Journal of Constructional Steel Research 138 (2017) 184–195

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

# Probabilistic ultimate buckling strength of stiffened plates, considering thick and high-performance steel

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ARTICLE INFO

*Article history:*
Received 9 February 2017
Received in revised form 30 May 2017
Accepted 8 July 2017
Available online xxxx

*Keywords:*
Stiffened steel plate
Initial imperfection
FE analysis
Response surface
Monte Carlo simulation

ABSTRACT

The probabilistic distribution of ultimate buckling strength for stiffened steel plates subjected to a distributed axial stress was obtained using Monte Carlo simulations in association with the response surface method. The plates of both normal and high-performance steel (SBHS) were taken into account, and their thickness was varied from 10 to 90 mm. The ultimate buckling strength was determined by nonlinear elasto-plastic finite element (FE) analysis, considering geometric and material nonlinearity. The initial out-of-plane deflection and residual stress were considered as two independent random variables upon which the ultimate buckling strength depends. The response surface, showing the variation of ultimate strength due to the initial deflection and residual stress, was estimated using the nonlinear FE results. Based on the obtained statistical distribution, partial safety factors for the ultimate buckling strength were proposed.



## Symbol List

| | |
|---|---|
| $A_l$ | cross-sectional area of longitudinal stiffener |
| $E$ | modulus of elasticity |
| $I_l$ | moment of inertia of a longitudinal stiffener with respect to its base |
| $N_e$ | number of elements per half subpanel width |
| $R_R$ | reduced slenderness parameter |
| $a$ | length of the stiffened plate in between two transverse stiffeners |
| $b$ | overall width of the stiffened plate |
| $b_s$ | width of a subpanel in between two longitudinal stiffeners |
| $f_N$ | nominal strength of the stiffened plate |
| $h_r$ | height of the longitudinal stiffener |
| $k_r$ | buckling coefficient |
| $n$ | number of subpanels divided by the number of longitudinal stiffeners |
| $p_f$ | probability of non-exceedance |
| $t$ | thickness of the panel plate |
| $t_r$ | thickness of the longitudinal stiffener |
| $t_0$ | critical thickness of the panel plate to avoid local buckling |
| $\Delta$ | maximum initial out-of-plane deflection for local mode deflection |
| $\alpha$ | aspect ratio $= a/b$ |
| $\alpha_0$ | critical aspect ratio |
| $\beta_T$ | target reliability index |
| $\gamma$ | partial safety factor |
| $\gamma_l$ | relative stiffness of the longitudinal stiffener |
| $\gamma_l, req$ | required relative stiffness of the longitudinal stiffener according to the Japanese Specification for Highway Bridges (JSHB) |
| $\delta_l$ | cross-sectional area ratio of one longitudinal stiffener to the panel plate $= A_l/bt$ |
| $\delta_{01}$ | maximum initial out-of-plane deflection magnitude for a whole-plate deflection shape |
| $\varepsilon$ | engineering strain |
| $\varepsilon_l$ | local strain in the longitudinal direction of the stiffened plate |
| $\varepsilon_y$ | yield strain |
| $\mu$ | mean value |
| $\nu$ | Poisson's ratio |
| $\sigma$ | engineering stress or standard deviation (as mentioned in the text) |
| $\sigma_{cr}$ | ultimate buckling strength |
| $\sigma_e$ | elastic buckling strength |
| $\sigma_{rc}$ | compressive residual stress |
| $\sigma_T$ | tensile strength |
| $\sigma_y$ | yield strength |

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http://dx.doi.org/10.1016/j.jcsr.2017.07.004

## 1. Introduction

Stiffened plates are often used to construct different parts of steel bridges, such as the bottom flange of box girders, and the box sections used as truss members or columns. Under compression, such thin plate components exhibit local buckling and may fail with sudden collapse. The collapse of large steel box girder bridges during the 1970s led to extensive research on buckling behavior and the ultimate load carrying capacity of steel plates, including stiffened plates [1].

Rigorous experimental and numerical studies were carried out during the 1970–80s to investigate the ultimate buckling strength, considering the effect of initial imperfections. For example, Komatsu et al. [2] measured the initial deflection and residual stress for 28 stiffened plate specimens including high-strength steel. The residual stress distribution inside stiffened plates was also reported. Komatsu et al. [3] obtained statistical data on the initial deflection and the ultimate buckling strength of steel bridge members. Komatsu and Nara [4] also investigated fundamental modes of initial deflection and their individual effect on the ultimate strength.

Employing a semi-analytical finite element (FE) analysis, Nara and Komatsu [5] proposed ultimate buckling strength curves corresponding to 1%, 5% and 10% probability of non-exceedance. Three different numbers of longitudinal stiffeners were considered to obtain the buckling strength curves. Stochastic variation of the initial out-of-plane deflection was taken into account, but the residual stress was assumed to be constant. Furthermore, Nara et al. [6] investigated the effect of the relative stiffness of longitudinal stiffeners on the ultimate strength, employing elasto-plastic finite displacement theory. The numerical results were compared with the strength curves specified by German design codes DASt Ri-012 [7] and DIN4114 [8]. It was found that stiffened plates, satisfying relative stiffness requirement of JSHB [9–10] showed lower ultimate strengths compared to DASt Ri-012 and DIN4114 code. Stiffened plates with twice the required relative stiffness yield the same ultimate strength as DASt Ri-012 at a reduced slenderness parameter $R_R = 0.7$. The reduced slenderness parameter $R_R$ is defined as

$$R_R = \frac{b}{t}\sqrt{\frac{\sigma_y}{E}\frac{12(1-\nu^2)}{\pi^2 k_r}} \tag{1}$$

where $b$ is the overall width of the plate, $t$ is the thickness of the plate, $\sigma_y$, $E$ and $\nu$ represent the yield strength, modulus of elasticity and Poisson's ratio for the steel, respectively, and the buckling coefficient $k_r = 4n^2$, where $n$ is the number of subpanels divided by the number of longitudinal stiffeners.

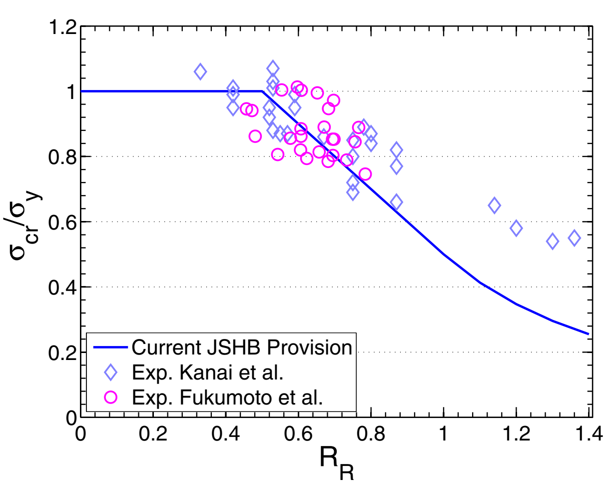


**Fig. 1.** Standard ultimate strength curve of stiffened plate in JSHB.

Kanai and Otsuka [11] carried out experiments on 43 stiffened plates under uniaxial loading and proposed an ultimate strength curve, which has been adopted in the current provision of JSHB [10]. Fukumoto et al. [12] also conducted experiments on stiffened plates with low reduced slenderness parameter ($R_R$ = 0.46–0.78). Fig. 1 shows the standard ultimate strength curve for a stiffened plate, as per the current JSHB provision, compared with the aforementioned experimental results. Here, $\sigma_{cr}$ is the ultimate buckling strength.

Previous research in the 1970–80s, generally dealt with relatively thin plates (about 10 mm thick). The experimental data of Kanai and Otsuka [11], which is the basis of the JSHB strength curve, were also obtained from experiments conducted with thin plates. Since 1996, the JSHB limit for the maximum thickness of steel plates that can be used in steel bridge construction has increased from 50 mm to 100 mm [9–10]. However, the effect on the ultimate load bearing capacity due to use of such thicker plates has not yet been investigated.

In 2008, Steel for Bridge High-performance Structure (SBHS) was incorporated into the Japanese Industrial Standards (JIS). SBHS offers advantages over ordinary steel, such as a higher yield strength, better weldability and ease of fabrication [13]. Nevertheless, its inelastic behavior differs from that for ordinary steel since it has a high yield-to-tensile strength ratio and almost no yield plateau [14]. The current strength curve for JSHB does not account for the effects of SBHS steel.

There is one more reason to re-examine the current JSHB strength curve. The present practice in developing design codes, i.e., AASHTO LRFD [15] and Eurocode [16], is to develop reliability-based design criteria with partial safety factors (PSF) so as to account for uncertainties originating from individual sources. The current JSHB code does not adopt the partial factor format. To develop a reliability-based strength curve for ultimate buckling strength, it is necessary to obtain probabilistic information, such as a probability density function, a mean value and a standard deviation for ultimate buckling strength. Even though the past study of Nara and Komatsu [5] proposed ultimate strength values for 1%, 5% and 10% fractile, the effects of thick plates and SBHS steel are still unknown.

This paper investigates the probabilistic distribution of ultimate buckling strength for longitudinally stiffened plates with 2 equidistant flat plate longitudinal stiffeners, satisfying the relative stiffness requirement of JSHB ($\gamma_l/\gamma_{l,req} = 1$) and with an aspect ratio $\alpha = 1$. This kind of plates is generally used in the bottom flange of a steel box girder bridge. The ratio of relative stiffness to the required relative stiffness of a longitudinal stiffener ($\gamma_l/\gamma_{l,req}$) is calculated according to the JSHB [10] as presented in the Appendix-A. The plates of both normal and high-performance steel (SBHS) were taken into account, and their thickness was varied from 10 to 90 mm. Based on the probabilistic distribution obtained from Monte Carlo simulation (MCS), PSFs are proposed for the ultimate buckling strength.

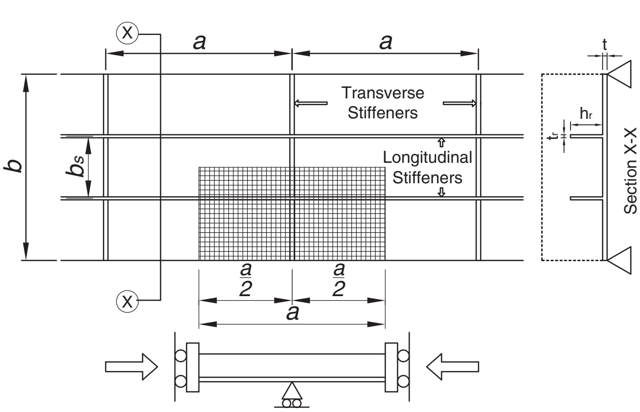


**Fig. 2.** Model geometry.