HOKKAIDO UNIVERSITY

| | |
|---|---|
| Title | A PROPOSAL FOR COMPRESSIVE DESIGN STRENGTH OF STAINLESS STEEL PLATES |
| Author(s) | MIYAZAKI, Y.; NARA, S. |
| Citation | Proceedings of the Thirteenth East Asia-Pacific Conference on Structural Engineering and Construction (EASEC-13), September 11-13, 2013, Sapporo, Japan, A-5-5., A-5-5 |
| Issue Date | 2013-09-11 |
| Doc URL | http://hdl.handle.net/2115/54223 |
| Type | proceedings |
| Note | The Thirteenth East Asia-Pacific Conference on Structural Engineering and Construction (EASEC-13), September 11-13, 2013, Sapporo, Japan. |
| File Information | easec13-A-5-5.pdf |

Instructions for use

Hokkaido University Collection of Scholarly and Academic Papers : HUSCAP

# A PROPOSAL FOR COMPRESSIVE DESIGN STRENGTH OF STAINLESS STEEL PLATES

Y. MIYAZAKI[1*†], S. NARA[2]

[1]*Department of Civil Engineering, Nagaoka National College of Technology, Japan*
[2]*Department of Civil Engineering, Graduate School of Engineering, Osaka University, Japan*

## ABSTRACT

Stainless steel has extremely higher corrosion resistance than carbon mild steel. Design method for stainless steel structures requires defining the strength behavior in structures in order to use effectively for material characteristics. This study proposes an estimation method for compressive strength of plates which consist of 5 grades of stainless steel. Firstly, clarified are distinct elasto-plastic behaviors of the stainless steel plates up to ultimate strength obtained by numerical analysis on the basis of stress-strain diagrams of coupon tests. Secondly, ultimate compressive strength for the plates is proposed at less than design strength. Moreover, it defined these estimation methods for more than design strength. Finally, these estimation methods for compressive strength of stainless steel plates defined to effect for material properties.

**Keywords:** Stainless steel, ultimate compressive strength, plate buckling, simply supported plate, outstanding plate.

## 1. INTRODUCTION

Stainless steels are used for main structural members of highway and pedestrian bridges in several countries (Euro Inox 2004), since Design codes for the stainless steel structures published in Europe (EN1993-1-4 1996) and the United States (ASCE 2002). Eurocode specifies design strength of structural members made of austenitic, ferritic and duplex stainless steels. Japanese stainless steel structural design code for building structures, which deals with only the austenitic stainless steel, is provided (Subcommittee for draw up design standard of stainless building structures 2001). On the other hand, stainless steels have not been used for bridge and civil structures in Japan. The reason is that stainless steel seems to have less advantage of cost performance in comparison with carbon mild steel and weathering steel mainly because of expensive material price and difficult fabrication works instead of extremely high corrosion resistance. However, a variety of stainless steels give the best solution for keeping design performance for a long life time under severe corrosion circumstances because of excellent corrosion resistance.

* Corresponding author: Email: y-miyazaki@nagaoka-ct.ac.jp

† Presenter: Email: y-miyazaki@nagaoka-ct.ac.jp

**Table 1: Mechanical property for stainless steels**

| Grade | Young's modulus $E$(GPa) | 0.1% proof stress $\sigma_{0.1}$(MPa) | 0.2% proof stress $\sigma_{0.2}$(MPa) | ultimate tensile stress $\sigma_u$(MPa) | elongation (% ) | yield ratio $\sigma_{0.2}/\sigma_u$ |
|---|---|---|---|---|---|---|
| SUS304 | 157 | 236 | 261 | 697 | 70.2 | 0.374 |
| SUS304N2 | 173 | 360 | 402 | 723 | 66.5 | 0.557 |
| SUS316 | 174 | 230 | 254 | 561 | 75.9 | 0.452 |
| SUS410L | 204 | 346 | 362 | 487 | 38.6 | 0.744 |
| SUS329J3L | 202 | 485 | 533 | 749 | 47.9 | 0.712 |

Therefore, this study presents an estimation method for predicting precisely ultimate strength and displacement of stainless steel plates under uniaxial compression. Based on stress-strain relationships of stainless steels obtained by coupon tests, the method consists of two classified parts. At the first part, the ultimate strength is estimated by plate slenderness and proposed constants of each stainless steel in the region of elastic buckling behavior. In the region of apparent difference of the stress-strain relationships between stainless steel and mild steel, the ultimate strength is calculated by predicted ultimate displacement and stress-strain relationships. The proposed method is independent of proof stress which is 0.1% or 0.2%, because of a proposed a conversion factor.

## 2. MATERIAL PROPERTIES FOR STAINLESS STEELS

Table 1 shows mechanical properties of 5 target materials in this study, which consist of 3 austenitic, a ferritic and a duplex stainless steel (Miyazaki et al 2010). The table displays that austenitic stainless steels have higher elongation and lower yield ratio than other stainless steels.

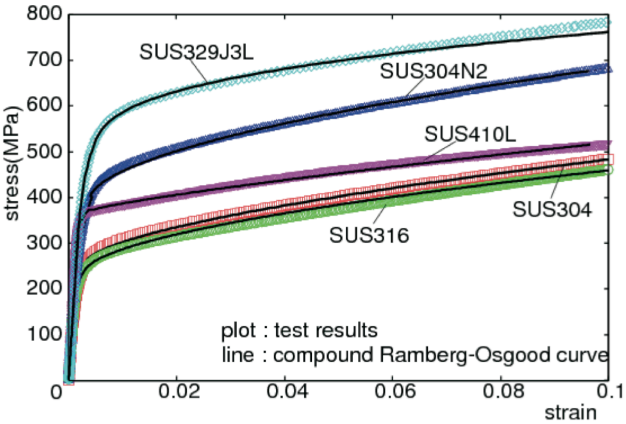



**Figure 1: Stress strain relationship**

Figure 1 represents stress-strain relationship for stainless steels. Plots and lines illustrate tensile coupon test results and stress-strain curves based on Ramberg-Osgood curve (Miyazaki et al 2010), respectively. The curve, which consist of an elastic straight line and 2 Ramberg-Osgood curves, is expressed by equation (1).

$$\varepsilon = \begin{cases} \dfrac{\sigma}{E} & \text{if } 0 \le \sigma < \sigma_P \\ \dfrac{\sigma}{E} + \varepsilon_A & \text{if } \sigma_P \le \sigma < \sigma_{0.2} \\ \dfrac{\sigma}{E} + \varepsilon_B + \varepsilon_C & \text{if } \sigma_{0.2} \le \sigma \end{cases} \tag{1}$$

where $\varepsilon$, $\sigma$ and $\sigma_P$ denote strain, stress and 0.01% proof stress for materials, respectively. $\varepsilon_A$, $\varepsilon_B$ and $\varepsilon_C$ are expressed by thefollowing equations.

$$\varepsilon_A = 0.002 \frac{\sigma^n - \sigma_P^n}{\sigma_{0.2}^n - \sigma_P^n} \tag{2}$$

**Table 2: Material parameters for including equations (1) to (4)**

| Grade | 0.01% proof stress $\sigma_{0.01}$(MPa) | material parameter | | | | | |
|---|---|---|---|---|---|---|---|
| | | $n$ | $m$ | $\varepsilon_{0.2}$ | $E_{0.2}$ (MPa) | $\varepsilon_{10}$ | $\sigma_{10}$ (MPa) |
| SUS304 | 143 | 2.88 | 1.67 | 0.00350 | 29700 | 0.100 | 481 |
| SUS304N2 | 253 | 3.93 | 1.79 | 0.00415 | 34400 | 0.100 | 680 |
| SUS316 | 162 | 6.97 | 1.74 | 0.00349 | 16500 | 0.0823 | 457 |
| SUS410L | 306 | 15.2 | 1.25 | 0.00382 | 11400 | 0.101 | 523 |
| SUS329J3L | 346 | 7.01 | 2.52 | 0.00469 | 30900 | 0.0597 | 729 |

$$\varepsilon_B = \frac{0.002n\sigma_{0.2}^{n-1}}{\sigma_{0.2}^n - \sigma_P^n}\sigma + \varepsilon_{0.2} - \frac{\sigma_{0.2}}{E_{0.2}} \tag{3}$$

$$\varepsilon_C = \left(\varepsilon_{10} - \varepsilon_{0.2} - \frac{\sigma_{10} - \sigma_{0.2}}{E_{0.2}}\right)\left(\frac{\sigma - \sigma_{0.2}}{\sigma_{10} - \sigma_{0.2}}\right)^m \tag{4}$$

where $m$ and $n$ are material parameters, $\varepsilon_{0.2}$, $E_{0.2}$, $\varepsilon_{10}$ and $\sigma_{10}$ denote strain, tangent modulus at 0.2% proof stress, strain and stress at 10% strain, respectively. Table 2 shows numerical values of parameters included in equations from (1) to (4). The extended Ramberg-Osgood equation (1) describes all test resultants for stainless steels accurately, as shown in Figure 1.

## 3. STAINLESS STEEL PLATES UNDER UNIAXIAL COMPRESSION

Analytical models for simply supported and outstanding plate under uniaxial compression are explained in this chapter.

### 3.1. Simply supported plate

Figure 2 shows the analytical model for simply supported plates under uniaxial compression. Aspect ratio $\alpha(=a/b)$ is fixed to be equal to 1.0. Plate slenderness $\bar{\lambda}_p$, which is expressed by equation (5), varies from 0.3 to 1.5 in equation (5).

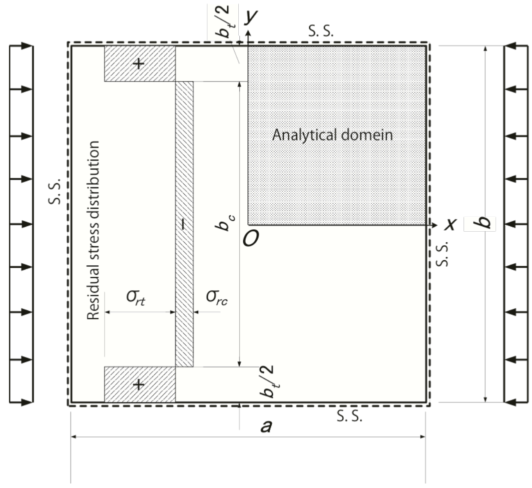



**Figure 2: Simply supported plate**

$$\bar{\lambda}_p = \frac{b}{t}\sqrt{\frac{\sigma_F}{E}\frac{12(1-\nu^2)}{\pi^2 k}} \tag{5}$$

where $\sigma_F$, $\nu$ and $k$ denote strength ($\sigma_{0.1}$ or $\sigma_{0.2}$ ) , poisson's ratio and buckling parameter (=4.0), respectively. Both out-of plane deflection and residual stresses are considered as the initial imperfections. Equation (6) expresses initial deflection.

$$w_0 = w_{0,s}\cos\frac{\pi x}{a}\cos\frac{\pi y}{b} \tag{6}$$

where $w_{0,s}$ (=$b$/150) is maximum value of initial out-of plane deflection. Numerical values of tensile $\sigma_{rt}$ and compressive residual stress $\sigma_{rc}$ are equal to $\sigma_{0.2}$ and -0.3$\sigma_{0.2}$., respectively. The distribution shape of residual stress is illustrated in Figure 2.

### 3.2. Outstanding plate

Figure 3 displays the analytical model for outstanding plate with three simply supported edges and a free one under uniaxial compression. Aspect ratio $\alpha(=a/b)$ is constantly equal to 3.0. Plate slenderness $\bar{\lambda}_p$ expressed by equation (5) is from 0.3 to 1.5, however, numerical value of $k$ in equation (5) changes to 0.425. The initial imperfections, that is, out-of plane deflection and residual stresses are also taken into consideration. Equation (7) expresses amplitude and shape of initial deflection.

$$w_0 = w_{0,o}\frac{y}{b}\cos\frac{\pi x}{a} \tag{7}$$

where $w_{0,o}$ $(=b/100)$ denotes maximum value of initial out-of plane deflection. The residual stresses are same values for simply supported plate. The distribution shape of residual stress is illustrated in Figure 3.

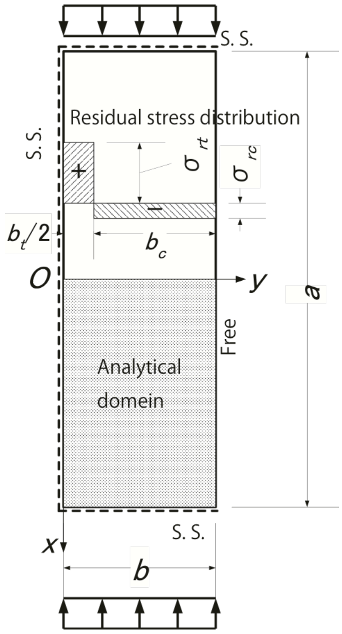



**Figure 3: Outstanding plate**

## 4. EVALUATION METHOD FOR COMPRESSIVE STRENGTH

This chapter describes the proposed evaluation method for the compressive strength for simply supported and outstanding stainless steel plates by using the numerical results.

### 4.1. Ultimate compressive strength

Figure 4 shows relationship between the ultimate compressive strength $\sigma_u/\sigma_F$ and plate slenderness $\bar{\lambda}_p$ for the simply supported and outstanding plate. In the figure, the ultimate strength is plotted against the plate slenderness, and curves indicate the ultimate strength estimated by the following equation.

$$\frac{\sigma_u}{\sigma_F} = \left(\frac{\bar{\lambda}_{p,cr}}{\bar{\lambda}_p}\right)^{b_p} \tag{8}$$

where $\bar{\lambda}_{p,cr}$ and $b_p$ denote material parameters and numerical values of the parameters are shown in Table 3. These values are determined by the least square method for the result of numerical analysis. Figure 4 ensures that equation (8) predicts the ultimate strength obtained from the numerical analysis in the region of

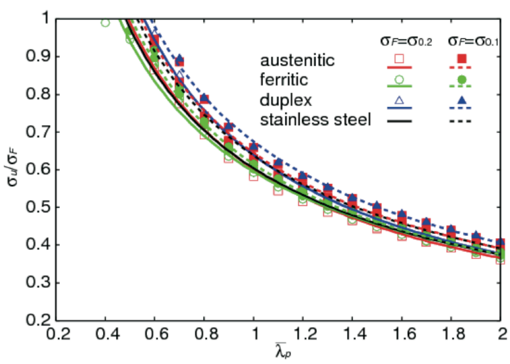



**Figure 4: Ultimate compressive strength curves for simply supported plate**

$\bar{\lambda}_p$ more than 0.4.

### 4.2. Estimation method for compressive strain

Equation (9), that estimates the strain at the ultimate compressive strength of the plates, is proposed in the region of $\bar{\lambda}_p$ less than 0.4.

$$\frac{\varepsilon_u}{\varepsilon_F} = \frac{C_1}{\bar{\lambda}_p^{C_2}} \quad (9)$$

where $\varepsilon_F$, $C_1$ and $C_2$ denote strain for equivalent design stress and material parameters, as shown in Table 4, respectively. Equation (9) is also useful to estimate the ultimate compressive strength for stainless steel plates more than design strength. How to predict the ultimate compressive strength is explained based on equation (9) and stress-strain relationships for the stainless steels in the next section 4.3.

**Table 3: Material parameters in equation (8)**

| Boundary condition | Type | Material strength | $\bar{\lambda}_{p,cr}$ | $b_p$ |
|---|---|---|---|---|
| Simply supported | Austenitic | $\sigma_F = \sigma_{0.2}$ | 0.494 | 0.719 |
| | | $\sigma_F = \sigma_{0.1}$ | 0.544 | 0.720 |
| | Ferritic | $\sigma_F = \sigma_{0.2}$ | 0.457 | 0.662 |
| | | $\sigma_F = \sigma_{0.1}$ | 0.506 | 0.712 |
| | Duplex | $\sigma_F = \sigma_{0.2}$ | 0.557 | 0.763 |
| | | $\sigma_F = \sigma_{0.1}$ | 0.584 | 0.731 |
| | All | $\sigma_F = \sigma_{0.2}$ | 0.482 | 0.690 |
| | | $\sigma_F = \sigma_{0.1}$ | 0.529 | 0.705 |
| Outstanding | Austenitic | $\sigma_F = \sigma_{0.2}$ | 0.565 | 0.466 |
| | | $\sigma_F = \sigma_{0.1}$ | 0.606 | 0.417 |
| | Ferritic | $\sigma_F = \sigma_{0.2}$ | 0.606 | 0.396 |
| | | $\sigma_F = \sigma_{0.1}$ | 0.613 | 0.353 |
| | Duplex | $\sigma_F = \sigma_{0.2}$ | 0.572 | 0.430 |
| | | $\sigma_F = \sigma_{0.1}$ | 0.647 | 0.403 |
| | All | $\sigma_F = \sigma_{0.2}$ | 0.583 | 0.436 |
| | | $\sigma_F = \sigma_{0.1}$ | 0.618 | 0.397 |

**Table 4: Material parameters in equation (9)**

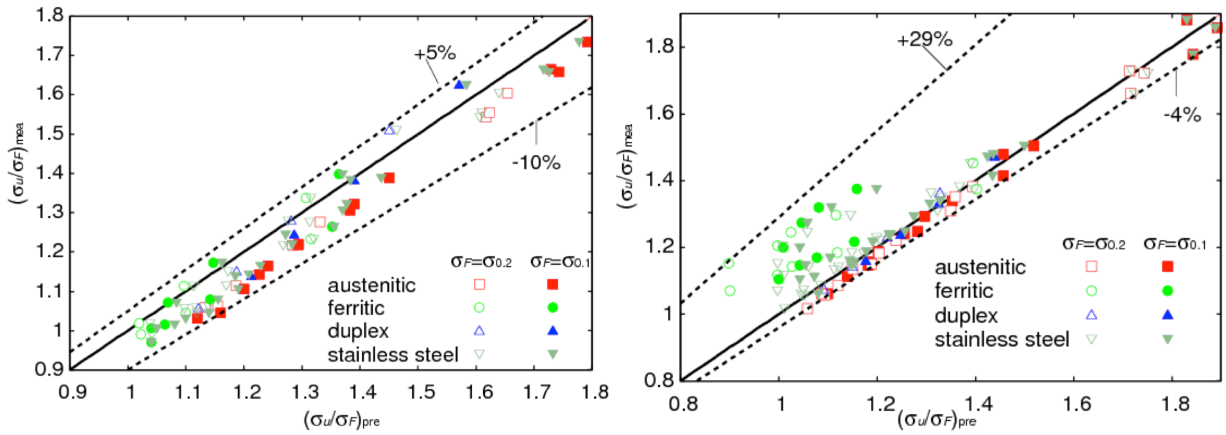
| Boundary condition | Type | Material strength | $C_1$ | $C_2$ |
|---|---|---|---|---|
| Simply supported | Austenitic | $\sigma_F = \sigma_{0.2}$ | 0.565 | 2.64 |
| | | $\sigma_F = \sigma_{0.1}$ | 0.510 | 2.69 |
| | Ferritic | $\sigma_F = \sigma_{0.2}$ | 0.270 | 3.06 |
| | | $\sigma_F = \sigma_{0.1}$ | 0.283 | 3.02 |
| | Duplex | $\sigma_F = \sigma_{0.2}$ | 0.688 | 2.45 |
| | | $\sigma_F = \sigma_{0.1}$ | 0.626 | 2.50 |
| | All | $\sigma_F = \sigma_{0.2}$ | 0.471 | 2.73 |
| | | $\sigma_F = \sigma_{0.1}$ | 0.442 | 2.76 |
| Outstanding | Austenitic | $\sigma_F = \sigma_{0.2}$ | 0.886 | 2.49 |
| | | $\sigma_F = \sigma_{0.1}$ | 0.803 | 2.55 |
| | Ferritic | $\sigma_F = \sigma_{0.2}$ | 0.209 | 3.41 |
| | | $\sigma_F = \sigma_{0.1}$ | 0.418 | 2.78 |
| | Duplex | $\sigma_F = \sigma_{0.2}$ | 0.793 | 2.58 |
| | | $\sigma_F = \sigma_{0.1}$ | 0.754 | 2.61 |
| | All | $\sigma_F = \sigma_{0.2}$ | 0.549 | 2.80 |
| | | $\sigma_F = \sigma_{0.1}$ | 0.589 | 2.74 |

**Table 5: Material parameters in equation (10)**

| Boundary condition | Type | Material strength | $\chi$ |
|---|---|---|---|
| Simply supported | Austenitic | $\sigma_F = \sigma_{0.2}$ | -0.125 |
| | | $\sigma_F = \sigma_{0.1}$ | -0.176 |
| | Ferritic | $\sigma_F = \sigma_{0.2}$ | -0.0576 |
| | | $\sigma_F = \sigma_{0.1}$ | -0.0808 |
| | Duplex | $\sigma_F = \sigma_{0.2}$ | -0.0484 |
| | | $\sigma_F = \sigma_{0.1}$ | -0.0588 |
| | All | $\sigma_F = \sigma_{0.2}$ | -0.0731 |
| | | $\sigma_F = \sigma_{0.1}$ | -0.113 |
| Outstanding | Austenitic | $\sigma_F = \sigma_{0.2}$ | -0.0535 |
| | | $\sigma_F = \sigma_{0.1}$ | -0.0409 |
| | Ferritic | $\sigma_F = \sigma_{0.2}$ | 0.343 |
| | | $\sigma_F = \sigma_{0.1}$ | 0.289 |
| | Duplex | $\sigma_F = \sigma_{0.2}$ | 0.0192 |
| | | $\sigma_F = \sigma_{0.1}$ | -0.00132 |
| | All | $\sigma_F = \sigma_{0.2}$ | 0.0902 |
| | | $\sigma_F = \sigma_{0.1}$ | 0.0762 |

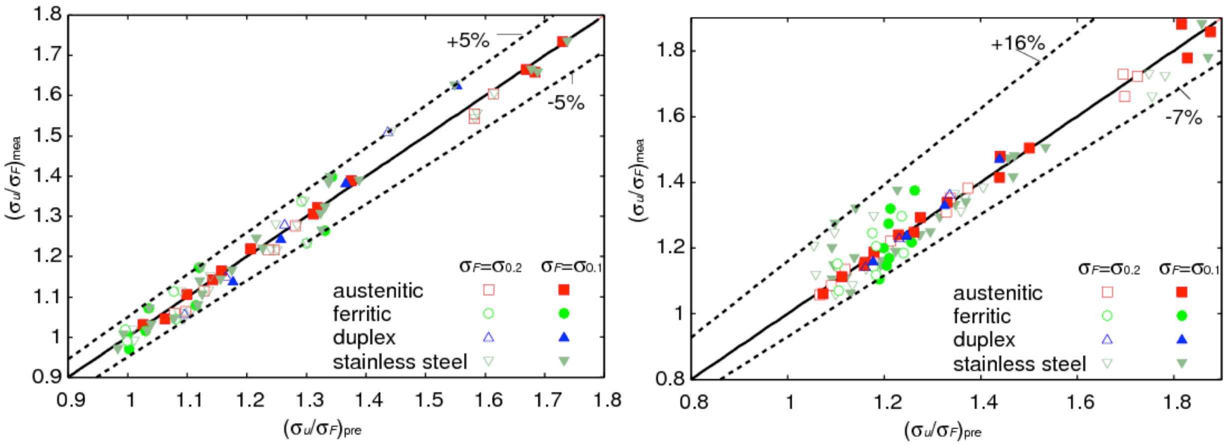
### 4.3. Evaluation method for ultimate compressive strength with stress strain relationship

Figure 5 shows differences between numerical ultimate compressive strength and predicted one, which is derived from both the ultimate strain and stress-strain relationship for stainless steels. The maximum errors of the predicted ultimate strength to numerical one are 10% and 29% for simply supported and outstanding plates, respectively. However, the predicted ultimate strength is at most 10% and 4% higher than numerical one for simply supported and outstanding plates, respectively. These differences increase as $\bar{\lambda}_p$ becomes larger. Therefore, after determining the stress so as to correspond to the stress-strain




**(a) Simply supported plate** **(b) Outstanding plate**

**Figure 5: Ultimate compressive strength for numerical results and predictions**




**(a) Simply supported plate** **(b) Outstanding plate**

**Figure 6: Improved ultimate compressive strength for numerical results and predictions**

relationship of the strain obtained by equation (9), and an ultimate strength values were corrected by multiplying the ultimate strength correction coefficient $C_{\sigma_u}$ shown in equation (10).

$$C_{\sigma_u} = e^{\chi \bar{\lambda}_p} \tag{10}$$

where χ denote material parameter listed in Table 5. In the same way, the ultimate compressive strength of stainless steel plates is obtained by stress-strain relationship and the revised ultimate strain.

Figure 6 shows differences between numerical ultimate compressive strength and predicted one, which is derived from both the refined ultimate strain and stress-strain relationship for stainless steels. The maximum errors are improved on average, and the new predicted ultimate strength is at most 5% and 7% higher than numerical one for simply supported and outstanding plates, respectively.

## 5. CONCLUSIONS

This study proposed design method for stainless steel plate under uniaxial compression, and obtained the following conclusions.

(1) Equation (8) is able to estimate precisely the ultimate compressive strength at the region where the ultimate strength is less than material strength, that is, where $\bar{\lambda}_p$ is approximately more than 0.4.

(2) The ultimate compressive strength of stainless steel plate, which is more than material strength, is estimated safely derived from both stress-strain relationship and the ultimate strain calculated by equation (9), in the region where $\bar{\lambda}_p$ is approximately less than 0.4.

(3) Proposed estimation method estimates accurately the ultimate compressive strength, which is derived from equation (9) multiplied by equation (10), at the region where the ultimate strength is more than material strength, that is, where $\bar{\lambda}_p$ is approximately less than 0.4.

## REFERENCES


EN1993-1-4 (1996). Eurocode 3: Design of steel structures – Part 1.4 General rules – Supplementary rules for stainless steel, CEN.

ASCE (2002). Specification for the Design of Cold-Formed Stainless Steel Structural Members, American Society of Civil Engineers, New York, ANSI/ASCE 8-02.

Euro Inox (2004). Pedestrian Bridge in Stainless Steel, Euro Inox, Vol.7, 1st edition.

Subcommittee for draw up design standard of stainless architectural structures (2001). Specification for Design of stainless architectural structures 2nd edition, SSBA.

Y. Miyazaki and S. Nara (2010). A Buckling Design Method for Unstiffened Stainless Steel Plates under Uniaxial Compression, Journal of Structural Engineering A., JSCE, Vol. 56A, pp.122-134.