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Non-Linear Seismic Response of Single Span Simply Supported Slab-on-Girder Steel Highway Bridges with Damaged Bearings

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ABSTRACT

Non-linear inelastic seismic response of existing single span simply supported bridges with damaged bearings that can remain stable and slide are investigated. It is found that narrower bridges with longer spans may have considerable sliding displacements and fall off their supports if adequate seat width is not provided. It is also found that for the same ratio of friction coefficient to peak ground acceleration, the sliding displacement of a structural system is linearly proportional to the amplitude of the peak ground acceleration beyond a certain threshold value. The distribution of the energy content of an earthquake, which is related to its velocity time history, can be an indication of the propensity of an earthquake to cause high sliding displacements. Ground motions with high frequency content or high A_p/V_p ratio may produce smaller sliding displacements than those with relatively lower A_p/V_p ratios.

INTRODUCTION

In the North American highway system, there are many short to medium span old steel bridges supported by sliding-bearings that were never designed for seismic-resistance and are thus vulnerable to earthquakes. The loss of lateral support due to bearing damage has been responsible for several bridge collapses in past earthquakes, markedly during the 1971 San Fernando California, 1976 Guatemala, and 1980 Eureka earthquakes (US.., 1987). Even minor earthquakes have caused failure of anchor bolts, keeper bar bolts, and welds in bridge bearings (US.., 1987). For many types of low-profile stable bearings, when the anchor bolts at the fixed type of sliding-bearings are severed, the deck is free to slide. When such a failure happens, frictional forces will develop between the disconnected bridge components. This friction is, in some cases, the only possible "second line of defense".

Past earthquakes have shown that disconnected bridge components can result in a most severe seismic hazard, especially in multi-span simply supported reinforced concrete bridges. Therefore, researchers have investigated the effectiveness of, and demonstrated the need for, longitudinal restrainer ties at the expansion joints of these types of bridges (Tseng and Penzien, 1973; Penzien and Chen, 1975). Analytical case studies on the seismic response of such bridges, considering their sliding in the longitudinal direction among many factors, have been performed by many researchers (Tseng and Penzien, 1973; Chen and Penzien, 1975; Zimmerman and

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Brittain, 1981; Imbsen and Penzien, 1986). Some of their findings are equally applicable to steel and concrete bridges, such as, for example, the importance of providing shear keys in bridges (Imbsen and Penzien, 1986). However, seismic response problems germane to steel bridges, (including single span bridges) such as the need to restrain the displacement of unstable rocker bearings (Douglas, 1979), have generally received far less research attention.

Recent North American earthquakes have demonstrated that steel bridges can also be vulnerable to earthquakes (EERI, 1990; Astaneh, 1993; EERI, 1994). A sizable number of the existing steel bridges have never been designed to resist earthquakes, particularly in Eastern North America, and a seismic retrofit of all these existing steel bridges is clearly prohibitive from a cost perspective. Fortunately, if the aforementioned "second line of defense" provided by frictional forces at the supports could be proven effective and sufficient to allow single-span simply supported steel bridges to resist small to moderate earthquakes, considerable savings are possible.

For seismic excitation in the longitudinal direction, when the friction resistance at the disconnected parts of single-span simply supported steel bridges is exceeded, collision of the deck with the abutment walls may occur repeatedly. Since there are abutment walls at each end of the bridge, the movement of the deck is restricted by the width of the expansion joint which is generally no more than 40-50 mm for the span ranges considered herein. Hence, in this direction, without concurrent severe abutment failures, the bridge is well constrained and the risk of failure is generally low. For seismic excitation in the transverse direction, when the friction forces at the disconnected parts of single-span simply supported steel bridges are exceeded, the bridge deck slides, and may fall off its support. Should that happen, the portion of the gravity load previously supported by the exterior girder is transferred to the nearest interior girder by cantilever action of the slab. If the slab does not have enough strength to resist this additional load, the exterior portion of the bridge deck could be severely damaged and make the bridge unusable. Therefore, sliding in the transverse direction seems critical and is studied in this paper.

For the purpose of this study, a nonlinear time-history analysis capable of accounting for the nonlinear response at the expansion joints, namely impact and friction, is conducted using the program NEABS (Penzien et al., 1981). The objective in performing this analysis is to find the maximum transverse sliding displacement at the bearings as a function of various earthquake intensities, friction coefficients, span length, and span width. Existing knowledge on the modeling techniques and nonlinear behavior of bridge components (Tseng and Penzien, 1973; Imbsen and Penzien, 1986; Douglas, 1979; Kawashima and Penzien, 1976, Imbsen and Penzien, 1979; Wilson, 1986) is used throughout this research to generate new information applicable specifically to single-span simply-supported slab-on-girder steel bridges.

PROPERTIES OF THE BRIDGES STUDIED AND OTHER ASSUMPTIONS

To investigate the seismic performance of existing steel bridges never designed to resist earthquakes, 2 and 3 lane bridges with spans of 20, 30, 40, 50 and 60 metres have been designed in compliance with the 1961 edition of the American Association of State Highways Officials code (AASHO, 1961), which is judged to be representative of the design requirements in effect at the time most highway bridges were constructed in North America. The 2 and 3-lane bridges have, respectively, 8 and 12 metres widths and girders spaced at two metres intervals. As seen in Figure 1, the superstructure of these bridges is generally attached to one abutment by fixed bearings and on the other abutment supported by expansion bearings. The fixed type of sliding-bearings is shown in Figure 2. The expansion type of bearing is nearly identical, but without the longitudinal stopper bars. A one metre overhang is assumed on both sides of the decks for all the bridges. Reinforced concrete deck is 200 mm thick.

Only low-profile stable bearings are considered in this study. Although it might be possible to extend the findings to cases where girders sit directly on the abutments after the failure of unstable bearings, this has not been formally investigated herein. The friction coefficient is assumed constant throughout the sliding history and the effect of vertical ground accelerations on friction forces at the bearings has been neglected assuming that the resulting fluctuations of frictional resistance will average themselves during any sliding excursion, simultaneously abating the significance of vertical accelerations. Skewed bridges deserve a particular treatment which is obviously beyond the scope of work reported herein. Abutment and foundation deformations and/or damage as well as soil-structure interaction are also beyond the scope of this study.

EARTHQUAKE LOADING

Ground motions can be characterized by the peak acceleration to peak velocity ratio, A_p/V_p, where A_p is expressed in units of the gravitational acceleration and V_p is expressed in meters per second (Zhu et al., 1988). Ground motions with very high frequency content would produce high A_p/V_p ratios whereas ground motions with intense long duration acceleration pulses would generally lead to low A_p/V_p ratios. The ground motions with highly irregular acceleration patterns result in intermediate A_p/V_p ratios.

Accordingly, four Western USA earthquake records having intermediate A_p/V_p ratios, all recorded on rock or stiff soil, and two Eastern Canada earthquake records having high A_p/V_p ratios, one on bedrock and another on alluvion deposit, are considered for the non-linear time history analyses. The properties of all the earthquake motions used in this study are shown in Table 1.

SLIDING OF BRIDGES IN THE TRANSVERSE DIRECTION

A total of 300 cases are analyzed using the program NEABS to obtain the sliding displacements at the support of previously described 2 and 3-lane simply supported bridges as a function of span length for various friction coefficient to peak ground acceleration (PGA) ratios, μ_f / A_p (A_p is expressed as a percentage of g), using the four Western USA and two Eastern Canada earthquakes listed in Table 1. The results are shown in Figures 3 to 6. In these figures, the vertical axis is the support sliding displacement in mm per unit PGA and the horizontal axis is the span length. Additionally, keeping the μ_f / A_p ratio constant, but changing the magnitude of the PGA, 60 new cases are also analyzed to obtain a relationship between the magnitude of the PGA and sliding displacement. It is found that, for the same μ_f / A_p ratio, the sliding displacement is linearly proportional to the amplitude of the PGA. This dependency is analytically demonstrated elsewhere (Dicleli and Bruneau, 1995).

The transverse direction sliding displacements of 2 and 3-lane simply supported bridges obtained by averaging the results from the four Western USA earthquakes are depicted respectively in Figures 3 and 4. As seen in the figures, the sliding displacement increases with increasing span length and decreasing μ_f/A_p ratio. Obviously, larger forces are applied on the bridges with longer span. This subsequently results in a higher amount of energy to be dissipated by friction and consequently larger sliding displacements. For the range of spans considered, the attracted seismic forces per unit mass are smaller for wider bridges than those for narrower bridges of the same length and therefore their sliding displacements are smaller as seen in Figures 3 and 4. Figures 5 and 6 are, respectively, for the transverse sliding displacements of 2 and 3 lanes bridges for Eastern Canada earthquakes. Almost the same trend as for Western USA earthquakes is observed in this case.

For the same bridges, the average of sliding displacements obtained using Western USA earthquakes are larger than those obtained using Eastern Canada earthquakes. Eastern Canada earthquakes, which have very high A_p/V_p ratios, contain very high frequency pulses which load and unload the structure in short time periods, and therefore, once the structure slides, this sliding motion cannot be sustained for a long time since the force applied on the system remains above the threshold of friction only for a short duration. Western USA earthquakes, which have intermediate A_p/V_p ratios, contain frequency pulses longer than those of Eastern Canada earthquakes. Thus, the sliding motion can be sustained for a longer time. Consequently, ground motions with high A_p/V_p ratio generally produce smaller sliding displacements than those with relatively lower A_p/V_p ratios. This is confirmed by comparison of Figures 4 and 6.

CONCLUSIONS

- For the same ratio of friction coefficient to peak ground acceleration, the sliding displacement of a structural system is linearly proportional to the amplitude of the peak ground acceleration.

- For the ranges of spans considered, sliding displacement increases with increasing span length and decreasing μ_f/A_p ratio.

- Sliding displacements of 3 lane bridges are smaller than those of 2 lane bridges. Nevertheless, the displacements are not considerable in either case for the earthquakes and range of spans considered.

- The distribution of the energy content of an earthquake, which is related to its velocity time history, can be an indication of the propensity of an earthquake to cause high sliding displacements. Ground motions with high frequency content or high A_p/V_p ratio produce very small sliding displacements, whereas ground motions with intense long duration acceleration pulses or low A_p/V_p ratios can cause remarkable sliding displacements. Accordingly, bridges in Western North America may potentially be subjected to higher sliding displacements than those in Eastern North America.

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REFERENCES

American Association of State Highway Officials, 1961 *Standard Specifications for Highway Bridges*, Washington, D.C..

Astaneh, A.A., 1993, Proceedings of the first U.S. Seminar on the Seismic Evaluation and Retrofit of Steel Bridges.

Chen, M., Penzien, J., 1975, "Analytical Investigations of the Seismic Response of Short, Single or Multiple-Span Highway Bridges", *Report No. EERC 75-4*, Earthquake Engineering Research Center, University of California, Berkeley, CA..

Dicleli, M. and Bruneau, M., 1995, "An Energy Approach to Sliding of Single Span Simply Supported Slab-on-girder Steel Highway Bridges With Damaged Bearings", Earthquake Engineering and Structural Dynamics, In print.

Douglas M. B.,1979,"Experimental Dynamic Response Investigations of Existing Highway Bridges",*Proceedings of A Workshop on Earthquake Resistance of Highway Bridges*, pp 497-523.

Earthquake Engineering Research Institute, 1990, "Loma Prieta Earthquake Reconnaissance Report", Spectra, Supplement to Volume 6.

Earthquake Engineering Research Institute, 1994, "Northridge Earthquake January 17, 1994, Preliminary Reconnaissance Report", Earthquake Engineering Research Institute.

Imbsen, R. A., Penzien, J., 1979, "Evaluation of Analytical Procedures Used in Bridge Seismic Design", *Proceedings of A Workshop on Earthquake Resistance of Highway Bridges*, pp 468-496.

Imbsen, R. A., Penzien, J., 1986, "Evaluation of Energy Absorbing Characteristic of Highway Bridges Under Seismic Conditions", *Report No. EERC 86/17*, Earthquake Engineering Research Center, University of California, Berkeley, CA..

Kawashima, K., Penzien, J., 1976, "correlative Investigations on Theoretical and Experimental Dynamic Behavior of a Model Bridge Structure", *Report No. EERC 76-26*, Earthquake Engineering Research Center, University of California, Berkeley, CA..

Penzien, J., Chen, M., 1975, "Seismic Response of Highway Bridges", *Proceedings of the US National Conference on Earthquake Engineering.*

Penzien, J., Imbsen, R., Liu, W. D., 1981, "NEABS, Nonlinear Earthquake Analysis of Bridge Systems", University of California, Berkeley, CA..

Tseng, W. S., Penzien, J., 1973, "Analytical Investigations of The Seismic Response of Long Multiple-Span Highway Bridges", *Report No. EERC 73-12*, Earthquake Engineering Research Center, University of California, Berkeley, CA..

US Department of Transportation, 1987, *Seismic Design and Retrofit Manual for Highway Bridges*, Federal Highway Administration, FHWA-IP-87-6.

Wilson, J. C., 1986, "Analysis of The Observed Seismic Response of A Highway Bridge", *Earthquake eng. struct. dyn.*, 14, 339-354.

Zimmerman, R.M., Brittain, R.D., 1981, "Seismic Response of Multi-Span Highway Bridges", *Third Canadian Conference on Earthquake Engineering*, pp.1091-1120.

Zhu, T. j., Heidebrecht, A. C., Tso, W. K., 1988, "Effect of Peak Ground Acceleration to Velocity Ratio on Ductility Demand of Inelastic Systems", *Earthquake eng. struct. dyn.*,16, 63-79.

Table 1 Properties of the selected earthquakes

Site (1)	Location (2)	Date (3)	Component (4)	Magnitude (5)	Source Distance (km) (6)	Soil Type (7)	Max. Acc. (xg) (8)
Imperial Valley	El Centro	1940	S00E (NS)	6.6	8	Stiff soil	0.348
Kern County	Taft	1952	S69E	7.6	56	Rock	0.179
San Fernando	Pacoima Dam	1971	S16E	6.6	8	Rock	1.170
Parkfield	Chaloma Shand. 2	1966	N65E	5.6	0.1	Stiff soil	0.480
Québec	Chicoutimi-Nord	1984	N18E	6.0	43	Rock	0.131
Québec	Baie-St-Paul	1982	S59E	6.0	91	Alluvium	0.174

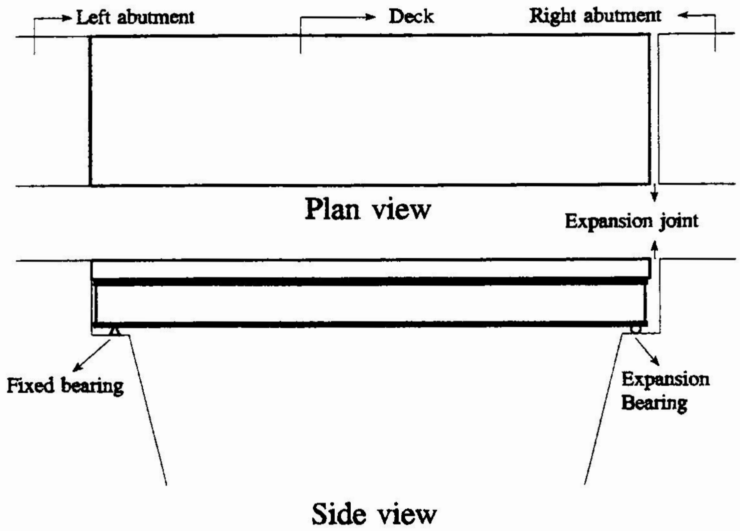

Figure 1 Typical single-span simply supported bridge

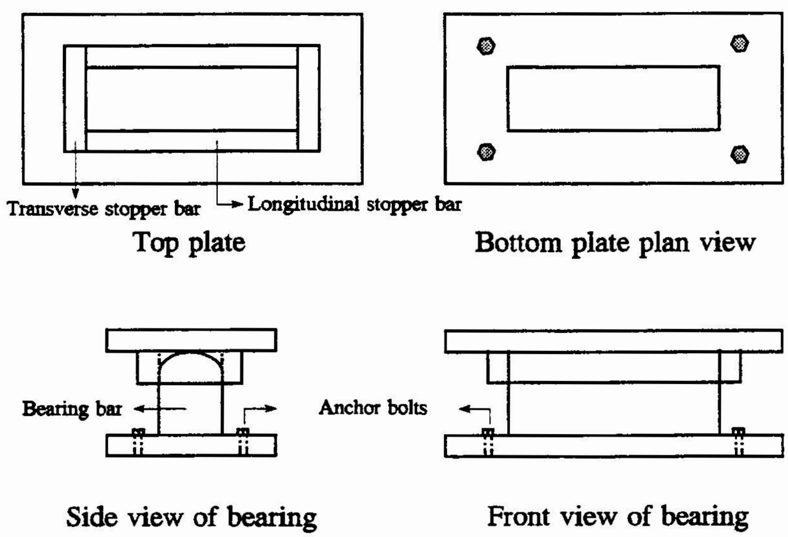

Figure 2 Typical fixed sliding bearing

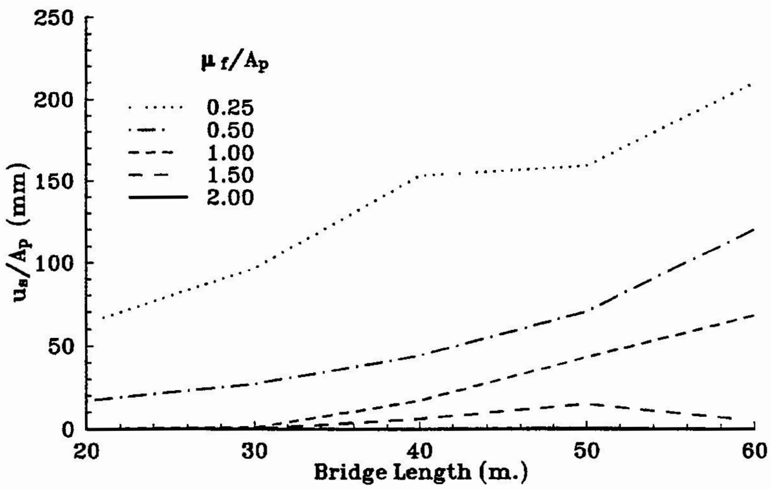

Figure 3 Transverse sliding displacement per peak ground acceleration (%g) of 2-lane bridges for various friction coeffficient to PGA ratio (average of Western USA earthquakes)

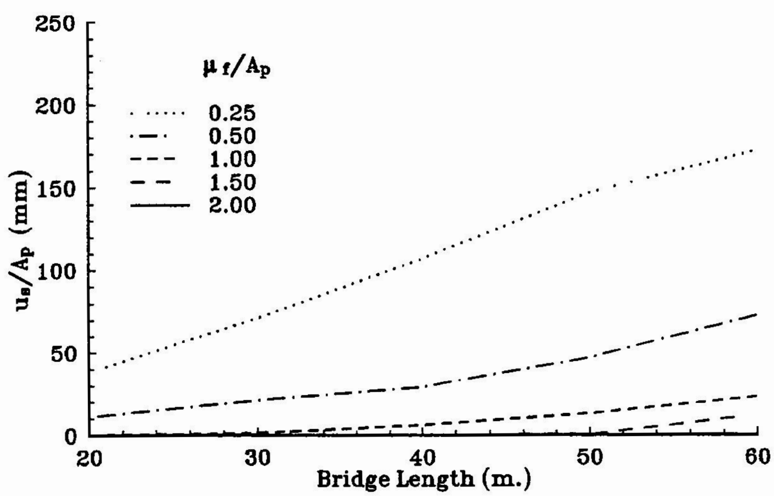

Figure 4 Transverse sliding displacement per peak ground acceleration (%g) of 3-lane bridges for various friction coeffficient to PGA ratio (average of Western USA earthquakes)

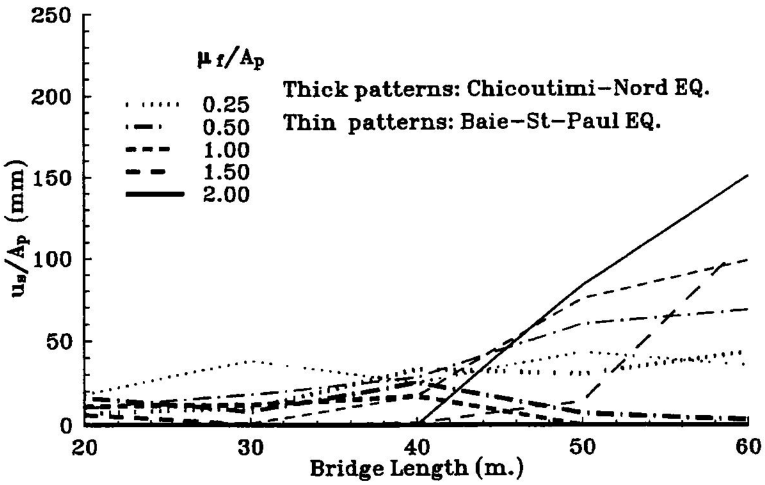

Figure 5 Transverse sliding displacement per peak ground acceleration (%g) of 2-lane bridges for various friction coeffficient to PGA ratio (Eastern Canada earthquakes)

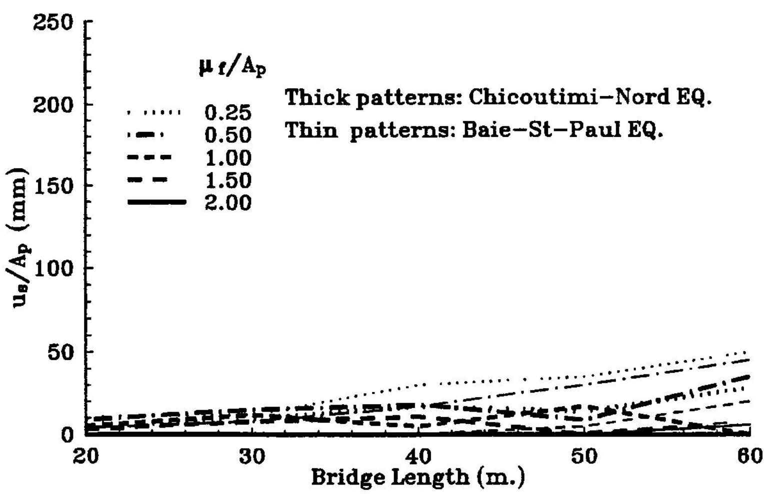

Figure 6 Transverse sliding displacement per peak ground acceleration (%g) of 3-lane bridges for various friction coeffficient to PGA ratio (Eastern Canada earthquakes)