AASHTO LRFD Provisions for the Seismic Design of Steel Plate Girder Bridges

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ABSTRACT

Recent earthquakes have exposed the vulnerability of steel plate girder superstructures to seismic forces. Damage has occurred in cross frames and their connections, shear connectors, and steel plate girders. These earthquakes have revealed the shortcomings of U.S. bridge design specifications for these types of bridges. Section 6 of the AASHTO LRFD specifications does not have any seismic design provisions for steel plate girder bridges. Recently, these specifications have adopted seismic design provisions that are proposed by the authors for steel superstructures to overcome this shortcoming. The adopted specifications are the result of analytical and experimental investigations by various researchers and work published by many seismic provisions and guide specifications. This paper summarizes the new seismic design provisions and outlines the background behind them.

Keywords: bridges, seismic design, AASHTO provisions, plate girders, cross frames, shear connectors.

INTRODUCTION

The AASHTO Load and Resistance Factor Design (LRFD) bridge design specifications (AASHTO, 2010) do not require the explicit design of concrete or steel bridge superstructures for earthquake loads. It is implicitly assumed that the superstructure that is designed for dead and live loads will have sufficient strength, by default, to resist earthquake loads. This assumption appears to be justified for structural concrete box girder superstructures, which are heavier and stiffer than steel plate girder superstructures. However, during the recent earthquakes of Northridge, Kobe and Nisqually, several components of steel plate girder superstructures experienced inelastic response and premature failure (Itani et al., 2010). This showed that these superstructure components were in the seismic load path and were subjected to seismic forces for which they were not designed. Therefore, improvement in the seismic performance of steel bridges is warranted, along with design provisions for steel superstructures. Better insight is required regarding the seismic load path, as well as the resistance of individual components and assembled systems.

Steel plate girder bridges have generally suffered minor to moderate damage in past earthquakes compared with the significant damage suffered by structural concrete structures. However, these earthquakes have identified critical components in the superstructure and substructure that should be designed and detailed to resist seismic demand. The common thread among these earthquakes is that the components of steel plate girder superstructures are vulnerable during seismic events and need to be designed and detailed to resist the seismic forces without premature failure and fracture. Failure in the superstructure components will interrupt the seismic load and will alter the overall seismic performance of such bridges.

The 1992 Petrolia earthquakes in northern California (Caltrans, 1992) exposed the importance of the support cross frames and the shear connectors in steel plate girder superstructures in transferring the seismic forces. The South Fork Eel River Bridge, a curved steel plate girder bridge, suffered considerable damage, including buckling and fracture of end cross frames and their connections and damage to the reinforced concrete deck at support locations. This earthquake highlighted the significance of shear connectors in transferring the lateral forces that are generated by the mass of the deck. The Northridge (Astaneh-Asl et al., 1994) and Kobe earthquakes (Bruneau et al., 1996) showed similar damage to support cross frames and their connections in addition to the damage of the steel plate girders at bents and abutment locations.

These earthquakes confirmed the vulnerability of steel-girder bridges during seismic events. New areas of concern that emerged included:

- Lack of understanding of the seismic load paths in steel-girder bridges.

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- Damage to steel superstructure components such as girders, shear connectors, end cross frames, bearing stiffeners, bearings and anchor bolts.
- Failure of steel substructures.

BEHAVIOR OF STEEL PLATE GIRDER BRIDGES UNDER LATERAL LOADING

Earthquake loading in the transverse direction causes transverse bending of the superstructure, resulting in transverse reactions at the abutments and bents. Consequently, the loads are distributed from the middle of each span to the supports. Because the reinforced concrete deck and concrete traffic barriers in a steel plate girder bridge typically account for around 80% of the bridge, the majority of the inertia loads are generated in the deck slab. The bearing supports are at the bottom flange of the girders; thus, the inertia loads need to be distributed down through the superstructure components. Numerical analyses have shown that these loads are largely distributed through the deck to the ends of each span. The seismic forces are distributed vertically through the abutment and bent cross frames (Itani, 1995; Itani and Rimal, 1996; Zahrai and Bruneau, 1999a). These forces are then transmitted to the bearings and shear keys at support locations. Because the primary function of the bearings is to allow the bridge to expand and contract longitudinally due to temperature variation, the bearings are usually restrained from translation in the transverse direction. Thus, the transverse shear forces in the bearings are transferred into the abutments and bents.

To ensure favorable transverse seismic load path, adequate composite action should be provided between the girders and the deck for transverse earthquake loading. Analytical investigation by Carden et al. (2002) showed the importance of having shear connectors along the entire length of the bridge. If shear connectors were not used over the negative moment regions, the entire transverse load path will be altered. Consequently, the intermediate cross frames between support locations will be subjected to significant seismic forces. Therefore, it is recommended in seismic zones that shear connectors be placed on the girders over the entire length of the bridge and over the top chord of support cross frames to ensure that the seismic forces will be transferred to the substructure. Experimental investigation (Bahrami et al., 2010) showed that attaching the top chord of the support cross frames to the reinforced concrete deck facilitated the transfer of the earthquake loads directly from the deck into the cross frames. The results of this experimental investigation showed that the shear connectors at support locations are subjected to tension forces in addition to lateral shear. This tension force can be substantial and may cause the failure of the connectors, thus interrupting the seismic load path.

End cross frames or diaphragms—elements placed transversely between the plate girders at the supports—have been identified analytically (Itani and Rimal, 1996; Astaneh-Asl and Donikian, 1995; Zahrai and Bruneau, 1998; Dicleli and Bruneau, 1995a, 1995b) and experimentally (Zahrai and Bruneau, 1999a, 1999b; Carden et al., 2005; Bahrami et al., 2010) as critical components in the transverse seismic load path. These members are designed and detailed as secondary members for straight steel bridges but become primary members at support locations responsible for transferring the seismic forces from the deck to the bearings. Any failure in these members will interrupt the seismic load path and alter the overall seismic response of the bridge.

SEISMIC DESIGN SPECIFICATIONS FOR STEEL BRIDGES

The 1971 San Fernando earthquake demonstrated the vulnerability of structural concrete box girder bridges to seismic forces (California Department of Public Works, 1971). Several bridges of the aforementioned type suffered complete collapse. Recognizing the urgent need for new design provisions, the California Department of Transportation (Caltrans) began to develop new criteria for the seismic design of bridges. The structural system of concrete box girders with monolithic connection between the superstructure and the substructure dictated that the inelasticity should occur in the column. Thus, the concept of "weak substructure–strong superstructure" emerged in the seismic design of highway bridges. No attention was given to steel bridges due to the fact that only one steel plate girder bridge (San Fernando Road Overhead) was damaged as a result of the bearing failure and short seat width (California Department of Public Works, 1971). Subsequently, the seismic design guidelines for bridges did not present information on the seismic design of steel plate girder bridges. This shortage of information continued in the 5th edition of the AASHTO LRFD specifications (AASHTO, 2010). Prior to May 2011, the AASHTO LRFD specifications had no provisions for the seismic design of steel bridges.

In an effort to remedy this lack of information, the AASHTO guide specification (AASHTO, 2009) offered provisions for the seismic design of steel bridges. However, the guide specifications lacked the depth and the breadth for the seismic design of steel plate girder bridge components. Furthermore, the basic design methodology of the guide specification is displacement-based, but for steel bridges the design methodology is force-based. This discontinuity in the guide specification forces bridge engineers to use two distinct specifications for the seismic design of steel bridges.

NEW AASHTO LRFD SEISMIC DESIGN PROVISIONS FOR STEEL PLATE GIRDER BRIDGES

An effort was undertaken to synthesize the available experimental research, analytical research and seismic guidelines to establish seismic provisions that could be adopted to be part of the AASHTO LRFD Section 6 (Itani et al., 2010). These new provisions are based on the recent work published by Itani et al. (2010), NCHRP (2002, 2006), ATC/MCEER (2003), Caltrans (2001), AASHTO (2009), and AISC (2005). These provisions are limited to the seismic design and details of steel-girder bridge superstructure components.

The new provisions for seismic design are presented under Article 6.16 of the AASHTO LRFD specifications. The overarching requirements for all seismic zones is the importance of seismic load path, minimum support length and capacity design to ensure that connections stay elastic where any expected inelasticity is limited to the members. An overview of the new provisions and background behind them are presented in the rest of this section.

General

The provisions require a clear seismic load path to be established within the superstructure to transmit the inertia forces to the substructure based on the stiffness characteristics of the concrete deck, cross frames or diaphragms and bearings. The flow of the seismic forces is accommodated through all affected components and connections of the steel superstructure within the prescribed load path, including, but not limited to, the longitudinal girders, cross-frames or diaphragms, steel-to-steel connections, deck-to-steel interface, bearings and anchor bolts.

Materials

Previous earthquakes, analyses and experimental investigations have shown that cross frames at support locations transfer the inertia forces from the superstructure to the substructure. Therefore, the connections of the adjoining cross-frame members must be protected during seismic events. This is achieved by utilizing a capacity-design methodology in which the cross-frame connections are designed based on the expected nominal resistance of the adjoining members. In the capacity-design methodology, all the components surrounding the nonlinear element are designed based on the maximum expected nominal resistance of that element. The capacity-design methodology requires a realistic estimate of the expected nominal resistance of the designated yielded members. To this end, the expected yield strength of various steel materials has been established through a survey of mill test reports, and ratios of the expected to nominal yield strength, R_y, have been provided by AISC (2005) and are adopted herein. The expected resistance of the designated member is therefore to be determined based on the expected yield strength, R_yF_y.

Design Requirements for Zone 1

For steel-girder bridges located in Seismic Zone 1, defined as specified in AASHTO (2010), no consideration of seismic forces is required for the design of the superstructure components—except that the design of the connections of the concrete deck to the girder at all support cross-frame or diaphragm locations, the connections of all support cross-frame or diaphragm members, and the connections of the superstructure to the substructure shall satisfy the minimum requirements specified in specifications.

Design Requirements for Seismic Zones 2, 3 or 4

The seismic performance criterion for steel plate girder bridges is to be classified into one of the following two response strategies:

- Type 1: Design an elastic superstructure with a ductile substructure.
- Type 2: Design an elastic superstructure and substructure with a fusing mechanism at the interface between them.

Type 1 represents the conventional seismic design response strategy in which the superstructure stays in elastic range while the inelasticity is limited to the substructure. The provision of an alternative fusing mechanism, Type 2, between the interface of the superstructure and substructure by shearing off the anchor bolts is also an adequate seismic strategy in the new provisions. However, it is important to mention here that caution must be taken to provide adequate seat width and to stiffen the girder web at support locations. It is anticipated that large deformations will occur in the superstructure at support locations during a seismic event when this strategy is employed.

The reinforced concrete deck and shear connectors are to be designed and detailed for the seismic forces. Support cross-frame members in either category are considered primary members for seismic design. Structural analysis for seismic loads will consider the relative stiffness of the concrete deck, girders, support cross-frames or diaphragms and the substructure.

Reinforced Concrete Deck

In general, reinforced concrete decks on steel-girder bridges with adequate stud connectors have sufficient rigidity in their horizontal plane that their response approaches rigid-body motion. Therefore, the deck can provide a horizontal diaphragm action to transfer seismic forces to support cross frames or diaphragms. The seismic forces are collected at the support cross frames or diaphragms and transferred to the substructure through the bearings and anchor bolts. Thus, the support cross frames or diaphragms must be designed for the resulting seismic forces. The lateral loading of the intermediate cross frames in between the support locations for straight bridges is minimal in this case, consisting primarily of the local tributary inertia forces from the girders. Adequate stud connectors are required to ensure the necessary diaphragm action; previous earthquake reconnaissance showed that, for some bridges in California in which the shear connectors at support locations were damaged during a seismic event, the deck in fact slid on the top of the steel girders (Roberts, 1992; Carden et al., 2005).

During a seismic event, inertia forces generated by the mass of the deck must be transferred to the support cross frames or diaphragms. The seismic forces are transferred through longitudinal and transverse shear forces and axial forces. The transverse seismic shear force on the deck, F_{px}, within the span under consideration shall be determined as:

$$F_{px} = \frac{W_{px}}{W} F \tag{1}$$

where

F = total of the transverse base shears, as applicable, at the supports in the span under consideration, kips

W = total weight of the deck and steel girders within the span under consideration, kips

W_{px} = weight of the deck plus one-half the weight of the steel girders in the span under consideration, kips

In cases where the deck can be idealized as a rigid horizontal diaphragm, F_{px} is distributed to the supports based on their relative stiffness. In cases where the deck must be idealized as a flexible horizontal diaphragm, F_{px} is distributed to the supports based on their respective tributary areas. Decks idealized as rigid diaphragms need only be designed for shear. Decks idealized as flexible diaphragms must be designed for both shear and bending because maximum in-plane deflections of the deck under lateral loads in this case are more than twice the average of the lateral deflections at adjacent support locations. Concrete decks may be designed for shear and bending moments based on strut and tie models.

In cases where the deck cannot provide horizontal diaphragm action, the engineer should consider providing lateral bracing to serve as a horizontal diaphragm to transfer the seismic forces.

Shear Connectors

Stud shear connectors play a significant role in transferring the seismic forces from the deck to the support cross frames or diaphragms. These seismic forces are transferred to the substructure at support locations. Thus, the shear connectors at support locations are subjected to the largest seismic forces unless reinforced concrete diaphragms connected integrally with the bridge deck are used. Failure of these shear connectors will cause the deck to slip on the top flange of the girder, thus altering the seismic load path (Caltrans, 2001; Carden et al., 2005, Bahrami et al., 2010).

The shear center of composite steel-girder superstructures is located above the deck (Zahrai and Bruneau, 1998; and Bahrami et al. 2010). Therefore, during a seismic event the superstructure will be subjected to torsional moments along the longitudinal axis of the bridge that produce axial forces on the shear connectors in addition to the longitudinal and transverse shears. Lateral deformations during a seismic event produce double curvature in the top chord of the cross frame, creating axial forces in the shear connectors on that member that must be considered. Experimental and analytical investigations (Carden et al., 2002; Bahrami et al., 2010) showed that the seismic demand on shear connectors that are placed only on the girders at support locations may cause significant damage to the connectors and the deck.

Appendix D of the ACI specification (2008) provides equations for anchorage to concrete of pre- and post-installed anchors subject to shear and axial forces. However, these equations are not used herein for the design of shear connectors on slab-on-steel-girder bridges subject to combined shear and axial forces. Mouras et al. (2008) investigated the behavior of shear connectors placed on a steel girder under static and dynamic axial loads. The effects of haunches in reinforced concrete decks, stud length, the number of studs and the arrangement of the studs in the transverse and longitudinal directions of the bridge were investigated. Based on this investigation, several modifications were recommended to the ACI Appendix D equations that are reflected in the equations in the AASTHO specifications. These modifications ensure a ductile response of the shear connectors that is beneficial in seismic applications. The modifications are as follows:

- Provision for adequate embedment of the shear connectors to engage the reinforcement in the deck slab.
- Use of an effective haunch height instead of the effective height given in the ACI Appendix D equations.
- Consideration of a group modification factor for longitudinal and transverse spacing. This factor accounts for the overlapping of the cones when studs are closely spaced.

The shear connectors on the girders assumed effective at the support under consideration shall be taken as those spaced no further than $9t_w$ on each side of the outer projecting element of the bearing stiffeners at that support. The diameter of the shear connectors within this region shall not be greater than 2.5 times the thickness of the top chord of the cross frame or top flange of the diaphragm. This requirement is new for the AASHTO specifications because shear connectors may be placed over cross-frame top chords.

At support locations, shear connectors on the girders and/or on the support cross frames or diaphragms, as necessary, are designed to resist the combination of shear and axial forces corresponding to the transverse seismic shear force, F_p. Experimental investigation by Bahrami et al. (2010) showed that the modified ACI equations for the shear and axial resistance and their interaction can be used to satisfactorily determine the resistance of stud shear connectors under the combined loading effects.

Elastic Superstructure

To achieve an elastic superstructure, the various components of the support cross frames or the support diaphragms, as applicable, must be designed to remain elastic under the forces that are generated during the design earthquake. The superstructure and its components should be capacity protected based on the material expected strength and overstrength of the ductile element. No other special seismic requirements are specified for these members in this case. The elastic superstructure can have steel cross frames of various configurations, steel diaphragms or reinforced concrete diaphragms. The Tennessee Department of Transportation and Caltrans have, as an alternative, used reinforced concrete diaphragms over bent locations. The details of these diaphragms and others are discussed in Bahrami et al. (2010) and Itani and Reno (1995).

CONCLUSIONS

The AASHTO LRFD specifications for the seismic design of steel bridges are relatively limited compared to those for concrete bridges. This is partly because the AASHTO specifications assume that all bridge superstructures have sufficient in-plane strength by default and remain elastic during the design earthquake. Thus, no special provisions are required for their seismic design, apart from requiring that a continuous load path be identified and designed for strength. While this may be a satisfactory approach for concrete superstructures—concrete box girder superstructures in particular—it is not necessarily the case for steel plate girder superstructures. Steel-girder superstructures may be vulnerable to collapse during seismic events if they are not designed and detailed properly to resist the seismic motions. Recent moderate earthquakes around the world have shown that a continuous seismic load path should be clearly defined, analyzed and designed to transmit the superstructure inertia forces to the substructure in order to prevent significant damage to the steel superstructure. Seismic design specifications summarized herein were recently included in Section 6 of the AASHTO LRFD specifications in a new Article 6.16. The new provisions are based on recent work published by NCHRP, ATC/MCEER, AASHTO [such as the *Guide Specifications for Seismic Design* (AASHTO, 2009)], Caltrans, and AISC. The new provisions are for the seismic design of steel plate-girder bridge superstructures located in Seismic Zones 2, 3 and 4. Bridges in Seismic Zones 3 or 4 are to be classified into one of the following two categories for seismic design: Type 1, an elastic superstructure with a ductile substructure; or Type 2, an elastic superstructure and substructure with a fusing mechanism at their interface. Bridges in Seismic Zone 2 may be classified into one of these two categories at the owner's discretion. Provisions for the seismic design of the superstructure components including the concrete deck, stud shear connectors, and support cross frames were summarized in this paper.

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