Influence of Variation in Material Strength on Ultimate Strength of Stainless Steel Plates under In-Plane Bending and Compression

Satoshi Nara and Yasuhiro Miyazaki

Osaka University, Nagaoka National College of Technology

Abstract

This study presents influence of variation in stainless steel strength on ultimate strength of simply supported plates under in-plane bending and compression. At first, lower and upper bound values of material strength of representative stainless steels, which denote 5% fractile and 95% one of 0.1% or 0.2% proof stress, respectively, are derived from data on a lot of tensile coupon tests. Secondly, based on stress-strain relationship including the obtained material strength values, which is modeled on the Ramberg-Osgood curve, numerical analysis of the plates with considered plate slenderness and initial imperfections is examined, and discussed are significant influences of the material strength, as well as the plate slenderness and initial imperfections, on the ultimate strength of the plates. Finally, it is clarified that difference in the ultimate strength of the plates between the plate with the lower and upper bound values of material strength is less than about 12% in the case of the plates under uniaxial compression, and less than about 17% under in-plane bending.

1 INTRODUCTION

Stainless steel bridges with excellent in corrosion resistance save life-cycle costs and works for maintenance and management by their aging deterioration. Above-mentioned reasons promote construction of bridges made of stainless steel in Europe, the United States and more countries. In order to utilize stainless steel for main structural members, their ultimate strength should be clarified. Design codes of structural components, which consist of stainless steel plate made by hot and cold-rolling process, have already been published in Europe and the United States. Moreover, a design code of austentic stainless steel buildings is established in Japan. Generally, stainless steel structural design codes are based on those of structural members made of the structural carbon mild steels, by replacing yield stress of the carbon steel with 0.2% proof stress of stainless steel. Although, proof stress specified by Japanese building code is not 0.2% but 0.1%, stress-strain relationship is not sufficiently reflected in current stainless steel structural design codes. Mahmud et al. proposed an effective method for evaluating the ultimate strength based on stress-strain relationship. Their experimental study clarified the ultimate strength of short columns with rectangular hollow section and circular section, has proposed an idea of calculating ultimate strength based on a significant amount of strain and a stress-strain diagram of stainless steel. According to

Table 1 Statistical data of austenitic stainless steels

Steel	Parameter	$\sigma_{0.1}$	$\sigma_{0.2}$	σ_1	σ_u	δ
SUS304	μ	226(MPa)	284.7(MPa)	347.9(MPa)	641.58(MPa)	59.7(%)
	s	23.76(MPa)	22.94(MPa)	25.58(MPa)	40.713(MPa)	6.4(%)
	sample number	86	78	48	89	63
SUS316	μ	268.8(MPa)	288.2(MPa)	357.4(MPa)	586.37(MPa)	53.3(%)
	s	26.25(MPa)	28.86(MPa)	25.08(MPa)	30.08(MPa)	4.23(%)
	sample number	23	21	20	27	23
SUS304N2	μ	393.7(MPa)	417.7(MPa)	503.5(MPa)	757.3(MPa)	50.5(%)
	s	38.59(MPa)	45.32(MPa)	57.36(MPa)	37.34(MPa)	6.41(%)
	sample number	50	22	15	42	41

Table 2 5% and 95% fractile based on statistical data

Steel		$\sigma_{0.1}$(MPa)	$\sigma_{0.2}$(MPa)	σ_1(MPa)	σ_u(MPa)	δ(%)
SUS304	min	183	242	300	565	48.1
	max	276	332	401	725	73.2
SUS316	min	221	236	311	529	45.5
	max	324	349	409	647	62.1
SUS304N2	min	323	335	400	687	39.1
	max	475	513	625	833	64.2

their results, it is pointed out that the existing design codes underestimate the ultimate strength of the columns with a section of small plate slenderness. Therefore, the ultimate strength should be estimated statistically taking into account of material properties of stainless steel and initial imperfections dependent on manufacturing process. This paper presents numerically the ultimate strength of the simply supported stainless steel plates under compression and in-plane bending, by using a past statistical data on material strength of austenitic stainless steels. Firstly, based on fundamental statistical data, which consist of mean value and standard deviation, and normal probability distribution, calculated are the minimum and maximum proof stress, which are defined as 5 % and 95 % fractile, both of 0.1% and 0.2% proof stress. 5 % and 95 % fractile denote critical values which 5 % and 95 % of all samples do not exceed, respectively. Next, the parameters of the Ramberg-Osgood curve are determined by the minimum and maximum proof stress, and numerical parametric analysis is carried out by means of nonlinear finite element solver Marc. Finally, the obtained numerical computation result is scrutinized, and discussed are influences of stainless steel strength upon ultimate strength of simply supported plates under in-plane bending and compression.

2 MATERIAL PROPERTIES

Three kinds of austenitic stainless steel dealt in this research are SUS304, SUS316 and SUS304N2. Before conducting the numerical analysis of the plates, 0.1% proof stress $\sigma_{0.1}$ and 0.2% proof stress $\sigma_{0.2}$ are settled based on past material strength data[3] in this chapter. Moreover, material constants and stress-strain diagram of the austenitic stainless steels is described.

2.1 Material Strength

Table1 shows the material strength of SUS304, SUS316, and SUS304N2. In the Table1, σ_1, σ_u, δ, μ and s are 0.1% proof stress, tensile strength, elongation, average, and standard deviation of the parameters, respectively. Generally, logarithm normal distribution fits closely probability distribution of material strength. Therefore, fundamental statistical data of a logarithm normal distribution are derived from those of normal distribution, μ and s.

$$\zeta^2 = \ln\left\{1 + \left(\frac{s}{\mu}\right)^2\right\} \qquad (1)$$

$$\lambda = \ln\mu - \frac{1}{2}\zeta^2 \qquad (2)$$

Where, ζ and λ express the standard deviation and average in logarithm regular probability. Table2 shows the minimum and maximum values, which are calculated by Eq.(1) and Eq.(2), for all parameters shown in Table1. Material strength of stainless steel specified by structural design codes is generally $\sigma_{0.2}$. Compared $\sigma_{0.2}$ specified by JIS, which is 205MPa, 205MPa and 345MPa for SUS304, SUS316 and SUS304N2, respectively, with that obtained by coupon tests[4], shown in Table1, and that of the minimum and maximum value calculated in Table2, the following results are recognized;

- the minimum values, that is, 5 % fractile values of SUS304 and SUS316 do not exceed $\sigma_{0.2}$ specified by JIS

- 5 % fractile value of SUS304N2 is equal to about 97 % of specified $\sigma_{0.2}$

- the maximum values, that is, 95 % fractiles of SUS304, SUS316 and SUS304N2 are about 1.6, 1.7 and 1.5 times larger than JIS specified values.

In consideration of these results, 0.1% and 0.2% proof stress are settled as shown in Table3.

Table 3 Maximum and minimum proof stress of analytical models

Steel		$\sigma_{0.1}$	$\sigma_{0.2}$
SUS304	min	$0.89\sigma_{0.2\_JIS}$	$1.00\sigma_{0.2\_JIS}$
	max	$1.35\sigma_{0.2JIS}$	$1.62\sigma_{0.2JIS}$
SUS316	min	$1.08\sigma_{0.2\_JIS}$	$1.00\sigma_{0.2\_JIS}$
	max	$1.58\sigma_{0.2\_JIS}$	$1.70\sigma_{0.2\_JIS}$
SUS304N2	min	$0.94\sigma_{0.2\_JIS}$	$1.00\sigma_{0.2\_JIS}$
	max	$1.38\sigma_{0.2\_JIS}$	$1.49\sigma_{0.2\_JIS}$

Table 4 Parameters of Ramberg-Osgood model

Steel		K	n	m_1	m_2
SUS304	min	7.33×10^{16}	6.579	0.489	0.347
	max	4.64×10^{28}	11.43	0.630	0.474
SUS316	min	7.33×10^{16}	6.579	0.489	0.347
	max	4.64×10^{28}	11.43	0.630	0.474
SUS304N2	min	2.39×10^{15}	6.579	0.617	0.472
	max	1.21×10^{26}	11.43	0.741	0.603

2.2 Ramberg-Osgood Curve

The Ramberg-Osgood curve[5], which is expressed by Eq.(3), is modeled on stress-strain relationship of the stainless steel for numerical computation. Applicability of this curve to stress-strain has been already confirmed by authors[6].

$$\varepsilon = \frac{\sigma}{E} + K\left(\frac{\sigma}{E}\right)^{n} \qquad (3)$$

Where, ε and σ denote strain and stress, respectively. *K* and *n* are defined as material parameters which are described by Eq.(4) and Eq.(5).

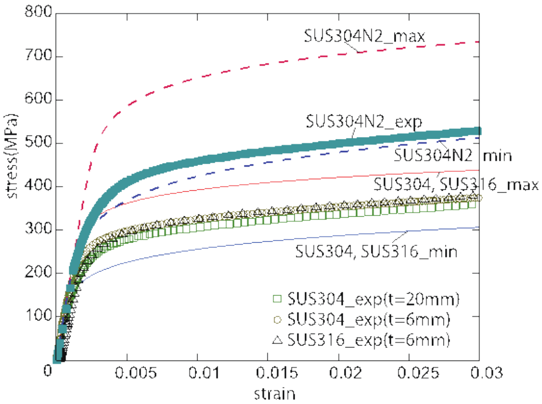


Fig. 1 Stress-strain curves of austenitic stainless steels

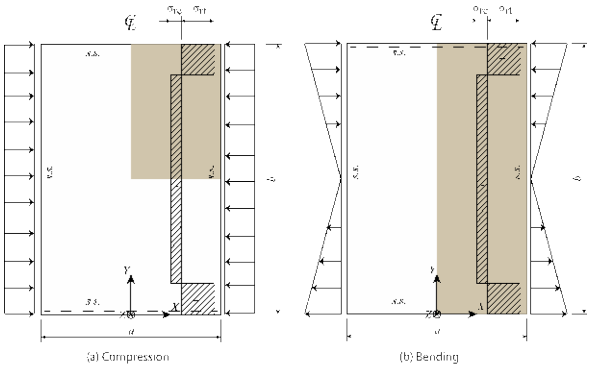


Fig. 2 Analytical plate models under compression and in-plane bending

$$K = \left(\frac{1}{m_1} - 1\right)\left(\frac{\sigma_{0.1}}{E}\right)^{1-n} = \left(\frac{1}{m_2} - 1\right)\left(\frac{\sigma_{0.2}}{E}\right. \quad (4)$$

$$n = 1 - \frac{\ln\left(\frac{m_2}{m_1}\frac{1-m_1}{1-m_2}\right)}{\ln\frac{\sigma_{0.1}}{\sigma_{0.2}}} \quad (5)$$

$$m_1 = \frac{1}{1 + \frac{0.001}{\sigma_{0.1}/E}}$$

$$m_2 = \frac{1}{1 + \frac{0.002}{\sigma_{0.2}/E}} \quad (6)$$

The values of those parameters are summarized in Table4.

Fig.1 shows the Ramberg-Osgood curve expressed by Eq.(3) for the minimum and maximum values of SUS304, SUS316 and SUS304N2. Additionally, Fig.1 indicates the stress-strain relationship obtained by tensile test result[4]. In the case of SUS304 and SUS316, the experimental results obtained by coupon tests are placed at the middle zone between the minimum and the maximum values. On the other hand, the test result for SUS304N2 is close to the stress-strain relationship with the minimum value, since the material parameters of the Ramberg-Osgood curve of SUS304N2 is determined by $\sigma_{0.1}$ and $\sigma_{0.2}$, which are higher than those of SUS304 and SUS316.

3 NUMERICAL ANALYSIS

Fig.2 shows the simply supported plate to use in this research. Fig.2(a) and Fig.2(b) describe the simply supported plate with initial imperfections under uniaxial compression and pure in-plane bending. Initial deflection is expressed by Eq.(8).

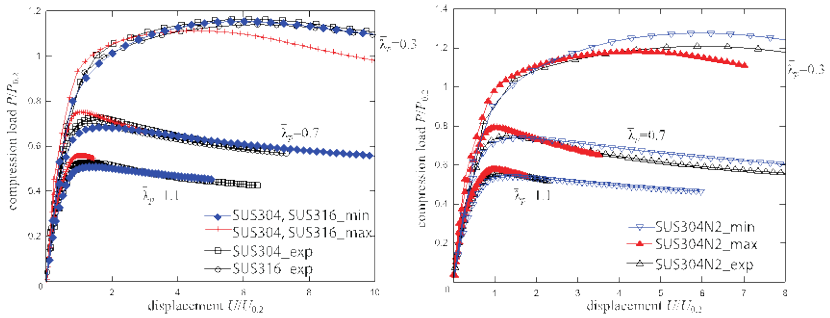
$$W_0 = W_{0\max} \cos\frac{\pi X}{a} \sin\frac{\pi Y}{b} \qquad (8)$$

Where, $W_{0\max}$ denotes maximum value of initial deflection(=*b*/250), *a* and *b* denote unloading and loading edge length. The plate slenderness $\bar{\lambda}_p$ defined by Eq.(9) varies with each 0.2 from 0.3 to 1.3, with change of plate thickness *t*. Moreover, aspect ratios of the plate α(=*a*/*b*) is equal to 0.5 for compressive plate, and 2/3 for in-plane bending one.

$$\bar{\lambda}_p = \frac{b}{t}\sqrt{\frac{\sigma_{0.2}}{E}\frac{12(1-\nu^2)}{\pi^2 k}} \qquad (9)$$

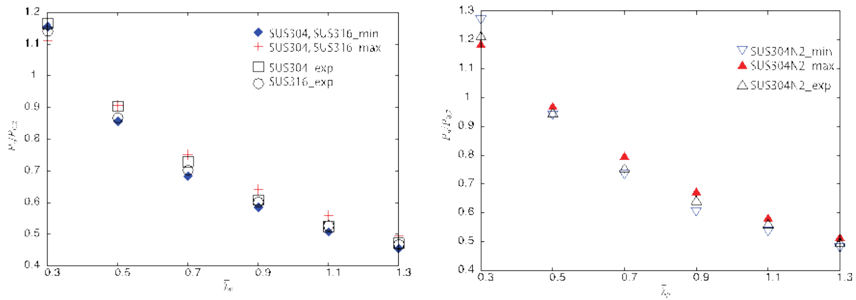
Where, *k* denotes buckling coefficient (4.0 for under uniaxial compression, 23.9 for under in-plane bending). Magnitude and shape of distribution of residual stress in the plate are assumed to be same as those of carbon steel plate[7]. This stress regards the rectangular distribution and maintains the self balance Magnitude of residual compressive σ_{rc} and residual tensile one σ_{rt} on the rectangular distribution, as shown in Fig.2, are equal to -0.3 $\sigma_{0.2}$ and $\sigma_{0.2}$, respectively.

The numerical computation is carried out by means of the nonlinear finite element analysis solver Marc. An 8 node iso-parametric shell element is selected for the plate in colored region of Fig.2. Moreover, an elasto-plastic large deformation analysis assumes stainless steel to be J2 material and isotoropic hardening, and carried out is a nonlinear numerical solution with a displacement increment type Newton-Raphson method.



(a) SUS304 and SUS316 (b) SUS304N2

Fig. 3 Axial load and displacement curves



(a) SUS304 and SUS316 (b) SUS304N2

Fig. 4 Ultimate compressive strength

4 COMPUTATIONAL RESULTS

This chapter describes the strength behavior of the simply supported plate obtained by the numerical computation, dividing into two sections for uniaxial compressive plate and pure in-plane bending one.

4.1 Unaxial Compression

Fig.3 shows normalized compressive load $P/P_{0.2}$ and axial displacement $U/U_{0.2}$ obtained by numerical analysis of the plate under uniaxial compression, when plate slenderness $\bar{\lambda}_p$ is equal to 0.3, 0.7 and 1.1. The figure indicates load-displacement curves based on the stress-strain relationship of tensile test, the minimum and the maximum proof stress as shown in Table3 and Table4. Ultimate normalized compressive load in the case of the maximum proof stress and $\bar{\lambda}_p$ equal to 0.3, is lower than that in the case of the minimum and measured proof one. Moreover, normalized axial displacement at the ultimate normalized compressive load in the case of the maximum proof stress is always smaller than that in the case of the minimum and measured proof one. On the other hand, when $\bar{\lambda}_p$ is equal to 0.7 and 1.1, curvature of the load-displacement curves are larger than that when $\bar{\lambda}_p$ is equal to 0.3.

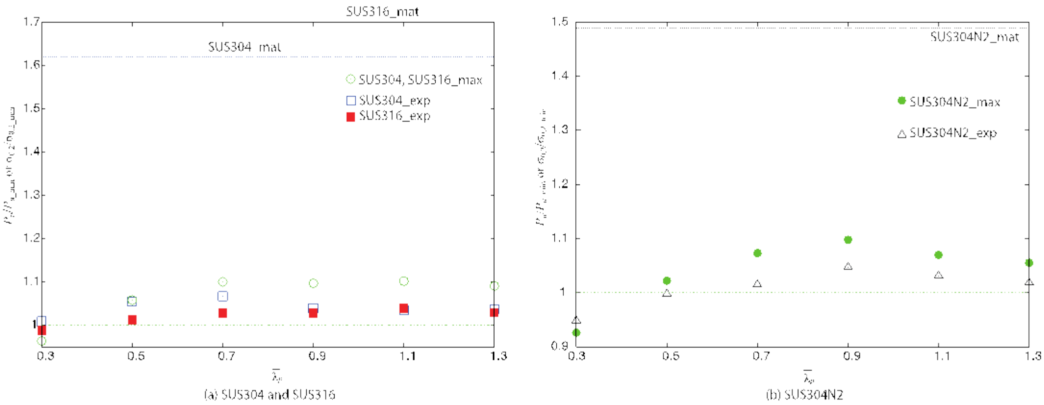
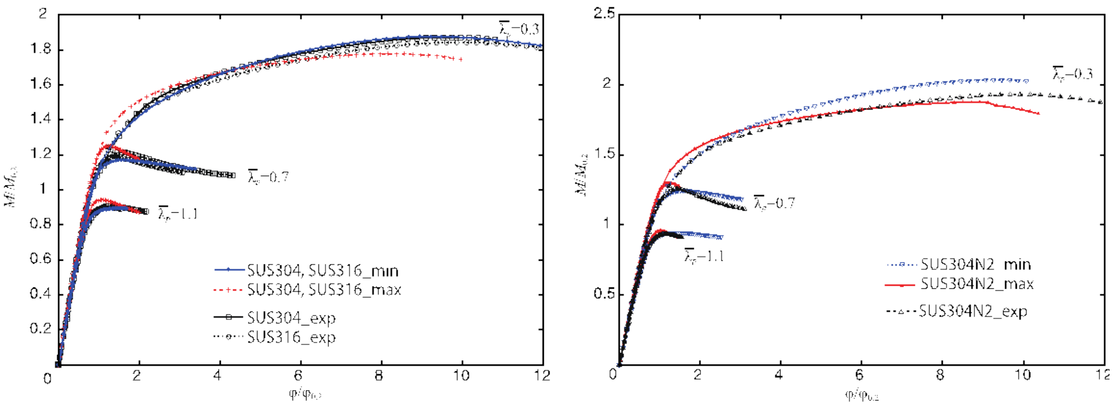


Fig. 5 Comparison of ultimate compressive strength based on the minimum proof stress



(a) SUS304 and SUS316 (b) SUS304N2

Fig. 6 In-plane bending moment and rotation angle curves

Fig.4 shows the ultimate strength $P/P_{0.2}$ and plate slenderness $\bar{\lambda}_p$ relationship of the austenitic stainless steel simply supported plate under uniaxial compression. From those figures, ultimate strengths of the plates under uniaxial compression with plate slenderness $\bar{\lambda}_p$ equal to 0.5 and more, vary in the same manner without the difference between three kinds of proof stress. On the other hand, when $\bar{\lambda}_p$ is equal to 0.3, the ultimate strength differs from the proof stresses. It seems that stress-strain curve causes above-mentioned differences between the values of the proof stress, and plate buckling causes negligible differences. Therefore, $\bar{\lambda}_p$ is an important parameter.

Fig.5 shows the relationship between the ultimate strength ratio P_u/P_{u_min} and $\bar{\lambda}_p$, where P_{u_min} denotes the ultimate strength of the plates with the minimum proof stress $\sigma_{0.2\_min}$, and P_u denotes

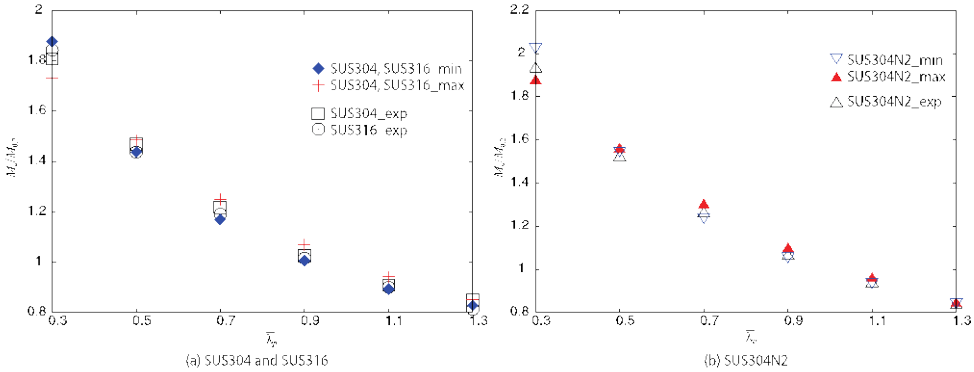


Fig. 7 Ultimate in-plane bending strength

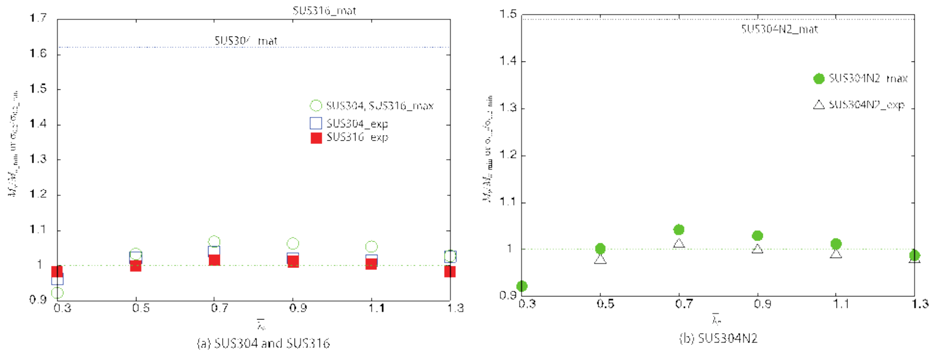


Fig. 8 Comparison of ultimate in-plane bending strength based on the minimum proof stress

the ultimate strength of the plates with the measured and maximum proof stress which are indicated as SUSxxx_exp and SUSxxx_max, respectively. In addition, in the figure, the ratio of material strength $\sigma_{0.2}/\sigma_{0.2\_min}$ is represented by the broken horizontal lines, which are equal to 1.62, 1.70, and 1:49 for SUS304, SUS316, and SUS304N2, respectively, and indicated as SUSxxx_mat. When $\bar{\lambda}_p$ varies from 0.5 to 1.1, the figure shows that the ultimate strength of the plate with the minimum proof stress, is always smaller than others regardless of stainless steel grade. Moreover, the ultimate compressive strength ratio of the plate is always smaller than the material proof stress ratio, and varies from 0.93 to 1.12. In contrast, the ratio of the maximum proof stress to the minimum one is equal to 1.62, 1.70, and 1:49 for SUS304, SUS316, and SUS304N2, respectively. Therefore, differences of the ultimate compressive strength of the plate due to the variety of proof stresses of austenitic stainless steel are sufficiently small compared to the differences in material proof stresses. On the other hand, when $\bar{\lambda}_p$ is equal to 0.3, the ultimate compressive strength ratio is smaller than 1, that is, the ultimate compressive strength of the plates with the minimum proof stress does not always become the minimum ultimate strength. When $\bar{\lambda}_p$ is less than equal to 0.3, it is necessary to investigate influences of the proof stress on the ultimate strength.

4.2 Pure In-Plane Bending

Fig.6 shows the relationship between normalized in-plane bending moment $M/M_{0.2}$ and normalized angle of rotation $\varphi/\varphi_{0.2}$ observed by numerical analysis of the simply supported plate under pure in-plane bending. M, $M_{0.2}$ φ, and $\varphi_{0.2}$ denote in-plane bending moment, specified in-plane bending strength based on $\sigma_{0.2}$, angle of rotation and specified angle of rotation based on $\varepsilon_{0.2}$, respectively. In the case of $\bar{\lambda}_p$ equal to 0.3, ultimate rotation angle at reaching to the ultimate strength progresses significantly large as compared with other cases of $\bar{\lambda}_p$ more than equal to 0.5. In the case of $\bar{\lambda}_p$ equal to 0.7 and 1.1, the relationship between the bending moment and the angle of rotation shows a similar behavior in spite of austenitic stainless steel grades. On the other hand, when $\bar{\lambda}_p$ is equal to 0.3, the relationship in the case of SUS304N2 is relatively different with that of SUS304 and SUS316.

Fig.7 represents the relationship between the ratio of the ultimate in-plane bending strength M_u to specified in-plane bending strength, that is $M_u/M_{0.2}$, and $\bar{\lambda}_p$. When $\bar{\lambda}_p$ has a greater than or equal to 0.5, the ultimate strength of the high proof stress is slightly higher than that of the low proof stress. On the other hand, in the case of $\bar{\lambda}_p$ equal to 0.3, the plate with the maximum proof stress has the lowest ultimate strength regardless of the austenitic stainless steel grades. The results mentioned above are similar to the results obtained by the analysis of the compressive plates.

Fig.8 indicates the relationship between the ultimate strength ratio M_u/M_{u_min} and $\bar{\lambda}_p$, where M_{u_min} denotes the ultimate in-plane bending strength of the plates with the minimum proof stress $\sigma_{0.2\_min}$, and M_u denotes the ultimate in-plane bending strength of the plates with the measured and maximum proof stress which are indicated as SUSxxx_exp and SUSxxx_max, respectively. When $\bar{\lambda}_p$ varies from 0.5 to 1.1, Fig.8(a) shows that the ultimate strength of the plate with the minimum proof stress of SUS304 and SUS316, is always smallest among others. As shown in Fig.8(b), the ultimate strength of the plate with the minimum proof stress of SUS304N2 is also always smallest among others, when $\bar{\lambda}_p$ varies from 0.7 to 0.9. Then, compared to the ratio of the maximum and minimum values of material strength, the ratio of the ultimate bending strength is sufficiently small. Both figures show that differences of the ultimate in-plane bending strength of the plate due to the variety of proof stresses of austenitic stainless steel are sufficiently small compared with the differences in material proof stresses. On the other hand, $\bar{\lambda}_p$ is equal to 0.3 and 1.3, the ultimate strength of the plates with the minimum proof stress is higher than that with the maximum one. Therefore, when the plate reaches to the ultimate in-plane bending strength after sufficient plastic progress, it is necessary to take advantage of the stress-strain relationship and to understand the behavior up to the ultimate strength.

5 CONCLUSION

Based on the statistical data of the material strength, that is the 0.1% and 0.2% proof stress, the study clarified influences which material strength of austenitic stainless steel gives to the ultimate strength of the plates under compression and in-plane bending. Main concluding remarks are summarized as follows;

(1) Material strength of austenitic stainless steels SUS304N2, SUS316 and SUS304 are clarified statistically and 5% and 95% fractile proof stress are also obtained. Measured 0.2% proof stress of 97% samples is higher than the proof stresses 0.2% specified by JIS.

(2) Stress-strain diagram is modeled by the Ramberg-Osgood curve, whose parameters are determined based on the 5% and 95% fractile proof stresses.

(3) Ultimate compressive strength of the plate with the minimum proof stress is lower than that with the maximum and measured one in the region of plate slenderness greater than or equal to 0.5.

(4) Ultimate in-plane bending strength of the plate with the minimum proof stress is lower than that with the maximum and measured one in the region of plate slenderness from 0.5 to 1.1.

(5) If the plate slenderness is equal to 0.3, the ultimate compressive and in-plane bending strength of the plate with the minimum proof stress is higher than that with the maximum proof stress. The similar behavior is observed in the case of in-plane bending plate made of SUS304 and SUS316 at the plate slenderness equal to 1.3, and in the case of the plate made of SUS304N2 at the plate slenderness larger than 1.1.

(6) Ratio of the maximum 0.2% proof stress of the minimum one results is equal to 1.62, 1.70, and 1.49 for SUS304, SUS316, and SUS304N2, respectively. On the other hand, ratio of the ultimate compressive and in-plane bending strength of the plate with the maximum proof stress to that with the minimum one is lower than 1.12 and 1.15, respectively.

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