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Earthquake Resistance of Steel Plate Girder Bridges

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ABSTRACT

The current AASHTO and Canadian bridge design specifications do not have guidelines for the seismic design of steel plate girder bridges. Previous earthquakes have shown that steel plate girder bridges exhibits a vulnerability to ground motions. This paper discusses the results of an analytical investigation of the seismic behavior of steel plate girder bridges. Full 3-D finite element analyses were conducted on a simply supported steel bridge to determine the load path of lateral and longitudinal seismic forces. The results of the analyses showed that the exterior cross frames between the steel plate girders played a significant role in the overall seismic behavior and performance of this type of highway bridges.

INTRODUCTION

During recent earthquakes in California, several steel plate girder bridges experienced buckling of cross frames and lateral bracing (Caltrans, 92, 94). In spite of this damage, these bridges were opened to traffic while new cross frames replaced the buckled ones. Although the damage was not so extensive as to require bridge closure for live load, this type of bridge is still vulnerable to earthquakes and such behavior should be investigated.

The current North American bridge design specifications such as AASHTO (1992) and OHBDC (1993) do not list any criteria or guidelines for the seismic design of steel plate girder bridges. In fact, the current AASHTO seismic specifications offer very limited guidelines for the design of steel bridges. Chapter 7 of the *Seismic Standard Specifications* contains only one-half of a page regarding steel bridges. For straight bridges, AASHTO treats the cross frames as secondary member that should be designed for minimum stiffness and compactness. Therefore, bridge designers are left to their own engineering judgment when it comes designing the various components of the steel plate bridges.

This paper discusses the results of an analytical study conducted on a typical simply supported steel plate girder bridge. The lateral and longitudinal load paths that the seismic load has to go through to reach the supports were identified. The members that lie in the seismic load path become primary members and should be designed for strength, stiffness, and ductility.

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ANALYTICAL INVESTIGATION

An analytical investigation was carried out to determine the seismic response of steel plate girder bridges. A typical steel plate girder bridge was chosen for this investigation. Figures 1 and 2 show the typical bridge which has two steel plate girders spaced at 2.74 m (9 ft), 45.7 m (150 ft) long, and a depth of 1.83 m (6 ft). The steel plate girder supports a 203 mm (8 inches) composite concrete deck. The plate girder top flange is 78.7 mm (20 inches) wide by 25.4 mm (1 inches) thick and the bottom flange is 78.7 mm (20 inches) wide by 50.8 mm (2 inches). The web of the plate girder has a depth of 1.83 m (6 ft) and 12.7 mm (0.5 inches) thick. The cross frames are of X-type with an area of 4839 mm^2 (7.5 in^2) placed at interval of 7.62 m (25 ft) according to *AASHTO Specifications*. One hinge supports the plate girder at one end while a roller supports the other end as shown in Figure 2.

A full 3-D elastic finite element model was used to determine the seismic response of the steel bridge. The elastic model consisted of the following components: concrete deck, steel girders, and cross frames. Shell elements were used to model the flanges and the web of the steel plate girder and the concrete slab. The shell element were modeled as 4-node element formulation which combines membrane and plate bending behavior. The membrane is an isoparametric formulation including translational in-plane stiffness components and a rotational in-plane stiffness component in the direction normal to the plane of the element (Taylor and Simo, 1985). The plate bending behavior includes two-way out-of-plane plate rotational stiffness components and a translational stiffness component in the direction normal to the plane of the element (Taylor and Simo, 1985). The cross frame were modeled as frame element truss members that can only take axial forces. The deck was connected to the top flanges of the plate girder along mutual nodes between the flanges and the deck. Figure 3 shows the mathematical model used in this investigation.

STATIC ANALYSIS

Little attention was given to the seismic load path when designing most of the existing steel plate girder bridges. These bridges were designed primarily for gravity and thermal loads. According to the practice at that time the only seismic design consideration was for the substructure that was designed for a lateral load of 10% of the bridge dead load. However, the superstructure was not designed for any seismic load.

Generally, the transverse inertia load of the bridge is generated in the deck and taken out of the structure through the piers and abutments. The transverse interia load in the concrete deck is transferred to the supports of the steel girder through the cross frames and lateral bracing. Thus, the cross frames and lateral bracing, currently designed as secondary members, act as primary members in transferring the seismic loads to the supports. On the other hand, the longitudinal inertia load is transferred by the steel plate girders through the web and then to the supports. The distribution of the transverse and longitudinal seismic loads through the plate girders and the cross frames is very complex and could not be obtained without full 3-D finite element analysis

Static analyses were performed prior dynamic analysis to determine the lateral and longitudinal load paths. The elements that lie in this load path are primary members, so any failure in these members would interrupt the flow of forces and might cause some damage. Lateral transverse and longitudinal loads were applied at the top of the deck to simulate the effect of intertia forces in each direction. Table 1 shows the support reactions of the steel plate girder due to the transverse and longitudinal static analyses. The x, y, and z directions represent lateral, longitudinal, and vertical direction of the bridge.

The applied lateral forces in the transverse direction along with the support reactions create a couple C on the bridge. The applied forces, H, and the reactions at the supports creates a couple C which equals to the applied lateral forces, H, multiplied by the depth of the bridge, d. A resisting moment M, created by the vertical reactions at the supports multiplied by the spacing between the girders, S, would resist the applied couple. Therefore, knowing the applied lateral forces, the vertical reactions of the supports could be calculated as:

$$V = \frac{Hxd}{S}$$

This force, when divided by the number of anchor bolts per each steel girder, would represent the applied tension or compression force in each anchor bolt. The lateral forces also create another couple at the hinged end of the bridge producing the longitudinal forces along the y-direction. These longitudinal forces, along with the transverse forces represent an applied shearing force on the anchor bolt. Therefore, due to transverse lateral only, anchor bolts will be subjected to shearing forces in the x and y directions and tension or compression forces in the z-direction.

Table 2 shows the distribution of forces along the cross frames of the entire bridge for the transverse and longitudinal static analyses. As expected, the exterior frames tend to resist most the forces because they collect all the lateral forces and transfer them to the supports. The intermediate interior frames do not resist significant forces since they do not transfer any substantial seismic forces as evidenced from Table 2.

The longitudinal load path is less complicated than the transverse lateral load path. The longitudinal forces are mainly transferred to the supports as axial forces through the web of the steel plate girder. Table 1 also shows the results of the longitudinal static analysis which clearly shows the coupling between the transverse and vertical directions due to the applied longitudinal forces. However, as Table 1 shows, these forces are not as significant as those generated by the applied lateral transverse forces.

DYNAMIC ANALYSIS

The linear analysis capability of SAP 90 was used to perform the dynamic structural analysis. The Complete Quadratic Combinations (CQC) method was utilized in the response spectra analyses to combine the resulting peak modal response quantities for various modes. The CQC method was chosen from among other available methods because it best represents the mode combinations when frequencies are closely spaced (Wilson, Der Kiureghian, and Bayo, 1981).

The ground motion used for the dynamic analysis is represented by Caltrans Response Spectra Curve D with a 0.7g peak rock acceleration (*Caltrans Bridge Design Specifications, 1987*). Figure 4 shows the Caltrans Curve D Spectra, an elastic spectrum obtained from the results of ARS where A represents the maximum credible peak rock acceleration, R represents the acceleration spectra in rock, and S represents the soil amplification factor. Usually, this spectrum is specified for sites with alluvium depth of more than 45.8 m (150 ft). This spectrum was used as the base motion for the longitudinal and transverse dynamic analysis, while two-thirds of the spectrum was used for the vertical direction ground motion analyses.

The dynamic analysis considered fifteen modes in order to include all critical response modes. More than 95% of the participating mass in the longitudinal, transverse, and vertical directions was captured in the analysis. Three separate analyses were performed for each case in longitudinal, transverse, and vertical directions.

Table 3 lists the first ten periods of the bridge. Tables 4 and 5 gives the results of the three dynamic analyses. Table 4 shows the support reactions due to transverse, longitudinal, and vertical loading. Table 5 shows the forces in the cross frames for the three analyses.

Support reactions and lateral and longitudinal load paths obtained from dynamic analyses showed the same trend as the results of the static analyses. The dynamic analysis also verifies the importance of the exterior cross frames for the transverse lateral loading. The coupling effect between lateral, longitudinal, and vertical loading subjected the anchor bolts to significant forces that are most often neglected during the design process.

CONCLUSIONS

This study determined the lateral and the longitudinal seismic load paths for simply steel plate girder bridges. The main conclusion of this study is that the exterior cross frames for a simply supported bridge play very important role in resisting lateral transverse loads. These cross frames should be designed and detailed as primary members because they lie in the seismic load path. The interior cross frames are not as significant as the exterior ones. The exterior cross frames should be designed for forces obtained from the dynamic analysis and should also be designed and detailed as ductile members. Also, the anchor bolts were subjected to significant shearing forces due to the coupling of transverse and longitudinal directions. These forces are substantial and should be included in the design process.

ACKNOWLEDGMENTS

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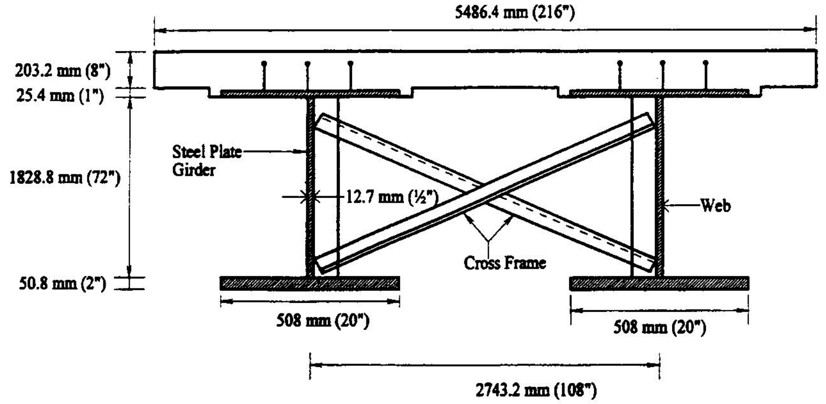

Figure 1: Cross Section of the Steel Plate Girder Bridge

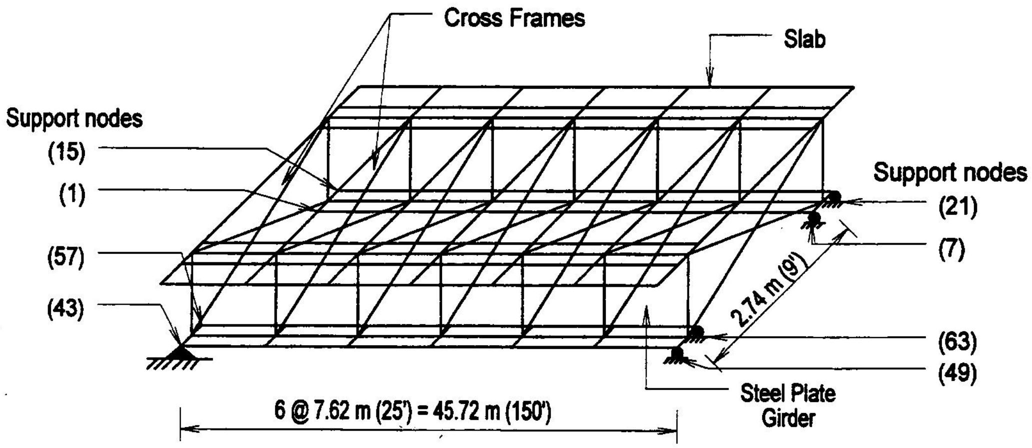

Figure 2: Bridge Elevation and the Support Node Numbers

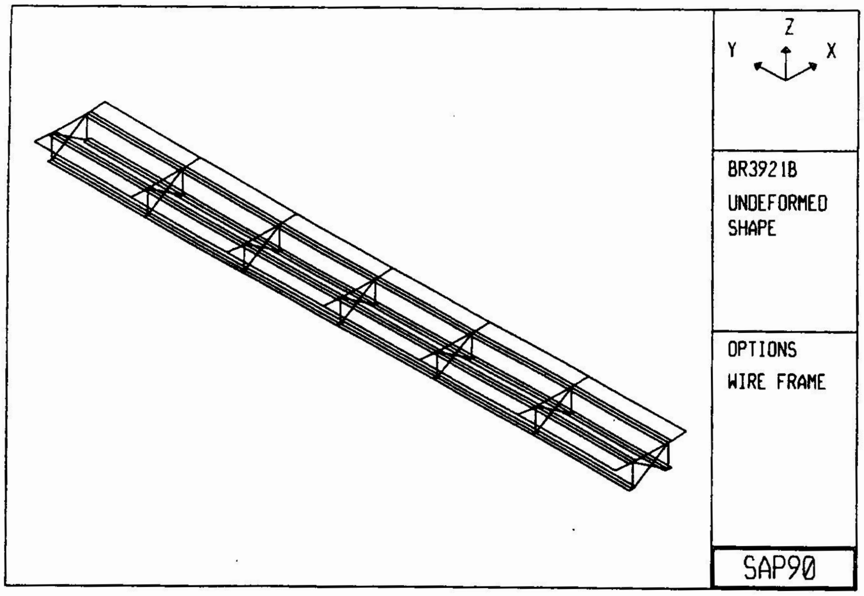

Figure 3: SAP 90 Bridge Mathematical Model

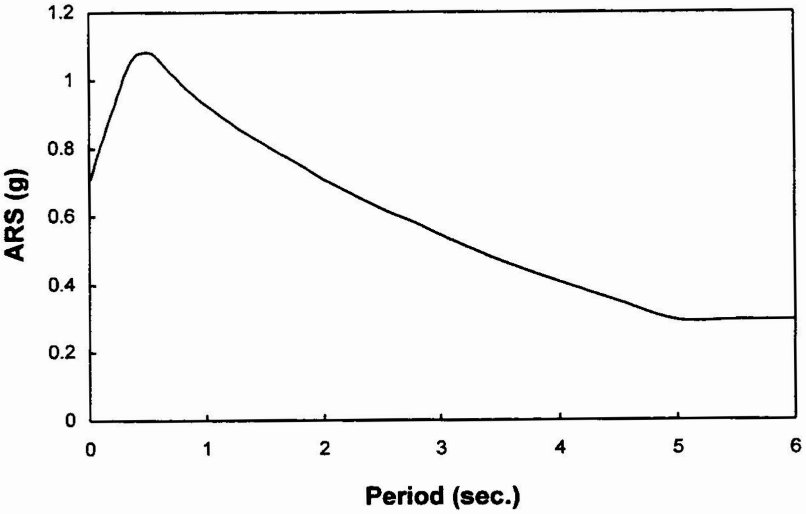

Figure 4: Caltrans Spectra Curve D

Table 1: Suppots Reactions for Transveres and Longitudinal Static Analyses

Node #	Static Analysis					
	Transverse Direction			Longitudinal Direction		
	Fx (kN)	Fy (KN)	Fz (KN)	Fx (KN)	Fy (KN)	Fz (KN)
1	-120	154	-294	51	-411	-16
7	-206	0	-280	18	0	16
15	-215	304	-295	-48	-407	-16
21	-204	0	-282	-17	0	16
43	-208	304	295	48	-407	-16
49	-195	0	282	17	0	16
57	-200	161	294	-51	-411	-16
63	-197	0	280	-18	0	16

Table 2: Cross Frame Forces For Transverse and Longitudinal Static Analyses

Cross Frames		Static Analysis	
Location	Number	Transveres Direction Cross Frame Forces (KN)	Longitudinal Direction Cross Frame Forces (KN)
E	1	479	4
I	2	57	1
I	3	39	0
I	4	25	0
I	5	17	0
I	6	11	0
E	7	489	2

Table 3: Various Period Values of First Ten Modes

Dynamic Analysis	
Mode	Period (Seconds)
1	0.47
2	0.23
3	0.13
4	0.1
5	0.08
6	0.07
7	0.055
8	0.054
9	0.053
10	0.052

Table 4: Suppots Reactions For Transveres, Longitudinal, and Vrtical Dynamic Analyses

Node #	Dynamic Analysis								
	Transverse Direction			Longitudinal Direction			Vertical Direction		
	Fx (KN)	Fy (KN)	Fz (KN)	Fx (KN)	Fy (KN)	Fz (KN)	Fx (KN)	Fy (KN)	Fz (KN)
1	259	183	222	414	191	41	425	41	113
7	180	0	211	143	0	40	358	0	115
15	233	174	223	412	188	41	423	49	113
21	141	0	212	142	0	40	352	0	115
43	233	174	223	412	188	41	423	490	113
49	141	0	211	142	0	40	352	0	115
57	259	183	222	414	191	41	425	41	113
63	180	0	211	143	0	40	358	0	115

Table 5: Cross Frame Forces For Transveres, Longitudinal, and Vertical Dynamic Analyses

Cross Frames		Dyamic Analysis		
Location	Number	Transverse Direction	Longitudinal Direction	Vertical Direction
		Force (KN)	Force (KN)	Force (KN)
E	1	366	2	3
I	2	19	0	1
I	3	46	1	1
I	4	4	1	1
I	5	34	1	1
I	6	12	0	0
E	7	369	2	2