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Experimental and analytical study on stiffened steel segment of hybrid structure

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ABSTRACT

Hybrid structures which innovatively and reasonably combine two different materials in longitudinal direction have been applied world-widely, such as hybrid girder, hybrid pylon and hybrid arch skewback. The hybrid structure segment generally consists of steel stiffened segment, concrete strengthened segment and hybrid joint. In order to investigate ultimate capacity and buckling mode of steel stiffened segment in hybrid structure, model tests on five different specimens have been carried out. The test results indicated that embedded T-reinforcing stiffeners had the best axial stiffness, while the out-plane stiffness, ultimate capacity and local stress concentration of circumscribed π-reinforcing stiffeners were best among the three traditional reinforcing stiffeners. Besides, the methods of extending reinforcing stiffener web and adding diaphragms on the end of reinforcing stiffeners not only obviously improved both axial and out-plane stiffness but also increased ultimate capacity and reduced local stress concentration. Five three-dimensional finite element (FE) models of steel stiffened segments considering initial imperfections and residual stress were established. Theoretical analysis based on the principle of stationary potential energy was carried out. The reduced parameters based on FE analysis results were consistent with those from tests and theoretical analysis and tended to be conservative at a safety level. The presented overall investigation may provide reference for the design and construction of stiffened steel segment in hybrid structure.

1. Introduction

In the 1970s, hybrid structures were originally developed in Germany [1,2] and had been widely used in Europe and Japan [3–7] for the benefits of combining two different materials in longitudinal direction reasonably. And the hybrid structures including hybrid girder [1–9], hybrid pylon [10,11] and hybrid arch skewback [12,13], have been applied in China since the 1990s due to their superior mechanical behavior, easy construction and good economic performance. By using steel girders as main spans and concrete girders as side spans, hybrid girder not only decreased dead weight and reduced the scale of substructures, but also efficiently avoided negative reaction for side pier. Hybrid pylon with steel pylon on the top and concrete pylon on the bottom could simplify the configuration in anchorage zone and shorten the construction period by manufacturing steel pylon and concrete pylon at the same time. Hybrid skewback could not only avoid concrete cracks caused by tensile stress compared with concrete skewback, but also avoid complex structure like gyro shape arch rib compared with steel skewback.

Hybrid structure segment generally consists of steel stiffened segment, concrete strengthened segment and hybrid joint. The schematic structure of the steel stiffened segment is shown in Fig. 1. Due to stiffness difference between steel parts and concrete components for the changes of material and cross section, it is necessary to ensure stiffness transition and smooth force transition in hybrid joint [1,2] with steel cells, bearing plate, studs and PBL connectors and etc. Merits of increasing reinforcing stiffeners are summarized as follows: (1) expanding the area of force transmission, reducing stress in steel segment; (2) as a result decreasing the local stress concentration of U stiffeners by restricting rotation of bearing plate, and improving the capacity and global or local bucking. (3) Lowering compressive stress in concrete segments. (4) Eliminating tensile stress caused by unbalanced loading and avoiding cracks in concrete segments. Three traditional types of reinforcing stiffeners (Fig. 2) are usually used for steel stiffened segment, including embedded T-stiffener (Type 1), circumscribed T-stiffener (Type 2) and circumscribed π-stiffener (Type 3).

In the process of designing steel stiffened segment, appropriate evaluation of buckling mode and ultimate strength of the steel segment is significant [14]. However, recent studies about buckling mode and compressive strength of stiffened plate mainly focus on uniform cross-section stiffeners, while few are related to stiffeners with variable height. The ultimate strength of stiffened plate has been determined

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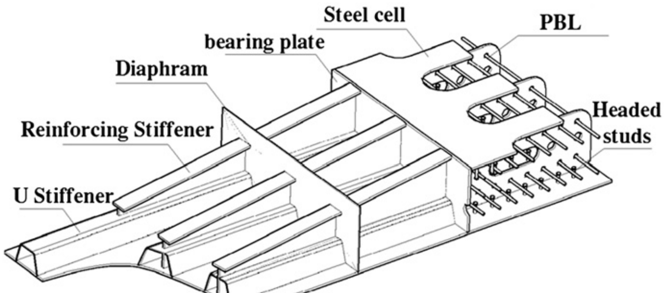

Fig. 1. Schematic of steel reinforcing stiffened segment.

by the following three methods: strut approach, orthotropic plate theory and finite element analysis. The equal interval stiffeners and plates are simplified as disconnected struts in the method of the strut approach, effective width was recommended to consider local buckling [15]. Von et al. [16] proposed concept of effective width and suggested that the capacity is equal to effective area multiply yield strength. Indeed, the value of effective width not only related to residual stress, initial imperfections etc., but also changed with increasing load. A design method to calculate effective width of multiple stiffeners was suggested by Schafer [17]. A formula considering the effects of stiffeners spacing, width–thickness ratio, residual stress and initial imperfections was proposed to predict the ultimate strength of stiffened plate by Horne et al. [18,19]. Besides, the strength was calculated based on Perry formula in BS5400 [20]. The computational formula of effective width in AASHTO [21] was proposed depending on experimental results. The formulas in JRA [22] were put forward by assuming initial imperfections (b/150) and residual stress ($0.4\sigma_y$ yield strength) through finite element analysis. In terms of the orthotropic plate theory, the stiffened plate converts to an equivalent plate. Buckling and post buckling properties of stiffened plate have been analyzed by Sherbourne [15], and the achievement has been adopted in Canadian Standards Association. Byklum [23] deduced a semi-analytical model for global buckling and post buckling analysis of stiffened plate based on large deformation plate theory. An ultimate strength formulation for stiffened compressive flanges of steel box girders under pure bending was put forward by Massonnet et al. [24]. The stress distribution and load–deformation relationship were predicted by Galerkin method. Bank and Yin [25] studied the impact of rotation restrain of unloaded edges to buckling coefficient for a stiffened planet. Two control equations about orthotropic plate were solved by Paik et al. [26] and the strength formulas for stiffened plate under unidirection or bidirection pressure or tensile stress were proposed. In recent years, with the development of commercial numerical simulation software incorporating nonlinear material and geometric nonlinearity, the ultimate compressive strength of stiffened plate was determined by finite element analysis (FEA). Grondin et al. [27–29] proposed an ultimate strength formula depending on test and FEA d by considering the factors of initial imperfections, residual stress, load direction, width–thickness ratio of stiffened plate,

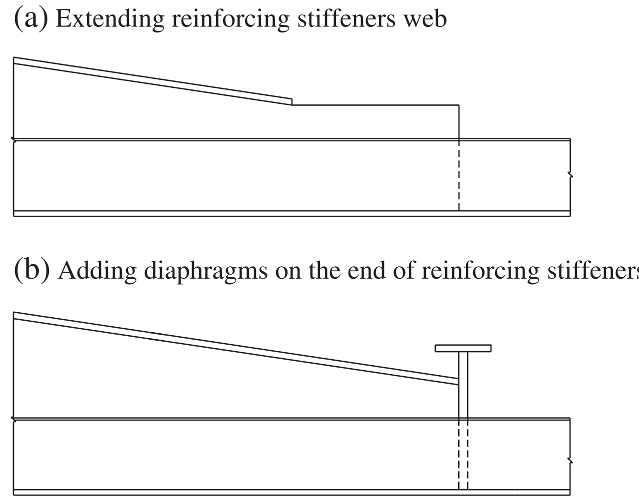

Fig. 3. Innovative reinforcing stiffeners.

length–width ratio of stiffened plate and area of stiffeners etc. The results of non-linear finite element analysis for stiffened plates subjected to axial compression load considering post-buckling behavior up to collapse were presented by Ghavamia and Khedmatib [30].

However, the buckling mode and the compressive strength of tapered columns were different from uniform ones [31–33]. Thus, the stability performance of reinforcing stiffeners was quite different from traditional uniform stiffeners. In addition, the pros and cons of each reinforcing stiffeners were not obvious and local stress concentration appeared at the end of the reinforcing stiffeners [34]. Thus, two innovative steel stiffened segments, extending reinforcing stiffeners web (Type 4) and adding diaphragms at the end of reinforcing stiffeners (Type 5) (Fig. 3), were proposed in this paper as a solution to the stress concentration problem.

In order to investigate ultimate capacity and buckling mode of stiffened steel segment and to verify rationality of innovative steel stiffened segments, model tests with five different specimens were carried out, and responses including variation of displacement, stiffness, strain and buckling mode were recorded and analyzed. On the basis of experimental work, three-dimensional FE models of stiffened segment considering initial imperfections and residual stress were built, and the theoretical analysis based on the principle of stationary potential energy was also carried out. All the results of experimental, numerical investigations and theoretical analysis of the steel stiffened segments in this study may provide reference for the design and construction of such type structures.

2. Experimental program

2.1. Test specimen

Five half-scaled specimens of steel stiffened segment were fabricated, as shown in Fig. 4. As for the reinforcing stiffeners, embedded T-stiffener

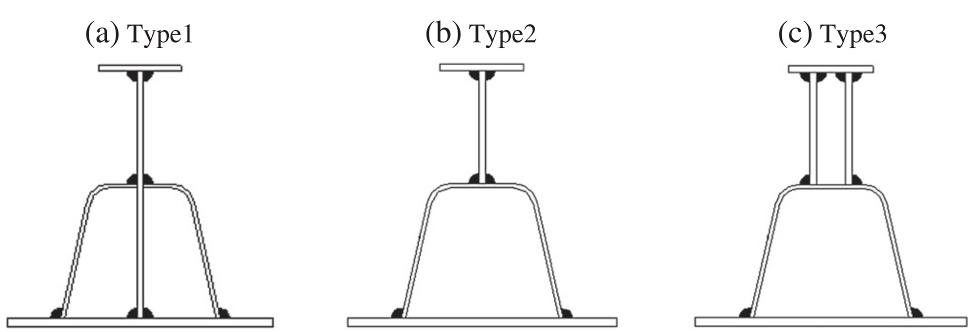

Fig. 2. Reinforcing stiffeners classification.