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Experimental and numerical evaluation of a folded plate girder system for short-span bridges – A case study

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ABSTRACT

Bridge owners and engineers focusing on bridge design, management and maintenance continue to search for more efficient ways to design, construct, and maintain their bridge inventory. Recently, a folded plate girder system has been promoted as a cost-effective alternative for the design and construction of bridge superstructures due to merits such as low cost and facilitation of accelerated bridge construction. The folded plate girder system has a structural shape strategically press-brake formed from a single sheet of plate steel and achieves composite action with a concrete deck utilizing shear studs in between. To further facilitate the development and adaptation of the system for bridge application, this paper presents a systematic performance evaluation of the folded plate girder system through experimental and numerical programs. To this end, a folded plated girder specimen was designed, fabricated, and tested to evaluate the constructability and capacity of the girder specimen. Finite Element (FE) Analysis was performed to understand the behavior of the girder specimen under different loading conditions. The predictions using traditional design calculations and FE analysis were compared with the test results. After the FE models were validated against the test data, a full bridge model was established to further investigate the behavior of the bridge under loading condition up to the ultimate load. It was found that the ultimate capacity of the bridge girders were much higher than the bridge demand and the bridge had good ductility until failure. The predictions using the design calculations based on the AASHTO LRFD Bridge Design Specifications were in reasonable agreement with the test results. The FE models showed better predictions since more sophisticated modeling techniques and material constitutive models were used. Results obtained from the sophisticated non-linear bridge model indicated that the girder distribution factors varied along with an increase of the truck loading and especially their change trend was gradually reversed after the yield of the girder steel. And according to the FE results, the distribution factor based on the AASHTO LRFD Bridge Design Specifications was sufficient for the design of the folded plate girder bridge investigated in this study.

1. Introduction

Bridge owners and engineers focusing on bridge design, management and maintenance continue to search for more efficient ways to design, construct, and maintain their bridge inventory. In the past, steel bridges, one of the most common types, have been comprised of superstructures consisting of either rolled steel beams or welded steel girders. Recently, a relatively newly developed concept, which consists of what is known as a folded plate girder system, has been promoted as a cost-effective alternative for the design and construction of short-span bridge superstructures. The structural shape of the folded plate girder system is strategically press-brake formed from a single sheet of the plate steel with a standard width. The system is also commonly known as the press-brake steel girder. The folded plate girder system is potentially a cost-effective system due to the followings: (1) relatively low cost of plate steel; (2) cost saving due to the minimization of steel cutting and welding; (3) modular fabrication with a composite deck in the fabrication plant and simple installation in the field, eliminating the use of external bracing or cross-frames, reducing the construction cost and labor, and facilitating accelerated bridge construction [1]. However, the interior of the folded plate girder is inaccessible due to the narrow enclosed space. Accordingly, it is recommended to use weathering steel or fully seal the girder interior to minimize inspection and maintenance of the girder system.

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The design of the folded plate girder system dates from 1979 when Taly [2] proposed two types of such system: the first system consists of a trapezoidal U-section press-formed from a steel plate and a steel deck comprised of a steel plate and a system with longitudinally and transversely welded WT sections; the second system consists of a trapezoidal U-section and a precast prestressed concrete deck with the welded and embedded studded plates to achieve composite action. Recently, more researchers have investigated the behavior of different folded plate girder systems. Nakamura [3] introduced a bridge system composed of continuous U-section beams and a reinforced concrete deck connected by shear studs, which can be applied for both positive and negative moment regions. Burgueño [4] focused on verifying the concept of placing and post-tensioning the prefabricated units (composed of a press-brake box girder and slab) to achieve accelerated bridge construction. Folded plate girders proposed by Glaser [5] and Burner [6] had an inverted U-section with an open bottom facilitating inspection, ties plates across the open preventing the separation of bottom flanges, and a concrete deck acting compositely with the girder. Barth et al. [1] introduced a modular press-brake formed tube girder which consists of a press-brake tub beam, reinforced concrete deck, shear studs, and internal diaphragms. They performed a parametric study to achieve the optimal girder design and also introduced ongoing experimental and analytical work for the evaluated girder system.

With the goal of further facilitating the development and adaptation of the folded plated girder systems for low volume road applications, Buchanan County in Iowa planned to utilize the folded plate girder system to construct a bridge superstructure which is supported on geosynthetic reinforced soil (GRS) abutments. The Iowa State University Bridge Engineering Center assisted with evaluating the bridge system through a performance evaluation.

The objective of this paper is to provide a systematic performance evaluation of the folded plate girder system through detailed experimental and numerical programs. First, an experimental program consisting of three structural tests was implemented to evaluate the constructability and capacity of the girder system. Finite Element (FE) analysis was performed to interpret the test results and further understand the behavior of the girder system under different construction stages and loading conditions. Analytical results obtained using both design calculations and FE analysis were compared with the test results. Additionally, the numerical study of a yet-to-be constructed bridge under various loading conditions was performed utilizing the validated FE modeling techniques. The last section presents a summary of this study and conclusions.

2. Research significance

Folded plated girders are a relatively new type of girder system and have seldom been utilized for real bridge construction in the United States. In theory, the conventional design approaches specified in the AASHTO LRFD Bridge Design Specifications [7] can be utilized for the design of bridges utilizing folded plated girders. However, the performance of the girder system under service and ultimate loading conditions still needs to be further evaluated before widespread adoption occurs. In this study, experimental tests were conducted to provide qualitative data about how the system behaves as well as data to be used to verify the adequacy of conventional design approaches and established FE models. The validated FE modeling techniques were utilized to further study the performance of a yet-to-be-constructed bridge and evaluate the adequacy of codified design parameters such as the lateral load distribution factor.

3. Experimental program

An experimental program was designed and implemented to evaluate the performance of the folded plated girder under different loading stages and conditions in the Structural Engineering Lab at Iowa State University. A single folded plate girder specimen was designed and fabricated based on the plan sheets of the yet-to-be-constructed bridge in Buchanan County, Iowa. Three separate tests were conducted on the girder specimen to examine its structural behavior during construction, service, and ultimate loading conditions.

3.1. Specimen design and fabrication

The folded plate girder specimen was designed following the details specified for the girder modules which are to be used in the yet-to-be-constructed bridge which has the cross-section as shown in Fig. 1. The simply supported bridge has a width of 9.14 m (30 ft), a span of 15.85 m (52 ft), and accommodates two design lanes. The bridge has five composite girder modules (consisting of a folded plate girder and a concrete deck) and four longitudinal joints between the decks allowing for transverse load distribution between girders. The longitudinal joints will be placed between the modules after the modules are placed side by side. Design of the girder modules was performed following the AASHTO LRFD Bridge Design Specifications [7]. Unfactored service moment, factored ultimate moment, and factored ultimate shear, which represent the demand of the bridge girders, were calculated to be 1265 kN m (933 kip-ft), 1965 kN m (1449 kip-ft), and 627 kN (141 kips), respectively.

The final design of the composite folded plate girder specimen is shown in Fig. 2. The specimen consists of a concrete deck with a width of 1.83 m (6 ft) and a depth of 216 mm (8.5 in.) and a folded plated beam cold-formed from a steel plate with a thickness of 12.7 mm (0.5 in.). Specific dimensions of the girder and the concrete reinforcement details are shown in Fig. 2(a). The shear studs are transversely spaced at 88.9 mm (3.5 in.), and are longitudinally spaced at 203 mm (8-in.) from each end to 4.26 m (14 ft) from the end and spaced at 305 mm (12 in.) from 4.26 m (14 ft) to the midspan as shown in Fig. 2(b). End diaphragms and bracing diaphragms are located at the two ends and at mid-span, respectively, as shown in Fig. 2(b) and (c).

The fabrication of the folded plate girder specimen started with a single steel plate of a standard thickness. The plate was cold formed using a large capacity press brake through a process that uses bending to achieve the desired bend radii. The folding sequence used for the folded plate girder specimen evaluated for this study is shown in Fig. 3. After bending, shear studs were welded to the girder top flanges as shown in Fig. 4(a) with concrete formed also shown. The deck reinforcement was then installed as shown in Fig. 4(b). A concrete deck was then placed on the top of the girder to fabricate a composite folded plate girder as shown in Fig. 4(c). The complete specimen after removing the formwork is shown in Fig. 4(d).

3.2. Test A – construction loading

To examine the behavior of the folded plate girder system during transportation, erection, and prior to attaining full composite action with the concrete deck, the girder specimen without the deck was tested under two-line, flexural loading. To simulate impact-type loadings during construction and to minimize the chances of damaging the girder, loads applied during this test were limited to produce a maximum moment which is equal to two times that produced by the beam's self-weight. The specimen was simply supported and loaded in the test set-up as shown in Fig. 5. The span