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In-plane ultimate compressive strengths of HPS deck panel system stiffened with U-shaped ribs

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Abstract: The ultimate compressive strengths of deck plates stiffened longitudinally by U-shaped stiffeners have been investigated by the nonlinear finite element analysis (FEA). A total of 112 hypothetical models with various combinations of slenderness parameters for the deck plates and column slenderness parameters for the stiffeners were modeled and analyzed. Both conventional and high performance steels were considered in models following elasto-plastic strain hardening constitutive relationships. Initial geometric imperfections and residual stresses were also incorporated in the FEA. Numerical results from FEA have been compared to compressive strengths from Eurocode 3 EN 1993-1-5, FHWA-TS-80–205, and other available formulas. Based on analysis results, new unified strength predictor equations have been developed for the stiffened plate systems with conventional steel and/or high performance steel (HPS). It has been found that use of Eurocode 3 EN 1993-1-5 and FHWA-TS-80–205 may lead to highly conservative design when large column slenderness parameters are encountered. The proposed equations have simple forms yet provide accurate strength predictions resulting in more economic design.

1. Introduction

Steel orthotropic deck systems have been widely used for long- and medium-span bridges due to overall light weight, expedient construction, large capacity for heavy loads, and structural redundancy, etc. Reducing dead weight is particularly important for long-span bridges and the span length records recently achieved would not be possible without steel orthotropic decks [1]. Longitudinal stiffeners welded to the deck plates can be either open types such as flat and T-shaped stiffeners or closed types such as U- and V-shaped stiffeners. Steel deck systems with closed-type stiffeners are preferred because of their lighter weight and fewer welds involved than those with open-type stiffeners, which require closer floor beam spacing due to relatively small wheel load distribution capacity in the transverse direction [2]. Fig. 1 shows a typical steel deck system with closed-type stiffeners frequently adopted in long-span cable-supported bridges.

In designing the longitudinally stiffened steel decks in compression, the rational evaluation of the compressive strength of the deck system is of primary importance. As the structural components of the deck system are basically comprised of thin plate elements, various buckling and postbuckling characteristics of the deck panels in compression govern the ultimate strength of the whole deck system. Four separate buckling modes, namely local buckling of flange plating between longitudinal stiffeners, local buckling of stiffener components, buckling of longitudinal stiffeners between transverse stiffeners or floor beams, and overall buckling of the stiffened panel, need to be considered in evaluating the compressive strength of the longitudinally stiffened deck panel. As the limit state design concept involving the ultimate strengths rapidly prevails worldwide, rational assessment of the ultimate compressive resistance, based on the complete understanding of the inelastic buckling and postbuckling behaviors of the deck panel, is required for design purpose. Since the inelastic buckling behaviors in thin-plate assemblages are influenced by the initial imperfections and residual stresses, much attention should be paid to the roles of these two phenomena in the investigation of the strength of box girders and their components [3]. It is also noted that the effect of component imperfections is most pronounced in the range of intermediate slenderness at which the critical buckling stress and the yield stress are roughly equal [4].

Basically, three approaches have been used to predict the ultimate compressive strength of the stiffened panel, namely the strut approach, orthotropic plate theory, and numerical methods such as the finite element or finite strip method [5]. In the strut approach, the stiffened panel is idealized as a series of disconnected struts, each of which consists of a stiffener and an associated portion of flange plate with a certain width. Horne and Narayanan [6–9] used this strut approach to present an approximate formula for the prediction of

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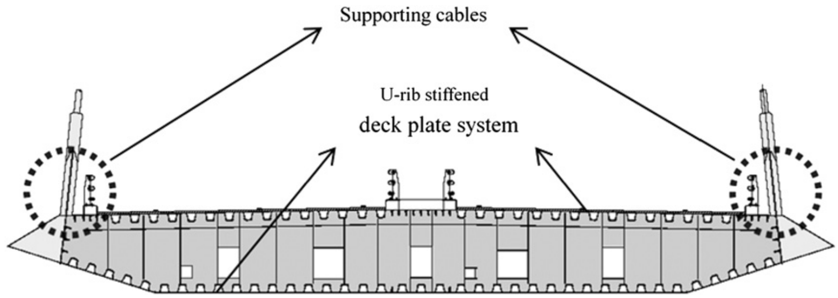

Fig. 1. Typical cross section of stiffening box girder adopted in cable-supported bridges.

ultimate compressive capacity of the stiffened panel. Their studies confirmed the importance of major parameters such as spacing of the stiffeners, width-to-thickness ratio of flange plates, overall panel slenderness, and residual stresses due to welding and initial plate imperfections. FHWA-TS-80–205 report [10], based on the theoretical work by Little [11], applied the diagram method using the interaction between the local buckling of the plate between the stiffeners and the overall buckling of the stiffener strut. The interaction diagram was originally constructed from averaging iterative numerical calculations for inelastic column analyses, considering initial out-of-flatness of flange plate between stiffeners and plate residual stress, with various types of stiffeners. Comparisons with the available test results [12–14] indicated that the strengths obtained from the interaction diagram are appropriate and conservative. The basic concept of the orthotropic plate theory is to convert the stiffened plate into an equivalent plate with constant original plate thickness and an additional layer representing the effect of stiffeners. Using this approach, Massonnet and Maquoi [15] proposed analytical formulations for the ultimate strength of the stiffened compressive flanges of box girders under pure bending. Mikami and Niwa [16] suggested an approximate method based on the orthotropic plate theory, to predict the ultimate compressive strength of orthogonally stiffened steel plates. The authors reported that many test results showed a good agreement with the ultimate strength predicted by their proposed method. Yoshida and Maegawa [17] used the finite strip method to evaluate the elastic and inelastic buckling strengths of orthotropic plate systems. The numerical results showed that improved buckling strength in the elastic and inelastic ranges could be reached when using appropriate rigidity and arrangement of longitudinal and transverse stiffeners. Recently, numerical studies using commercially available finite element package programs incorporating material and geometric nonlinearities have been conducted by many researchers to determine the ultimate compressive strength of stiffened plates [18–23]. Moreover, design rules based primarily on the test results on stiffened panels were suggested in Fujita and Galambos [24] and Chen and Yang [25]. The strength curve in Fujita and Galambos [24] was suggested by taking the mean of the assorted test results obtained from various Japanese institutions. An experimental research by Chen and Yang [25] focused on inelastic behavior of the orthotropic steel deck stiffened by U-shaped ribs. A series of 30 full-scale orthotropic steel deck specimens were tested to determine the ultimate in-plane strength and the limiting width-to- thickness ratio either for the deck plate or its stiffeners to ensure that the premature failure does not occur due to the inelastic local buckling. Chou et al. [23] carried out compression tests on two reduced scale orthotropic plates that simulate a portion of the top and bottom deck plates of the steel box girders for the east span of the New San Francisco–Oakland Bay Bridge and compared the results with those from Japanese Road Association (JRA) specification [26] and the AASHTO LRFD specification [27]. A correlation study using the nonlinear finite element analysis program ABAQUS [28] with the consideration of both the effects of residual stresses and initial geometric imperfections was also performed and the good agreement between the test and FE analysis confirmed that the ultimate strength and postbuckling behavior can be predicted reliably through the FE method.

The present study revisits the investigation of the ultimate compressive strength of stiffened deck plates in compression with U-shaped closed-type stiffeners. Furthermore, with the development of high performance steels (HPS) in recent years, the applicability of the provisions FHWA-TS-80–205 [10] and Eurocode 3 [29] to the HPS steel are re-examined in this study.

The objectives of the present study consist of (1) determining the ultimate compressive strength as well as the failure mode of the U rib stiffened deck plate made of HPS steel, (2) evaluating numerical results by comparing with those from current design procedures in FHWA-TS-80–205, Eurocode 3, and Fujita and Galambos [24]; Mikami and Niwa [16]; Chen and Yang [25], and (3) proposing a new equation for prediction of the inelastic ultimate strength of the stiffened deck plate under uniaxial compression.

To accomplish the objectives mentioned above, the nonlinear finite element analysis of various U-rib stiffened plates was performed using ABAQUS [28] with the consideration of the initial imperfection and the residual stress. Both conventional and HPS steels were considered and assumed as elasto-plastic strain-hardening materials. One hundred and twelve models with a wide range of slenderness ratios for deck plate and aspect ratios of the stiffened plate were selected for FE analysis. After examining the validity of the present FE analysis procedure by comparing FE solutions with a test result available in the literature, the ultimate compressive strengths of 112 selected models through FE analysis were compared with those calculated in accordance with the specifications in FHWA-TS-80–205 and Eurocode 3, and by the formulas proposed by previous researchers. Based on the numerical analysis and comparison with the results by codes and formulas available, a new equation for the prediction of the ultimate compressive capacity of U-rib stiffened deck plate was developed.

2. Code provisons and strength formulas

2.1. FHWA-TS-80–205

The provisions on box girder bridges in current AASHTO LRFD specifications [30] are primarily intended for use on open-top trapezoidal or tub girder bridges rather than a very wide single- or multi-cell box girder bridges usually adopted in cable-supported bridges. The AASHTO LRFD in Commentary C6.11.1 recommends using FHWA specifications proposed by Wolchuck and Mayrbourl [10] for the design of long-span steel box girder bridges with a wide box girder. In the FHWA specifications, the ultimate compressive strength of the stiffened flange is calculated depending upon the slenderness of flange plate and the slenderness of a