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Transverse displacement capacity and stiffness of steel plate girder bridge superstructures for seismic loads

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Abstract

Ductile end cross frames have been shown to reduce the transverse seismic demand in composite steel plate girder bridge superstructures. However, the effectiveness of these cross frames is strongly influenced by the transverse flexibility of the superstructure and its capacity for potentially large relative transverse displacements between the deck slab and bearing supports. A simplified method is developed in this paper for the calculation of these displacements based on the elastic girder stresses and transverse girder stiffnesses, which are shown to compare well with results given by the finite element method. In addition the method is shown to give results that compare well with experimental data from a 0.4 scale model subject to shake table excitation. Parametric studies are then described that show typical I-girder superstructures are able to accommodate large transverse drifts (up to 17% of the girder height) while remaining in the elastic range. These large drifts are possible without distress to the slab-to-girder connection, by omitting shear studs over a short length of the girder at the support cross frame locations. Based on the above, a step-by-step procedure is proposed for evaluating the transverse displacement, stiffness and capacity of the steel girder superstructures in the region of the end and intermediate supports.

Keywords: Steel bridge; Steel girder; Ductile end cross frame; Ductile end diaphragm; Seismic behavior

1. Introduction

End cross frames or diaphragms, which are members placed transversely between the girders at the supports of steel plate girder bridges, have been previously identified as critical components in the transverse seismic load path, analytically by Itani and Rimal [1] and Zahrai and Bruneau [2] and experimentally by Carden et al. [3,4]. It has also been recognized that these members could be designed as ductile members and thereby reduce the transverse seismic forces in a bridge during an earthquake [3–6]. The advantages of this approach range from protecting the foundations of bridges, where damage is difficult to identify and repair, to reducing the seismic demand and damage in the substructure of a bridge. Furthermore, confining damage to purpose-built ductile elements, which have a secondary role during normal operation of a bridge and can be replaced after an earthquake, is a desirable feature that potentially reduces the need for expensive substructure repair and bridge closures.

Experiments have been performed with X-braces, buckling restrained braces and other systems used as ductile end cross frames or diaphragms with promising results [3–6]. However, in order for these systems to be effective, the top flange of each girder must be able to displace transversely relative to the bottom flange at the supports of each span. While the end cross frames are secondary members during normal operation of a bridge, the girders are important primary members and their integrity must be protected for functionality of the bridge after an earthquake. Fortunately, steel I-girders are flexible for out-of-plane flexure and torsional deformations. Therefore,

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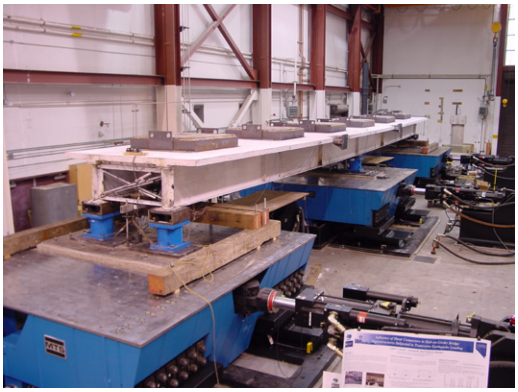

Fig. 1. Two girder bridge model used for large scale experiments with flexible ductile end cross frames to reduce transverse seismic shear.

provided that certain design measures are met, they can deform elastically, allowing the end cross frames to respond in a ductile manner and reducing the base shear in a bridge.

The objectives of this paper are to investigate the transverse stiffness and displacement capacity of composite steel I-girders and discuss methodologies that can be used to ensure the integrity of bridge girders during a large seismic event when using ductile end cross frames. The study is based on numerical analysis of girders along with shake table experiments on a large scale steel girder bridge model, and is limited to straight I-girders, without skew. The bridge model used in this study consisted of two 18 m long steel built up I-girders with a reinforced concrete deck slab, as shown in Fig. 1. Full details of the bridge model are described by Carden et al. [3,4] and only specific additional details are given, as necessary, in the following sections.

2. Simplified model for transverse girder displacements at the supports of a bridge

When a transverse load is applied at the deck slab level of a steel I-girder superstructure, with flexible cross frames at end or intermediate supports, the girders will deform transversely at the support locations. This deformation can be characterized by one or a combination of the modes of deformation shown in Fig. 2. The deformation in Fig. 2(a) results from minimal rotational fixity at the top and base of the girder, whereby the girder appears to rock at the support and resistance to deformation is primarily through the torsional stiffness of the girder. For this mode relative translation between the deck slab and the girder is assumed to be prevented by a connection between the support cross frames and deck slab. Fig. 2(b) shows a mode in which flexural deformation occurs in the end of the deck slab instead of in the connection between the deck slab and the girders. Fig. 2(c) illustrates a mode of deformation resulting from full rotational fixity at the top and base of the girders with resistance to deformation primarily through the flexural resistance of the bearing stiffener. Thus the transverse stiffness of a girder, K_g, is assumed to be dependent on:

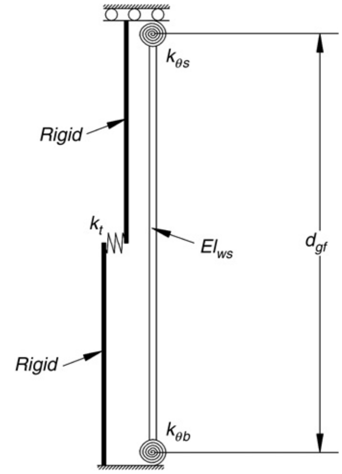

Fig. 3. Model for the transverse deformation of a steel I-girder at a support.

1. The torsional stiffness of the girder,
2. The rotational stiffness of the bearing,
3. The flexural stiffness of the bearing stiffeners,
4. The rotational stiffness of the deck slab or connection between the deck slab and the girders.

A model to capture the response at the end of the girder, incorporating the above factors, is illustrated in Fig. 3. An equivalent translational spring is used to model the torsional stiffness of the girder, while rotational springs model the bearings at the base of the girder and resistance at the top of the girder, and a beam element is used to model the stiffened web. Two variations of this model are necessary, one to model the girder at the end of simple or continuous spans in a bridge and a second to model the intermediate support region of a continuous girder. The stiffness and capacity of each component in the

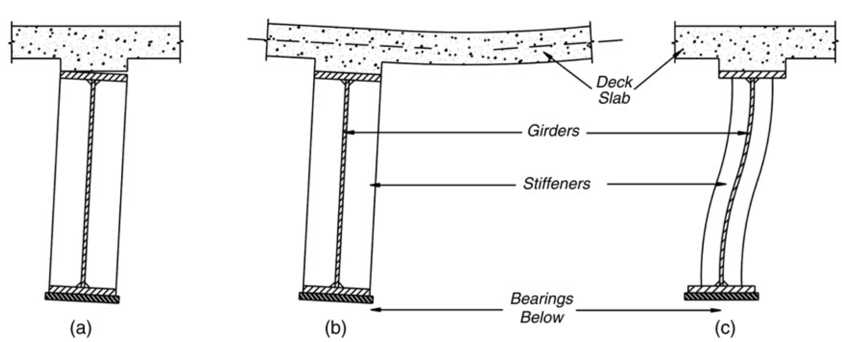

Fig. 2. Transversely deformed girder ends with (a) rotationally flexible connections at top and bottom of girders and (b) flexure in the end of the deck slab and (c) full fixity at top and bottom of girder.