RESEARCH NOTES

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Seismic Analysis and Design of Ductile End Cross Frames in Steel Plate Girder Bridges

RESULTS:* A series of experimental and analytical studies on ductile end cross frames in steel plate girder superstructures was conducted at the University of Nevada, Reno (UNR) through a research project funded by the California Department of Transportation (Caltrans). The purpose of the study was to investigate the behavior of ductile end cross frames and develop seismic design guidelines for bridges with these types of cross frames. The project included designing and testing five, one-half scale, subassemblies of the end cross frame region that included the R/C deck, shear connectors, plate girders, cross frames, and bearings, under cyclic lateral loading. Based on these analytical and experimental investigations it was concluded that specially designed and detailed support cross frames will respond in a ductile manner under large cyclic deformations. The effectiveness of ductile end cross frame strategy for a wide range of parameters was investigated. It was shown that the lateral stiffness of the substructure plays an important role in attracting lateral seismic forces to the support cross frames and to achieve optimal behavior, the relative lateral stiffness of the substructure to the cross frames should be equal to 2 or greater. In this situation it is possible to design the cross frames such that the substructure is undamaged under the effect of seismic forces.

Why We Pursued This Research

Current practice in the seismic design of composite steel plate girder bridges assumes the superstructure does not need to be explicitly designed for earthquake loads. These superstructures are supposed to remain elastic by virtue of their inherent strength and in-plane stiffness which is required for the design of strength and serviceability limit states. As a consequence, few codes require detailed design of composite plate girders and their components for the extreme event (seismic) limit state. However, the performance of these bridges in recent earthquakes has cast doubt on the validity of this approach. In particular, significant damage has occurred within the support end cross frame locations. These support cross frames are the primary element in the seismic lateral load path of straight bridges. Figure 1 shows damage to a steel plate girder bridge superstructure after the 1995 Kobe Earthquake.

Fig. 1: Damage to steel plate girder bridge superstructure

Experimental and analytical investigations have showed that designing the support cross frames to respond in a ductile manner can reduce lateral seismic loads. This strategy involves dissipating the energy through controlled yielding and buckling of support cross frames while other bridge components remain elastic. Implementing this strategy will confine the damage to the support cross frames which are easier to replace when compared to that of the substructure after a major seismic event.

What We Did

Nonlinear finite element analyses were conducted on steel plate girder bridges to identify lateral load paths and elements that contribute to the lateral stiffness and strength. Parameters such as span length, bridge width, girder spacing, single and multi-column bents were investigated. The analytical results showed that the end region of the support cross frames is subjected to a large lateral load and the stud connectors play an important role in transferring these forces to the cross frame diagonal members. It was shown that the stud connectors, normally designed for shear only to achieve composite action between the steel plate girder and the R/C deck, are subjected to combined shear and axial forces. Any premature failure of these connectors will alter the seismic load path. Figure 2 shows the deformations in a computational model of a steel plate girder bridge with rigid and two-column bent substructure under lateral loading.

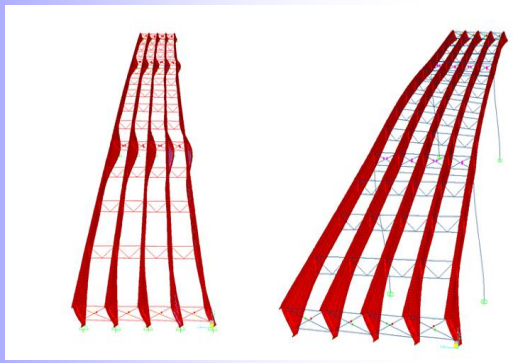

Fig. 2: Deformation of steel plate girder bridges under lateral loading

To better understand the cyclic response of the support cross frame end region, an experimental investigation was conducted on five, one-half scale subassemblies. These subassemblies included R/C deck, stud connectors, plate girder, cross frames, and bearings. Figure 3 shows an overview of the test set-up and one of the five subassemblies.

Fig. 3: Views of test subassembly

The objective of these experiments was to establish the lateral cyclic response of the end region including the initial stiffness, ultimate strength and failure mode of stud connectors with different configurations. The stud connectors were designed for combined tensile and shear forces according to ACI 318-05 Appendix D. The diagonal members of the cross frames were designed and detailed according to special seismic requirements of compactness (b/t) slenderness (KL/r) ratios and end connections. The test results showed that the stud connectors, designed according to revised ACI requirements to accommodate the haunch, group effect, and the diameter of the stud to the steel plate thickness, behaved adequately under large cyclic deformations. Buckling and yielding of the cross frames, designed according to the special seismic requirements, behaved in a ductile manner. The inelasticity was limited to the diagonal members of the cross frames followed by the formation of plastic hinges in the top and the bottom chords of the cross frame. Based on this controlled behavior, the ultimate lateral strength of the subassembly can be estimated using plastic analysis and thus the design force of the other components that are intended to stay elastic can be determined using limit state analysis. Figures 4 and 5 show the cyclic response of two test specimens with and without diagonal members with various locations of stud connectors.

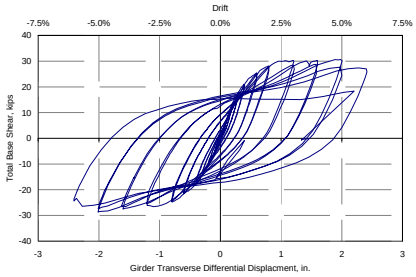

Fig. 4: Cyclic response of test specimen with no diagonal members and stud connectors on the plate girder only

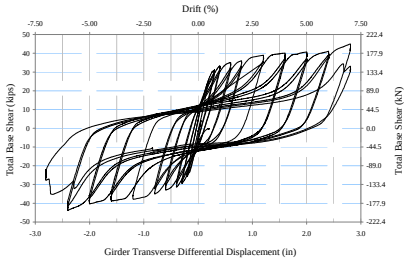

Fig. 5: Cyclic response of test specimen with diagonal members and stud connectors on the top chord only

The results of these experiments also showed that the specimens can undergo significant lateral displacement up to 5% drift without significant damage in the R/C deck or fracture of the diagonal cross frame members.

Based these experiments and other system shake table experiments conducted previously,, calibrated computational models of shear connectors and diagonal cross frame members were developed. These models were used to further investigate the seismic response of steel plate girder bridges to better understand their system response and develop seismic design guidelines. Approximate methods were proposed to determine the axial force demand on stud connectors due to seismic loading and to account for the system effect of superstructure under lateral loading.

Simplified analysis and design methods were developed as part of this study to determine the seismic response and design steel girder bridges with ductile end cross frames. The proposed displacement-based analysis method showed good agreement with results from nonlinear time history analyses.

References

Bahrami, H., Itani, A., Buckle, I., 2010, “Guidelines for the Seismic Design of Ductile End Cross Frames in Steel Girder Bridge Superstructures,” CCEER 09-04, University of Nevada, Reno.