the deck has been increased. The geometry of this bridge is shown in Fig. 1. Further details on the bridge properties can be found in Tuladhar (1995).

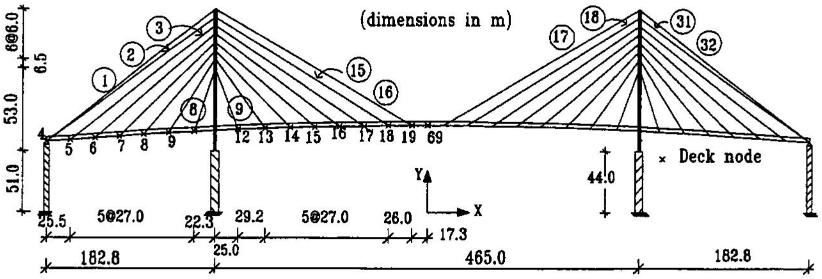


FIG. 1 Bridge Geometry of a Conventional Type Cable-Stayed Bridge

Different types of longitudinal constraints

In the original bridge, the deck is supported at both towers on elastomeric bearings. In the present study, these bearings are modelled by flexible beam elements having lateral and vertical stiffnesses equal to those of the elastomeric bearing. This type of bearing is labelled as Elastic-Elastic (E-E) and is shown schematically in Fig. 2(a). To study the effects of different longitudinal constraints, the elastomeric bearings are replaced by different combinations of pins, rollers and fixed supports at the two towers. The different combinations of support conditions considered are Pinned-Rollers (P-R), Pinned-Pinned (P-P), Rollers-Rollers (R-R), and Fixed-Fixed (F-F) as shown respectively in Figs. 2(b) to (e). At the end piers, the roller supports of the original bridge are retained for all cases.

(a) Elastic-Elastic (E-E) (b)Pined-Roller (P-R)

(c)Pined-Pined (P-P) (d) Roller-Roller (R-R) (e) Fixed-Fixed (F-F)

FIG. 2 Different Longitudinal Constraints between the Deck and the Tower

Mode frequency and seismic response comparison

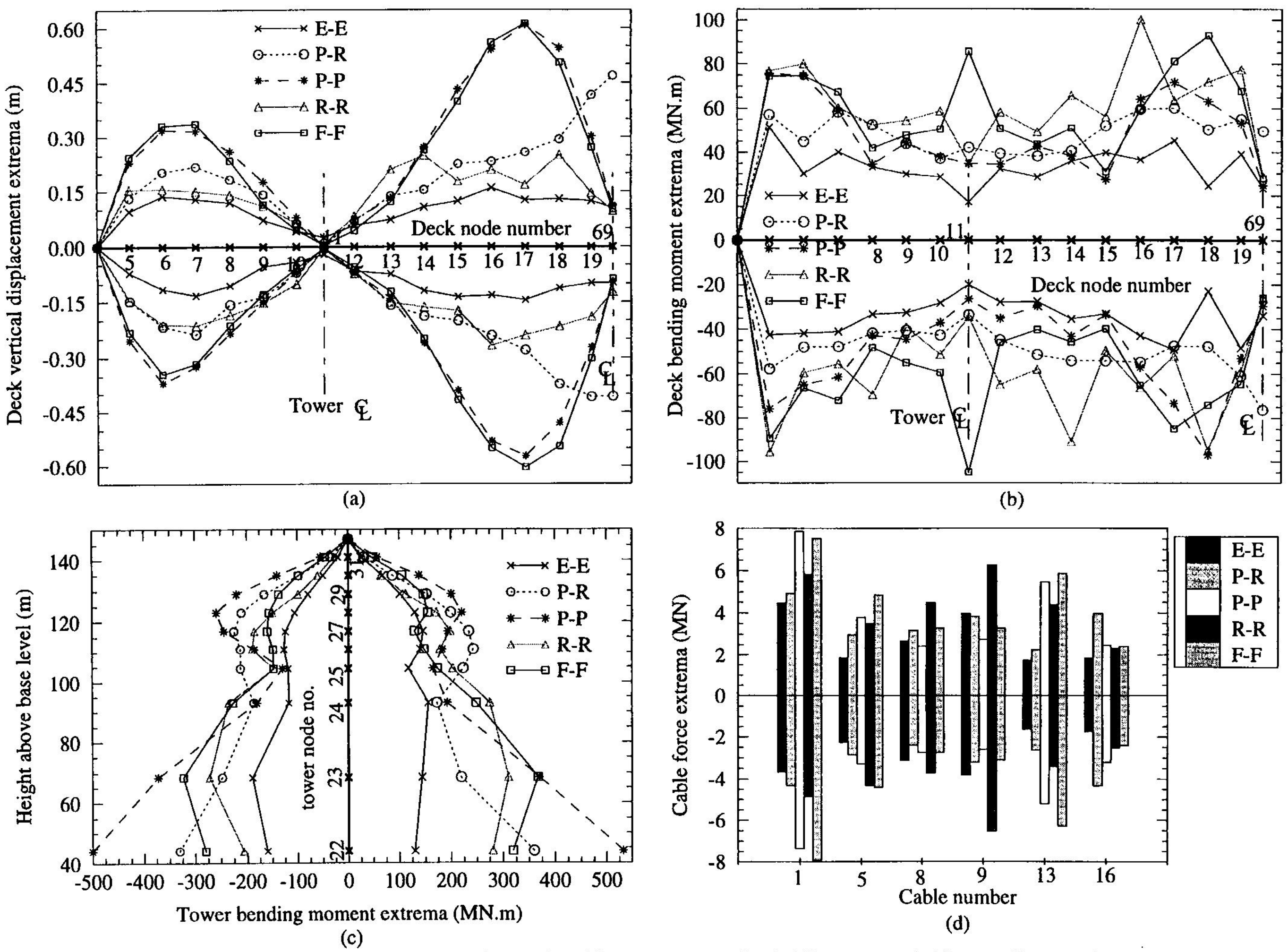
Modal and linear seismic analyses were performed on the bridge described in Fig. 1 with the above mentioned five different types of longitudinal constraints between the deck and tower. Each seismic analysis was performed for a duration of 15 seconds. Out of these 15 seconds, the first 10 seconds were with forced motion due to the El Centro Earthquake ground acceleration input in the vertical and longitudinal directions and the latter 5 seconds were with free motion. The direct integration method was employed and damping was not considered in the analysis. The mode frequencies and the seismic response of the bridge are discussed below.

From the modal analysis, it was observed that the first few antisymmetric mode frequencies were considerably affected by the type of deck-to-tower connection. However, the symmetric mode frequencies and the higher mode frequencies were not as much affected. The analysis gives the first antisymmetric mode frequency as 0.226, 0.201, 0.251, 0.079, and 0.252 Hz and the first symmetric mode frequency as 0.232, 0.245, 0.239, 0.223, and 0.244 Hz for the connection types E-E, P-R, P-P, R-R, and F-F, respectively. The first antisymmetric mode frequency decreased drastically when the R-R type connection is used, as compared to the other connection types. Because of the unsymmetric boundary conditions for the connection type P-R, significant interaction occurs between the symmetric and unsymmetric modes and this significantly affects the response of the bridge at mid-span. For the other symmetric connections, the modes participating in one direction have almost zero participation factors in other directions.

Figure 3 shows the comparison of the vertical displacement time histories at deck mid-span. The large displacements for the connection type P-R is due to the contribution of the longitudinal motion. For symmetric connection types, the longitudinal motion does not contribute to the deck displacement or bending moment at mid-span which acts like a hinge point for antisymmetric loads. In Fig. 4 the extreme values of vertical displacements and bending moments of deck, bending moments of tower, and the cable forces due to seismic loads are presented. As expected, the original connection E-E shows the best behaviour of all connections. Connections P-P and F-F result in the largest displacements. Again for the unsymmetric connection P-R, the displacements are quite enhanced at nodes near deck mid-span. The deck and tower bending moments, and cable forces are also higher for connections P-P and F-F. Connection F-F attract significantly higher deck bending moment at tower support. It is also interesting to note that for connection E-E, not only the deck displacement and bending moment, but also the tower moments are smaller than those for connection R-R. The absolute peak values of moments at the tower base are 492, 607, 639, 960, and 1055 MN.m for connections E-E, R-R, P-R, P-P, and F-F, respectively.

The type of deck-to-tower connection affects the overall longitudinal stiffness of the bridge and the seismic response of the bridge is found quite sensitive to it. For this particular bridge subjected to the 1940 El Centro Earthquake, the E-E type connection gives the most favourite response of all connections.

FIG. 3 Comparison of the Vertical Displacement Time History at Deck Mid Span



(a) (b)

(c) (d)

FIG. 4 Comparison of Extreme Values of Bridge Response for Different Deck-Tower Connection Types

INVESTIGATION ON A MULTI-SPAN CABLE-STAYED BRIDGE

Bridge geometry

A multi-span cable-stayed bridge was one of the designs developed by SCI-Strait Crossing Inc. during a competition for the design and construction of a fixed link across the Northumberland Strait in Eastern Canada. The planned bridge is 13 km long comprising over 40 spans of 250 m length and shorter spans for approaches. A 500 m long continuous deck supported by two towers constitutes a typical module of the bridge. Modules are interconnected by expansion joints transferring shear only. The bridge deck is a 0.6 m deep and 12 m wide solid concrete slab and the towers are also concrete with $E_c = 35$ GPa. A typical module of the bridge is shown in Fig. 5. Further details of the bridge can be found in Dilger et al. (1992).

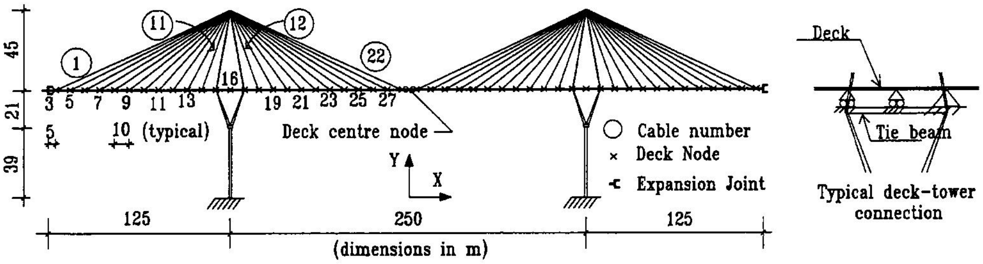


FIG. 5 Geometry of a typical module of the multi-span bridge

Seismic response and effect of wave propagation

A linear seismic analysis was performed with similar loading and duration as for the previous bridge, but damping was considered in this case. To consider the interaction of adjacent modules, the three typical modules of Fig. 6 were used for the seismic analysis. Considering 3 modules was found adequate for representative seismic analysis of the complete bridge (Tuladhar and Dilger 1994). The effect of wave propagation was studied on the 3-module bridge using six different wave velocities: infinite velocity (uniform motion), 1560, 780, 312, 200, and 156 m/s.

The structural system shown in Fig. 5 provides two longitudinal constraints (one at each tower) between the expansion joints. This was found most suitable to provide overall stiffness for live load (Sherif 1991). But for such configuration, very large forces and displacements were observed at the lower wave propagation velocity. At lower wave velocities, the towers can be moving out of phase in the longitudinal direction and this can cause very large deck deflection and high deck axial forces. Figure 7 shows the deflected shape of the central module after 12.0 s. In this figure, the simultaneous inward sway of the two towers and consequently an excessive sagging of the deck towards mid-span is evident.

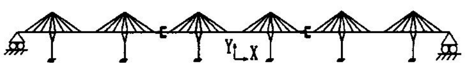


FIG. 6 A Three-Module Bridge

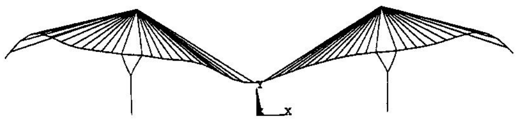


FIG. 7 Deflected Shape of Central Module at t = 12.0 s

Figure 8(a) shows the time history of deck node 27 vertical displacement and Fig. 8(b) shows the extreme values of vertical displacement of the deck for different wave velocities. From these figures, the excessive deck deflection for lower wave velocities is evident. Similarly, high deck forces, cable forces etc. were observed at lower wave velocities. Detailed discussion of these results can be found in Tuladhar (1995). While the longitudinal constraints at two towers are efficient for live load cases, they are detrimental for the seismic response during lower wave velocities.

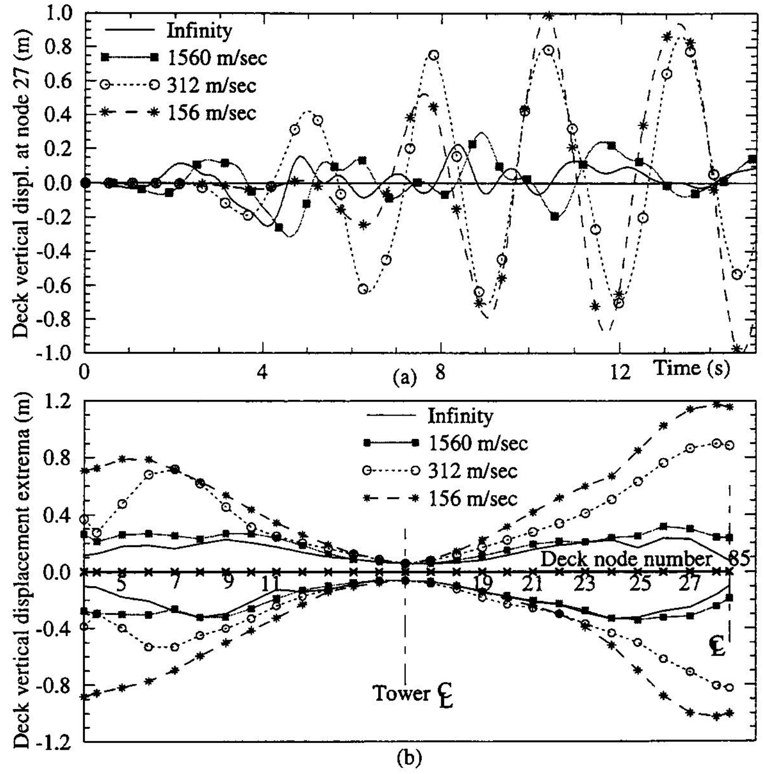
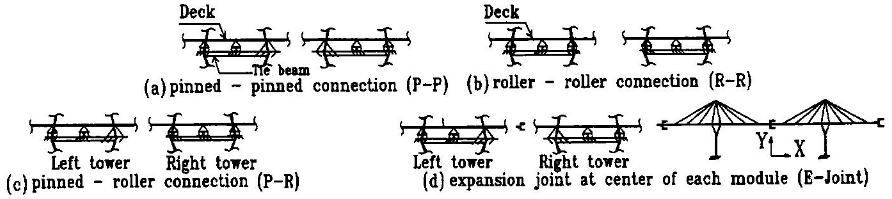


FIG. 8 Comparison of (a) Time History, and (b) Extreme Values of Deck Vertical Displacements for Different Wave Velocities

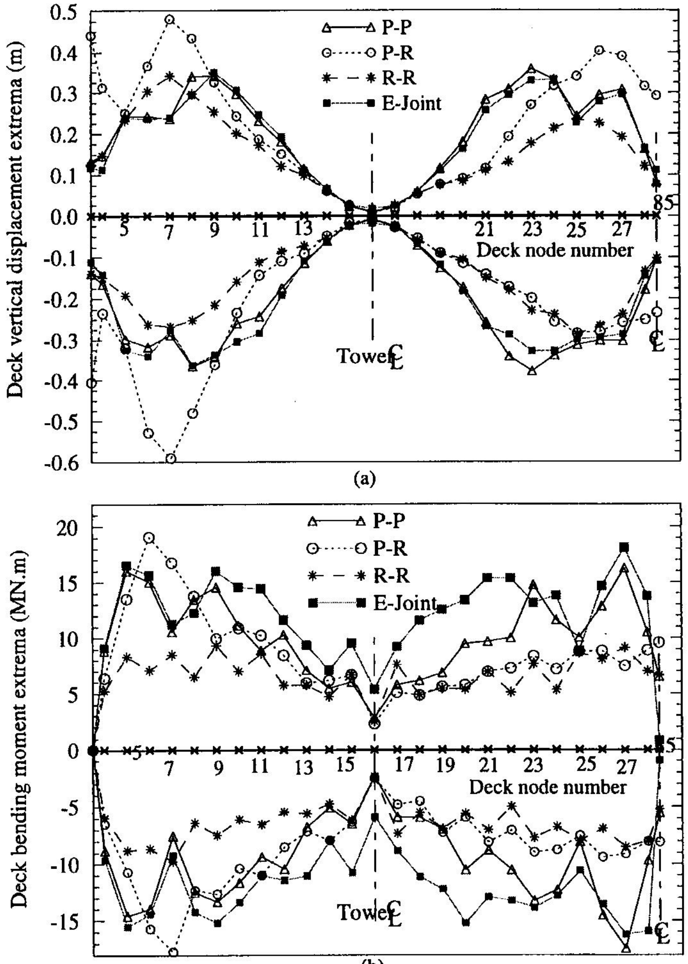
Effect of different longitudinal constraints

In the previous section, it was discussed that the longitudinal constraints at the two towers of each module can cause severe impact on the seismic response of the bridge at lower wave velocities. In this section, the effects of different types of longitudinal constraints are investigated. Figure 9 shows four cases of longitudinal constraints: (a) Pinned-Pinned (P-P), (b) Roller-Roller (R-R), (c) Pinned-Roller (P-R), and (d) an expansion joint (E-Joint) at the middle of each module. The longitudinal constraint P-P is the original case, and the E-Joint case is the same as P-P but with an expansion joint at the middle of each module.



(a) pinned - pinned connection (P-P)
(b) roller - roller connection (R-R)
(c) pinned - roller connection (P-R)
(d) expansion joint at center of each module (E-Joint)

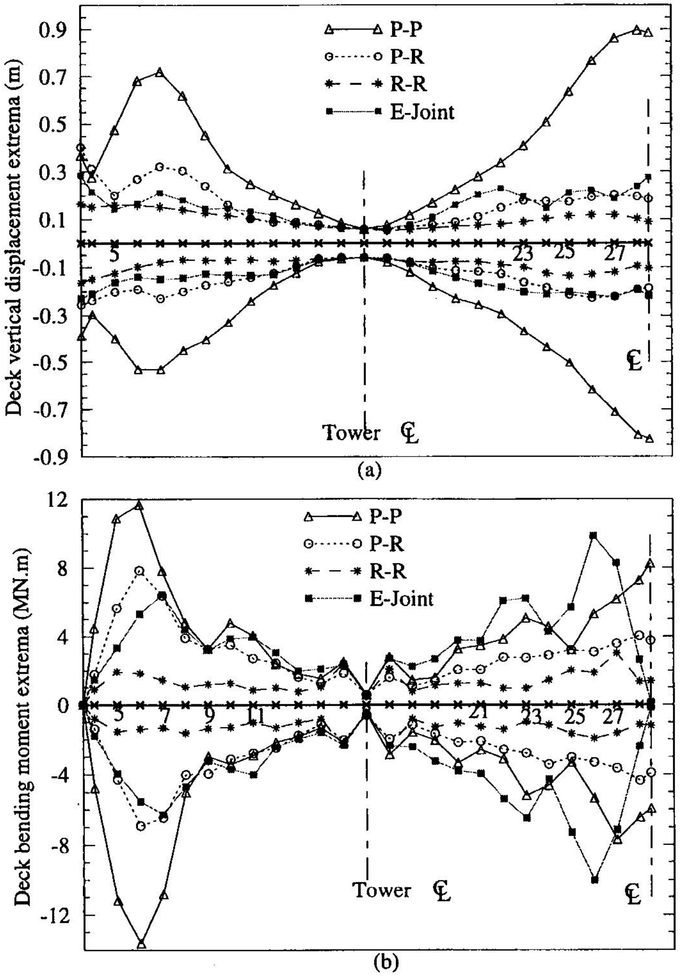
FIG. 9 Different Cases of Longitudinal Constraints of the Multi-Span Bridge



(a)

(b)

FIG. 10 Undamped Seismic Response Comparison of Bridges with Diff. Long. Constraints for Uniform Ground Motion



(a)

(b)

FIG. 11 Damped Seismic Response Comparison of Bridges with Diff. Long. Constraints for Wave Velocity of 312 m/s

Mode frequency analyses were performed for a one-module bridge with the different longitudinal constraints of Fig. 9. The first antisymmetric mode frequency changed from 0.290 Hz for the P-P case to 0.207 Hz, 0.177 Hz, and 0.241 Hz, for the P-R, R-R, and E-Joint cases, respectively. For the three-module bridge with different longitudinal constraints, the seismic responses under the effect of uniform ground motion were compared with those for the different cases of wave propagation. Figure 10 shows the extreme values of vertical displacements and bending moments of the deck for the uniform motion case. Significant differences in seismic response can be observed due to the change in the longitudinal constraints. For the unsymmetric case of P-R connections, the symmetric and antisymmetric modes interact. The displacement toward the side span is significantly larger for this case than for the others because of the larger interaction between adjacent modules. The deck displacement extreme values and the time history are similar for the P-P and E-Joint cases, however, the deck moment extreme values at several nodes are significantly larger for the E-Joint case. The seismic response of the bridge with P-P longitudinal constraint is substantially different from other cases at lower velocity wave propagation earthquake. Figure 11 shows the extreme values of displacements and bending moments of the deck for the wave velocity of 312 m/sec. More detailed results and discussion can be found in Tuladhar (1995). As mentioned earlier, for the P-P case with longitudinal constraints at the two towers, at lower wave velocities, the towers can move out of phase longitudinally causing very high vertical displacements, axial forces, and bending moments in the deck, tower moments as well as cable forces. The responses are drastically improved when the longitudinal constraints are released in some way. The seismic response of the bridge with R-R longitudinal constraint is considerably smaller than for other longitudinal constraint types for the uniform ground motion as well as wave propagation cases.

SUMMARY AND CONCLUSIONS

The seismic response of cable-stayed bridges is quite sensitive to the type of longitudinal constraint between the deck and the tower. This was demonstrated on two cable-stayed bridges each having different types of longitudinal constraints for the deck. First, a conventional type cable-stayed bridge model derived from the Annacis Bridge in Vancouver, B.C., was studied. For this particular bridge subjected 1940 El Centro Earthquake, the elastomeric bearing supports for the deck gave the best seismic response. Significant differences in deck displacements as well as deck, tower and cable forces were observed when longitudinal constraints were changed. In the second example, a multi-span cable-stayed bridge was investigated. Similar impact of the longitudinal constraint type on the seismic response was observed as for the first bridge. Moreover, it was demonstrated that fixing the deck longitudinally at two towers can lead to very large forces in the bridge particularly during lower velocity wave propagation cases and, thus, can have a detrimental effect on the seismic response of the structure.

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