SERVICEABILITY LIMIT STATES FOR SLENDER STIFFENED STEEL PLATES UNDER AXIAL COMPRESSION: A PROBABILISTIC STUDY

Saitama University IEB Member ○Mahmudur Rahman
Saitama University Member Yoshiaki Okui

1. INTRODUCTION

Structural parts widely used in steel structures are often constructed from stiffened steel plates due to high strength to weight ratio. In the continuous support zone of a steel box girder bridge, bottom flange of box girder is usually constructed from stiffened steel plates which is subjected to axial compressive load and design of such member is governed by the ultimate buckling strengths. However, the stiffened plates with high slenderness i.e. width-to-thickness ratio parameter R_R >1.0 (R_R as defined in JSHB) shows large out-of-plane deflection due to elastic buckling, which may occur before reaching ultimate buckling strength. Thus, restriction of such out-of-plane deflection exceeding the fabrication tolerance, is important from a serviceability point of view.

The probability based limit states design method has become popular in the modern design specifications for steel structures i.e. AISC LRFD. Along with the development of high-performance steels (SBHS) for bridge construction, it has become possible to construct more slender structures now-a-days, which necessitates paying more attention to the deflection serviceability problems. The current paper focuses on the probability based serviceability limit states (SLS) for both normal and high-performance (SBHS) stiffened steel plates with R_R >1.0 under axial compressive stress.

2. DETERMINISTIC FINITE ELEMENT ANALYSIS

To obtain the compressive strengths for SLS, deterministic nonlinear elasto-plastic finite element (FE) analysis were carried out considering both geometric and material nonlinearity. The material nonlinearity was modeled by applying Mises plasticity and isotropic strain hardening theory. As a source of variability of the compressive strengths, initial imperfections i.e. initial out-of-plane deflections and residual stresses were considered simultaneously in the nonlinear FE analysis. Based on respective mean values and standard deviations, 12 different combinations of imperfections were considered for a single stiffened plate model. A total of 144 FE analyses were carried with two different material grades (SM570 and SBHS500) under R_R = 1.2 and 1.4, and different plate thicknesses ranging from 10 mm to 50 mm. Schematic diagram of the stiffened plate model is shown in Fig. 1. Simply supported boundary condition was applied along the longitudinal edge of the stiffened plate. To reduce the computational time, only the shaded rectangular area as shown in Fig. 1 was analyzed considering the symmetric geometric and loading conditions.

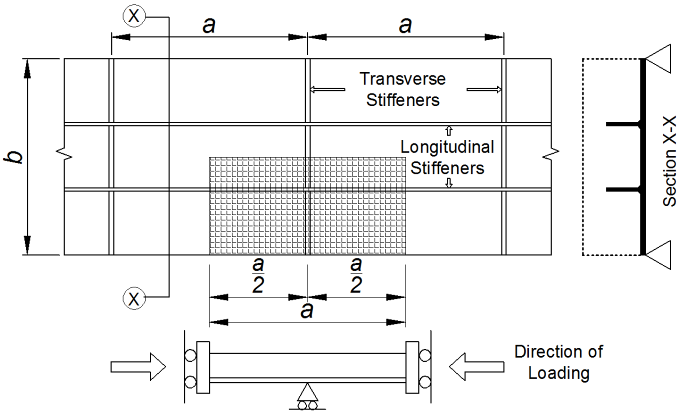


Fig.1 Stiffened plate model.

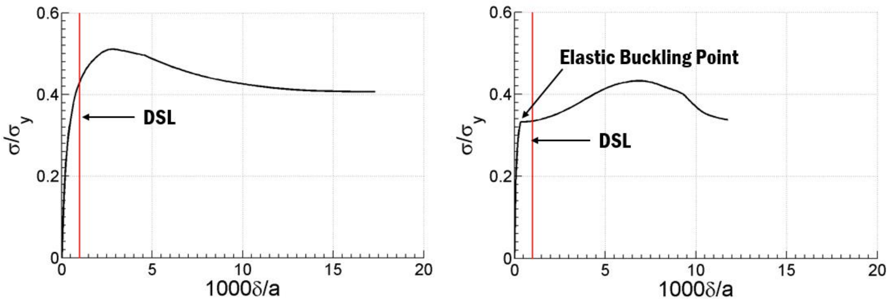
3. COMPRESSIVE STRENGTHS AT SLS

Among different SLS design criteria for steel plate elements, out-of-plane deflections limit is the prime concern of this study. For efficient design, it is necessary to discard the reserve strength beyond elastic buckling for slender plates, involving large out-of-plane deflections. The limit for out-of-plane deflections is often taken as the fabrication tolerance, which is different for different buckling modes. As reported by Nara et al. (1988), deflections limit for distortional buckling mode is $a/1000$ and for local buckling mode is $b_s/150$, where a and b_s are the length of the plate and width of subpanels in between the longitudinal stiffeners, respectively. These limits will be termed as the deflection serviceability limit (DSL) in this paper.

From the FE analysis results, normalized compressive stress σ/σ_y (σ_y = yield strength) versus normalized out-of-plane deflection $1000\delta/a$ (δ = out-of-plane deflection after loading) curves were plotted. Clearly two types of curves were found in the analyses as shown in Fig. 2.

Keywords: Stiffened plates, serviceability limit states, initial imperfections, response surface, Monte Carlo simulation.
Contact address: Room 803, Bldg. of Research and Project, Saitama University, Saitama 338-8570 Japan.

Curve type-1 did not show a distinct elastic buckling point, while curve type-2 showed a clear elastic buckling point. For curve type-1, SLS was proposed as the smaller one of compressive stresses corresponding to DSL and service load level (considered equal to the 75% of ultimate strength). Similarly, for curve type-2, SLS was proposed as the smaller one of compressive stresses corresponding to DSL and elastic buckling strength.



(a) Curve Type -1 (b) Curve Type-2

Fig.2 Normalized compressive stress-stain curves

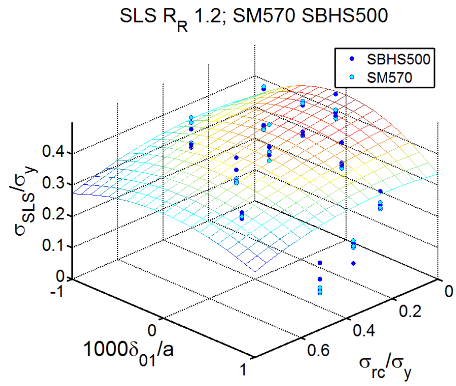


Fig.3 Response Surface for R_R 1.2.

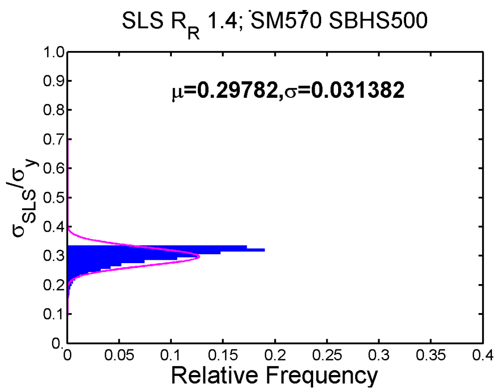


Fig.4 Relative frequency distribution for R_R 1.4.

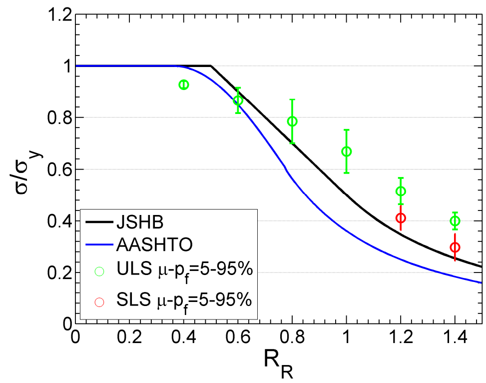


Fig.5 Comparison of MCS result.

4. PROBABILISTIC ANALYSIS

The probabilistic distribution of buckling strengths for SLS was obtained by employing Monte Carlo simulations (MCS) in association with the response surface method. The response surface, showing the variation of buckling strength for SLS due to the initial deflection and residual stress, was estimated using the nonlinear FE results. The response surface function was approximated as the following second-order polynomial:

$$\frac{\sigma_{SLS}}{\sigma_y} = \sum p_{ij} x_1^i x_2^j; \quad i = 0 \sim 2,\ j = 0,2; \quad i + j \le 4 \qquad (1)$$

where σ_{SLS} is the compressive strength for SLS, σ_y is yield strength, $x_1 = \sigma_{rc}/\sigma_y$ normalized residual stress, $x_2 = 1000\delta_{01}/a$ normalized initial deflection, δ_{01} is the magnitude of initial out of plane deflection and p_{ij} are the coefficients of the polynomial, determined by nonlinear multiple regression analysis. Figure 3 shows the response surface obtained for $R_R = 1.2$ as an example. In the MCS, x_1 and x_2 were considered as two independent random variables. After randomly generating pairs of x_1 and x_2 values according to their respective probability density functions, the response surface function was used to determine the compressive strength for SLS for each pair of values. This process was repeated for a number of iterations, until the mean and standard deviation for the σ_{SLS} obtained from the MCS converged. Figure 4 shows the relative frequency distribution obtained from MCS for $R_R = 1.4$.

5. RESULT AND DISCUSSION

The study result was compared with ultimate limit sate (ULS) reported in a previous study of the authors (Rahman et al. 2016) as well as different design codes i.e. JSHB and AASHTO as shown in Fig. 5. It was found that, AASHTO provides significantly conservative design while JSHB prediction matches well with 5% probability of non-exceedance of the compressive strength at SLS.

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