Investigation on Mechanical Behaviors for Bolted Connections in Carbon Steel and in Stainless Steel Using FEM

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A finite element (FE) analysis with three-dimensional solid elements has been performed for estimating the structural behaviors of single shear bolted connections fabricated with cold-formed austenitic stainless steel by utilizing the existing test data for calibration. Failure and curling (out-of-plane deformation perpendicular to the direction of loading) criteria were proposed. Therefore, the failure mode and ultimate strength, predicted by FE analysis method, showed good agreements with those of experimental results. In this study, FE analyses for 10 test specimens fabricated with cold-formed carbon steel as well as stainless steel including failure mode of bolt shear fracture are carried out and the validity of numerical prediction for ultimate behaviors in cold-formed carbon steel bolted connections is also verified, based on the applicability of FE method for predicting the mechanical behaviors of bolted connections in cold-formed stainless steel. It is known from the coupon test results of steel materials that austenitic stainless (SUS304) steel has a higher tensile strength of material due to the effect of strength enhancements (considerable strain hardening) by means of cold-working process and much lower yield stress when compared to carbon steel. The influence of curling on the strength reduction of bolted connections is estimated quantitatively. In addition, characteristics of mechanical behaviors and the influence of curling in bolted connections between two different steel materials are compared through detailed investigation of FE analysis results.

KEY WORDS: carbon steel; austenitic stainless steel; cold-formed steel; bolted connection; ultimate behavior; curling; finite element analysis.

1. Introduction

Japanese research on applicability of stainless steel for structural members in buildings has developed with a construction rush of high-rise buildings by virtual growth of economy in the late 1980s. These movements led to the establishment of design and construction standards1) and design and specifications of stainless steel structures2) published by Stainless Steel Building Association of Japan (SSBA), which focused on hot-rolled stainless steel. In recent years, due to the high cost in fabrication and materials, the main application of stainless steel in buildings shows a tendency to be changed in the form of cold-formed members relying on its predominant corrosion resistance.

Therefore, experimental research on mechanical behaviors of bolted connections fabricated from cold-formed austenitic stainless steel (SUS304), which were composed of two types of connections (single shear and double shear) and bolted connections fabricated from cold-formed carbon steel (SS400), which just included single shear type for comparison of ultimate behaviors according to difference of material properties was conducted by Kuwamura et al.3,4) Bolted connections were planned by thin-walled steel plate as test specimens which are deformable. From the test results and theoretical analysis, modified formulae for calculating the ultimate strength of bolted connection were proposed, which were found to provide a reasonable accuracy in predicting the failure mode and ultimate strength.

However, it was reported that the formulae revised by Kuwamura et al.5) as well as current design standards2,5) may overestimate ultimate strength of bolted connections due to no sufficient consideration about influence of curling on ultimate strength. Therefore, numerical study was tried first for predicting the ultimate behaviors of single shear bolted connection specimens in stainless steel by Kim and Kuwamura.6,7)

FE analysis methodology was established through various parametric studies such element type, mesh size, loading pattern etc. and embodied the curling behavior, which was occurred in test specimens with a long end distance. In addition, failure and curling criteria were suggested. It was thus found that FE analysis results predicted by above-mentioned procedures were in a good correspondence with test results of bolted connections with cold-formed stainless steel.

In this paper, based on the effectiveness of numerical simulation for estimating the structural behaviors of stainless steel bolted connections, FE analysis for test specimens fabricated from cold-formed carbon steel and stainless steel including bolt shear fracture is performed and its validity of prediction for failure mode and ultimate strength is also verified in cold-formed carbon steel bolted connections. Moreover, comparisons of mechanical behaviors in bolted connections with different material properties are made in the following.

2. Existing Test Results of Bolted Connections in Cold-formed Steel

As stated in the previous chapter, a series of experimen-
tal study regarding the structural behaviors of shear bolted connections fabricated from thin-walled steel (SUS304 austenitic stainless steel and SS400 carbon steel) using 1.5 mm or 3.0 mm thick plate and 12 mm/16 mm diameter bolt (common bolt or high tensioned bolt) were performed by Kuwamura et al. A tensile force was applied gradually to the test specimen with monotonous enforced displacement control. Figure 1 displays the geometry of test specimens consisted of single shear bolted connections, where 3.0 mm thick plate was planned as test specimens and 6.0 mm thick plate as rigid part to set up the specimens. The both ends of test specimens were gripped through chucks onto a tensile test machine. Five test results of connections with 3.0 mm thick plate as representative test specimens are summarized in Tables 1 and 2 for carbon steel and stainless steel, respectively.

In order to predict failure mode of specimens in case that bolt is simulated as a rigid body in FE analysis, specimens which failed by bolt shear are adopted as can be seen in Tables 1 and 2. The object specimens has following variables and common parameters: nominal plate thickness, t=3.0 mm; bolt diameter, d=12 mm; pitch and gauge distance, p=g=30 mm; end distance, e, from the center of a bolt hole to end of plate in the direction of loading and edge distance, b, perpendicular to the direction of loading; three bolt arrangements (Series A and SA: single bolt, Series B and SB: two bolts, Series C and SC: four bolts). Four types of failure modes including bolt shear fracture in bolted connections were observed, i.e., for connected plate, net section fracture (N), end opening fracture (shear-out fracture or bending fracture, E) and block shear fracture (B). Failure mode of each specimen adopted from test results can be discerned. Especially, specimens A2-3, C2-4 and SA2-3 reached the ultimate strength by bolt failure and for specimen SB2-1, shear-out fracture (E) occurred first at the bolt hole nearest the end of specimen and subsequently shear failure of bolt shank in the second column took place. Furthermore, specimens, SC2-3 and SC2-4 with a relatively long end distance showed out-of-plane deformation, i.e., curling.

3. Finite Element Modeling

Finite element package ABAQUS (Ver. 6.4) was utilized for the analysis in previous numerical research. In the following sections, the procedures for implementation of an FE model of bolted connection fabricated from cold-formed carbon steel and stainless steel are described.

3.1. Description of FE Model

In order to account for geometric nonlinearities in analysis step, a large-displacement formulation (NLGEOM= YES) is applied. A hexahedral eight-node linear brick, reduced integration with hourglass control solid element, C3D8R was used for connection plate. C3D8R element has six stress components. Meshing of connected plate is divided into two areas with each different mesh density. Therefore, the vicinity of the bolt hole has a refined mesh size based on the thickness of plate (t). The mesh of the stress concentration part is divided into t/3×t/3 through surface by thickness. Since ultimate strength of bolt shear fracture obtained from test results agreed well with that predicted by design standard, the bolt failure mode does not consider in the numerical simulation and thus, bolt shank is modeled as rigid cylindrical body as mentioned above.

Only thinner plate (3.0 mm) out of single shear bolted connection with 3.0 mm and 6.0 mm thick plates was modeled as displayed in Fig. 2. Previous research recommended 150 mm as a reasonable model length. Based on the symmetry considerations, for specimens with even-numbered column in bolt arrangement such as Series C and SC using the symmetric geometry, FE model simulated only half the width of specimen and symmetric geometrical boundary conditions (U3, UR1, UR3=0) are applied to all nodes in a symmetric plane (1–3 plane) as depicted in Fig. 2. Since the shear section of ordinary bolt is designed to be located...
at the non-threaded part of bolt shank, bolt element is assumed to be threadless. Specimens with snug-tightened bolt are bearing typed connection, thus, pre-tension in bolts is not considered. In addition, no friction between plate and washer and between specimen plate and rigid plate is assumed.  

3.2. Material Properties and Model

An elastic-plastic constitutive law with isotropic strain hardening rule based on Von Mises yield criterion was adopted in FE modeling of connected plate. The nominal stress–nominal strain \((\sigma_n-\varepsilon_n)\) curves were obtained from coupon tests in tension for carbon steel and stainless steel and the material data input in FE program, that is, true stress–true strain \((\sigma_t-\varepsilon_t)\) is converted from Eqs. (1a) and (1b) for the proper definition of the uniaxial material response. These true stresses–strains are defined with respect to the current dimension of length and cross-sectional area, respectively. In addition, plastic behaviors after material yield are established by true stress–true plastic strain \((\sigma_t-\varepsilon_{pl})\) and \(\varepsilon_{pl}\) is given in Eq. (2).

\[
\begin{align*}
\sigma_n &= \sigma_t (1 + \varepsilon_n) \quad \text{(1a)} \\
\varepsilon_n &= \ln(1 + \varepsilon_n) \quad \text{(1b)} \\
\varepsilon_{pl} &= \ln(1 + \varepsilon_n) - \frac{\sigma_t}{E} \quad \text{(2)}
\end{align*}
\]

Figure 3 shows stress–strain curves for carbon steel, SS400 and austenitic stainless steel, SUS304 and measured material properties such as Young’s Modulus \((E)\), yield stress \((\sigma_y)\), tensile stress \((\sigma_u)\) and yield ratio \((\sigma_y/\sigma_u)\) are summarized in Table 3. The most distinguishable difference between carbon steel and austenitic stainless steel is the shape of stress–strain curve obtained from coupon test of material. Carbon steel exhibits typically linear elastic behavior up to yield strength and the yield plateau in stress–strain curves, while stainless steel shows a rounded stress–strain curve, with no sharp yield point as can be seen in Fig. 3(c). Yield strength of carbon steel for design is defined as 0.2% proof stress for coupon test, while yield strength of stainless steel is obtained as 0.1% proof stress specified by Stainless Steel Building Association (SSBA) of Japan. In particular, since stainless steels have high ductility, are easily formed, are readily weldable, and offer good corrosion resistance, austenitic stainless steels are the most commonly used in structural members of buildings. It has been known that stainless steel has noticeable characteristics of mechanical properties compared with carbon steel as follows: (a) proportional limit of stainless steel is relatively low and nonlinearity appears at a low stress level, (b) extensive strain hardening of stainless steel is considerable due to cold working and thus yield ratio \((\sigma_y/\sigma_u)\) is very low, and (c) initial Young’s modulus of stainless steel is slightly less than that of carbon steel.

3.3. Boundary Conditions

Supported ends of right side in FE model are fully restrained in the translational displacement of all directions \((U_1, U_2, U_3=0)\) as illustrated in Fig. 2. Boundary conditions on symmetric plane, 1–3 for Series C and SC specimens are defined. Rigid body reference points marked by * are assigned at the bottom end of bolt so that loading and constraint conditions specified to the reference point can be applied identically to the entire bolt element. Displacement, \(U_1\) of 1 axis parallel to the direction of loading is allowed in

| Steel grade | Actual thickness \(t\) [mm] | Elastic Modulus \(E\) [kN/mm²] | Yield stress \(\sigma_y\) [N/mm²] | Tensile stress \(\sigma_u\) [N/mm²] | Yield ratio \(\sigma_y/\sigma_u\) | YR [%] | Elongation limit \(EZ\) [%] |
|-------------|-----------------|-----------------|-----------------|-----------------|-----------------|-------|---------------|
| SS400       | 3.01            | 205             | 342             | 422.76          | 80.9            | 1.24  | 27.9          |
| SUS304      | 2.92            | 204             | 288             | 842.35          | 34.2            | 2.92  | 63.0          |
reference point for avoiding rotation and tilting of bolts. Bolt shank and bolt hole are simulated as bearing contact and contact surface between the bolt shank and bolt hole is assumed frictionless. Loading is applied to the reference point on the bolt with enforced displacement control as adopted in experimental research.4,19)

3.4. Curling and Failure Criteria

3.4.1. Curling Criterion

It can be found from experimental and FE analysis results that out-of-plane deformation, i.e., curling affected the strength reduction of bolted connections in thin-walled stainless steel.4,6) Two reference points for acquiring the deformation value of 3-axis direction (out-of-plane deformation) and stress value are also installed at location 30 mm apart from the center of the nearest bolt hole from plate end as shown in Fig. 4. RP1 and RP2 are assigned at both faces of plate model for carbon steel and stainless steel. It was noted that stress distributions ($\sigma_{11}$, $\sigma_{22}$) observed in both sides of FE models with curling got different at around 0.3 mm value of out-of-plane deformation ($d_3$) in comparison with stress distribution of FE models which curling was restrained.6,7) Figure 5 represents the relationship between enforced displacement, stresses normalized by yield strength ($\sigma_y$) and out-of-plane deformation obtained from FE analysis results of bolted connections (C2-4 and SC2-4) in carbon steel and stainless steel, respectively.

Consequently, specimen C2-4 of carbon steel was found to have the same correlation as specimen SC2-4 of stainless steel. Therefore, it is recommended that when the value of out-of-plane deformation ($d_3$) extracted from reference point approaches 0.3 mm, the curling of bolted connection begins to occur; out-of-plane deformation, 0.3 mm is assumed as criterion of curling occurrence.

3.4.2. Failure Criterion

FE analysis research conducted by Kim and Kувамура6,7 for single shear bolted connections in cold-formed stainless steel reported that failure criterion based on direct stress/shear stress is applicable for predicting the failure mode of bolted connection including curling. Therefore, failure criterion recommended above is attempted to estimate the failure mode of carbon steel bolted connection and is simplified as follows.

Direct stress or shear stress in critical section:

$$\frac{\sigma_y}{\sigma_{1\text{max}}} \geq 1.0 \text{ or } \frac{\tau_{ij}}{\tau_{1\text{max}}} \geq 1.0 \quad \text{equation (4)}$$

Where, $\sigma_y$: Direct stress in the axial direction, $\tau_{ij}$: Shear stress, $\sigma_{1\text{max}}$: Maximum true stress, $\tau_{1\text{max}}$: Maximum true shear stress.

4. Validation of FE Analysis Results

A total of 10 specimens fabricated from SS400 carbon steel and SUS304 stainless steel including three specimens (SB2-4, SC2-3 and SC2-4) already analyzed in previous study4 and four specimens (A2-3, C2-4, SA2-3, SB2-1) failed by bolt fracture are modeled to predict the failure mode and ultimate strength of thin-walled bolted connections using numerical simulation. In order to verify the effectiveness of the FE analysis model, the analysis results are compared with the test results in the following.

Fig. 5. Relationship between enforced displacement and stress distribution/out-of-plane deformation.
4.1. Ultimate Strength and Failure Mode

Tables 4 and 5 represent the comparison of FE analysis results against test results in bolted connections for carbon steel and stainless steel, respectively. The ultimate strengths \( (P_{ua}) \) predicted by FE analysis are compared with the experimental ultimate strengths \( (P_{ue}) \). For specimens failed in connected plate such as B2-1, B2-4, C2-3, SB2-4, SC2-3 and SC2-4, the ultimate strength ratios \( (P_{ua}/P_{ue}) \) of FE analysis results to test results ranged from 0.81 to 1.09 and the mean value of ultimate strength ratio was 0.96 with corresponding COV (coefficients of variation), 0.089.

For specimens governed by bolt fracture such as A2-3, C2-4, SA2-3 and SB2-1, ultimate strengths by FE analysis generally showed a tendency to be higher values compared to test results, that is, the ultimate strength ratio \( (P_{ua}/P_{ue}) \) showed the range of 1.00 to 1.30 as can be seen in Tables 4 and 5. This discrepancy of ultimate strengths between the FE analysis results and experimental results can be explained by analysis condition that bolt element is assumed as a rigid body without any deformation. As a result, bolt shear fracture did not occur in FE analysis and the ultimate state of FE model relied on the fracture of connected plate.

Figure 6 depicts the equivalent Mises stress distribution investigated at ultimate strength level \( (P_{ua}) \) of several specimens for typical failure mode and deformed shapes of FE analysis. In addition, failure modes are predicted from yield zone patterns of Fig. 6. The failure modes obtained from FE analysis results are summarized in Tables 4 and 5.

Specimens A2-3, C2-4 and SA2-3 which failed by bolt shear in test results exhibit net section fracture (N mode), block shear fracture (B mode) and net section fracture (N mode), respectively, in FE analysis. Specimen B2-1 which has relatively a short end distance \( (e/H = 12 \text{ mm}) \) when compared to width of plate \( (w/H = 50 \text{ mm}) \) failed by end opening fracture (shear out fracture, E) accompanied by protrusion of plate end as shown in Fig. 6(a). Specimen B2-4 like specimen SB2-4 of previous numerical study\(^7\) showed net section fracture accompanied by necking in the second column of bolt (Fig. 6(b)) and block shear fracture for specimens C2-3 and SC2-3 was predicted, where an apparent yield zone of the net section between the two bolt holes the furthest from plate end (rupture of net tension plane) and a subsequent partial yield zone of the gross shear area (rupture of the shear plane) were observed as can be seen in Figs. 6(c) and 6(d).

It is therefore concluded from the comparisons discussed above that failure modes of bolted connections using FE analysis method except specimens with bolt fracture were a good agreement with those of test results.

4.2. Curling Behavior

It is noted that FE analysis can simulate the curling of bolted connections in cold-formed carbon steel as well as cold-formed stainless steel and curling criterion for carbon steel is also confirmed in Sec. 3.4.1. The specimens which were curled in test results or have a long edge distance as shown in Tables 1 and 2 are selected and are modeled in order to investigate the influence of curling on ultimate strength of bolted connections. Tables 6 and 7 represent the list of object specimens and FE analysis results.

Two types of FE models per specimen are analyzed ac-
According to constraint of curling of plate ends; e.g., FE models such as A2-3, C2-3, C2-4, SA2-3 etc. mean that all edges of plate except supported end are free (curling is not restrained) and FE models such as A2-3R, C2-3R, C2-4R, SA2-3R etc. imply that displacement of thickness direction at the edges of plate is zero ($U_3 = 0$, curling is restrained). 

Figures 7 and 8 display deformed shapes and load-displacement curves of specimens, respectively. It is obvious that failure modes predicted for two types of FE analysis models are the same irrespective of constraint condition of curling in the previous study for stainless steel connections,\(^7\) load–displacement curve for specimen SC2-3 curled was almost identical to those of SC2-3R, where curling was assumed not to occur. Since the curling in specimen SC2-3 is likely to take place after the ultimate strength is reached as plotted in Fig. 8(b), the curling of SC2-3 had little influence on the ultimate strength. Undoubtedly, this assumption is applicable for specimen C2-3 as can be seen in Figs. 7(b) and 8(b).

### Table 6. Ultimate strength and influence of curling in SS400 carbon steel.

| Specimen | Curling $\delta_{cca}$ [mm] | Curling strength $P_{cca}$ [kN] | Max. Disp. $\delta_{uu}$ [mm] | Ultimate strength $P_{uu}$ [kN] | $P_{uu}/P_{ uu R}$ | Failure mode |
|----------|-----------------------------|-------------------------------|-----------------------------|-------------------------------|-------------------|-------------|
| A2-3     | 6.19                        | 33.62                         | 7.06                        | 33.70                         | 0.99              | N           |
| A2-3R    | -                           | -                             | 7.58                        | 34.17                         | 1.00              | B           |
| C2-3     | 11.50                       | 80.58                         | 4.37                        | 96.07                         | 1.00              | B           |
| C2-3R    | -                           | -                             | 4.38                        | 96.17                         | 1.00              | N           |
| C2-4     | 2.27                        | 112.87                        | 2.31                        | 112.93                        | 0.87              | B           |
| C2-4R    | -                           | -                             | 8.55                        | 130.37                        | 1.00              | B           |

### Table 7. Ultimate strength and influence of curling for SUS304 stainless steel.

| Specimen | Curling $\delta_{cca}$ [mm] | Curling strength $P_{cca}$ [kN] | Max. Disp. $\delta_{uu}$ [mm] | Ultimate strength $P_{uu}$ [kN] | $P_{uu}/P_{ uu R}$ | Failure mode |
|----------|-----------------------------|-------------------------------|-----------------------------|-------------------------------|-------------------|-------------|
| SA2-3    | 5.85                        | 49.66                         | 8.25                        | 53.47                         | 0.72              | N           |
| SA2-3R   | -                           | -                             | 37.78                       | 74.32                         | 1.00              | N           |
| SC2-3    | 22.51                       | 165.89                        | 18.00                       | 176.97                        | 1.00              | B           |
| SC2-3R   | -                           | -                             | 18.15                       | 176.98                        | 1.00              | B           |
| SC2-4    | 1.28                        | 105.89                        | 15.38                       | 153.03                        | 0.75              | B           |
| SC2-4R   | -                           | -                             | 17.20                       | 202.70                        | 1.00              | B           |

Fig. 7. Deformed shape and curling of specimens.

Fig. 8. Load–displacement curves for specimens.
5. Comparisons of Connection Behaviors in Carbon Steel and Austenitic Stainless Steel

Characteristics in material properties of SS400 carbon steel and SUS304 stainless steel were already discussed in Sec. 3.1. Utilizing the FE analysis results suggested above, this section performs comparisons of structural behaviors, for example, ultimate strength, curling and stress distribution in bolted connections between carbon steel and stainless steel as follows.

### 5.1. Ultimate Strength

Tables 8 and 9 show the comparisons of ultimate strength between two different steel materials and are classified, respectively according to curling occurrence. $P_{u\alpha}$ in Table 8 denotes the ultimate strength of bolted connections obtained from FE analysis results and ultimate strength ratios of SS400 carbon steel connections to SUS304 stainless steel connections are expressed as $P_{u\alpha}/P_{u\alpha(SUS304)}$. However, since actual plate thickness of carbon steel connections differs from that of stainless steel connections as can be seen in Tables 1 and 2, e.g., specimen B2-1 has 3.04 mm thick plate, while specimen SB-1 has 2.88 mm thick plate, thickness ratio (Thk. Ratio, that is, $t$(SUS304)/$t$(SS400)) should be considered additionally for calculating reasonable ultimate strength ratios.

Henceforth, the value of ultimate strength ratios between two steel materials denote ultimate strength ratio multiplied by Thk. Ratio as shown in Tables 8 and 9. For specimens with no curling of Table 8 and with restrained curling of Table 9, the mean value of ultimate strength ratios of SS400 to SUS304, which range from 0.44 to 0.61 is 0.54. It can be noted that the ultimate strength ratio between bolted connections of two different materials shows a good correspondence to tensile strength ratio, i.e., $\sigma_{u(SS400)}/\sigma_{u(SUS304)}$ of the steel materials, which is computed as 0.5 in Table 3. As already stated in Sec. 3.1, stainless steel can have a higher tensile strength of material compared with carbon steel due to the effect of strength enhancements by means of cold-working.

Obviously, SUS304 stainless steel revealed yield strength enhancements up to 2.92 times, on the contrary, tensile strength of SS400 carbon steel was increased by 1.24 times yield strength as depicted in Table 1 and Fig. 3(c). It can be also found from Figs. 9(c) and 9(d) that strength reduction of SS400 bolted connections (1-$P_{u\alpha}/P_{u\alpha(SS400)}$, 25–28%) induced by curling is higher than strength reduction of SUS304 bolted connections (1-$P_{u\alpha}/P_{u\alpha(SUS304)}$, 1–13%) by curling as shown in Tables 6 and 7. $P_{u\alpha}$ in Table 9 is the ratio of ultimate strength against curling strength ($P_{u\alpha}$) in specimens curled. $P_{u\alpha}$ values of two carbon steel connections; A2-3 and C2-4 are close to 1.0, i.e., the specimens A2-3 and C2-4 result in a ultimate state (fracture) without any additional increase in strength just after onset of curling and $P_{u\alpha}/P_{u\alpha}$ values of two stainless steel connections; SA2-3 and SC2-4 are 1.08 and 1.44, respectively, i.e., even if the value of strength enhancement may differ from bolt arrangement, austenitic stainless steel connections expect an additional increase in the strength after curling of plate ends begins to occur as can be seen in Figs. 9(c) and 9(d).

### 5.2. Stress Distribution

This section examines the distribution of in-plane stresses in FE models, e.g., C2-4 and SC2-4 with a noticeable curling according to the increase of enforced displacement and provides comparisons of stress distribution in two different steel materials, i.e., carbon steel and stainless steel. Two paths to investigate the stress distribution obtained from FE analysis results for bolted connections are displayed in Fig. 4. Paths 1 and 2 are expressed with dotted line from $\vec{t}$ to $\vec{e}$ (Total length of path is 120 mm.) in both surfaces of FE models and go through bolt hole center in the direction of loading as shown in Fig. 4. Path 1 is located in front side (curled direction) of FE model and Path 2 is located in back side (opposite to curled direction) of FE models.

| Specimen | Thickness $t$ [mm] | Ultimate strength $P_{u\alpha}$ [kN] | Failure mode |
|----------|-------------------|-----------------------------|-------------|
| A2-3     | 3.04              | 33.70                       | N           |
| SB-2     | 2.88              | 53.47                       | E           |
| B2-4     | 3.10              | 96.07                       |            |
| SB-4     | 2.90              | 176.97                      |            |
| C2-3     | 3.04              | 96.07                       | B           |
| SC2-3    | 2.91              | 176.97                      |            |

| Specimen | Thickness $t$ [mm] | Ultimate strength $P_{u\alpha}$ [kN] | Failure mode |
|----------|-------------------|-----------------------------|-------------|
| A2-3     | 3.04              | 33.70                       | N           |
| SA2-3    | 2.91              | 54.67                       | E           |
| A2-3+    | 3.04              | -                           |            |
| SA2-3+   | 2.91              | -                           |            |
| C2-4     | 3.04              | 112.87                      |            |
| SC2-4    | 2.90              | 152.03                      | B           |
| C2-4+    | 3.04              | -                           |            |
| SC2-4+   | 2.90              | -                           |            |

| Specimen | Thickness $t$ [mm] | Ultimate strength $P_{u\alpha}$ [kN] | Failure mode |
|----------|-------------------|-----------------------------|-------------|
| A2-3     | 3.04              | 33.70                       | N           |
| SA2-3    | 2.91              | 54.67                       | E           |
| A2-3+    | 3.04              | -                           |            |
| SA2-3+   | 2.91              | -                           |            |
| C2-4     | 3.04              | 112.87                      |            |
| SC2-4    | 2.90              | 152.03                      | B           |
| C2-4+    | 3.04              | -                           |            |
| SC2-4+   | 2.90              | -                           |            |
model on Fig. 10. Mark + denotes tensile stress and mark − denotes compressive stress from Fig. 10.

Three steps on load–displacement curve for specimen C2-4 and four steps for specimen SC2-4 in order to investigate stress distribution in each step are assigned as depicted in Fig. 11. Figures 12 and 13 show stress distributions ($\sigma_{11}$: direct stress in 1 axis, $\sigma_{22}$: direct stress in 2 axis, $\sigma_{eq}$: equivalent von Mises stress) in Paths 1 and 2. It can be seen that two specimens; specimens C2-4 and SC2-4, which are fabricated from carbon steel and austenitic stainless steel, respectively have similar stress distributions. Direct stress ($\sigma_{11}, \sigma_{22}$) of axial direction in Paths 1 and 2 generally becomes higher as enforced displacement increases, that is, Step proceeds from A to D except the vicinity of $\check{2}$ which contacts directly with bolt shank. $\sigma_{11}$ and $\sigma_{22}$ of Step C or Step D (after curling occurred) for the vicinity of $\check{2}$ in Path 1 have compressive stresses (−) as shown in Fig. 12, whereas, $\sigma_{11}$ and $\sigma_{22}$ for Path 2 show tensile stresses (+) as shown in Fig. 13. It is also found that $\sigma_{22}$ between $\check{1}$ and $\check{2}$ of Path 1 gets transferred from tensile stress ($/H11001$ value) to compressive stress ($/H11002$ value) with the development of curling. However, equivalent stress ($\sigma_{eq}$) gets higher in proportion to enforced displacement through the all steps. Although there are no initial imperfection and eccentricity of connections, bolted connections for two different steel materials (SS400 and SUS304) from test results and FE analysis results showed out-of-plane deformation perpendicular to the direction of loading.
Fig. 12. Stress distribution in Path 1.

Fig. 13. Stress distribution in Path 2.
As a result, it can be noted that occurrence of curling has an effect on change of stress distribution of connection plate, especially direct stress, namely, stress distributions in both surfaces of plate at same location are different and tensile or compressive region of stress gets turned into opposite stress as curling becomes larger.

In addition, for specimen C2-4 with carbon steel, equivalent stresses ($\sigma_{eq}$) of overall section between ① and ④ for Step C approached to maximum true stress ($\sigma_{true}$) of carbon steel obtained from Fig. 3(a) as displayed in Figs. 12(a) and 13(a). Thus, load carrying capacity of specimen C2-4 does not increase any more after curling occurred as displayed in Fig. 11(a). On the contrary, for specimen SC2-4 with austenitic stainless steel, as can be seen in Figs. 12(b) and 13(b), equivalent stresses ($\sigma_{eq}$) in the vicinity of ② and ④ get higher generally instead of overall section as enforced displacement increases. In particular, only $\sigma_{eq}$ of Steps C and D is close to maximum true stress ($\sigma_{true}$ of 486 MPa) of stainless steel obtained from Fig. 3(b). Specimen C2-4 showed a sudden strength drop due to influence of curling, but load carrying capacity began to increase again as displayed in Fig. 11(b). It is noted that the stress distribution of stress concentration part and the subsequent structural behavior of thin-walled bolted connections may differ from mechanical properties of different steel materials; carbon steel and stainless steel.

6. Conclusions

In this paper, based on the effectiveness of numerical simulation for estimating the structural behaviors of austenitic stainless steel bolted connections proposed by Kim et al.,6,7) FE analyses for 10 test specimens fabricated from cold-formed carbon steel (SS400) as well as austenitic stainless steel (SUS304) were conducted with analysis procedures of Chap. 3. The analysis results were valid for the prediction of failure mode and ultimate strength, as shown in Chap. 4. It is found that failure criterion of carbon steel bolted connection was adopted based on direct stress and shear stress in terms of stainless steel bolted connection; i.e., when the direct stress or shear stress obtained from FE analysis results in the vicinity of bolt hole reaches maximum true stress, the bolted connection at the beginning of crack leads to the ultimate state.

Curling was assumed to occur, when out-of-plane deformation observed from reference point approached about 0.3 mm at which stress distributions obtained from both surfaces of FE model were different, Failure mode and ultimate strength of FE models including specimens which failed by bolt shear were predicted, using the FE analysis procedures presented above and the FE analysis results were in good agreements with test results in terms of failure mode and ultimate strength.

In order to make comparisons of mechanical behaviors in bolted connections according to the difference of material properties, detailed investigations through FE analysis results were conducted. The strength reduction ratios (1–13%) of carbon steel bolted connections with curling against connections with curling restrained showed a tendency to be lower than those (25–28%) of stainless steel bolted connections. The mean value (0.54) of ultimate strength ratios of carbon steel to stainless steel for connection with no curling and restrained curling was close to the tensile stress ratio (0.50) of carbon steel material to stainless steel material. It can be noted that austenitic stainless steel (SUS304) has a higher tensile strength of material owing to the strength enhancements by cold-working when compared with carbon steel (SS400). This may imply the difference of structural behaviors in bolted connections with stainless steel and carbon steel. Moreover, the mean value (0.76) of ultimate strength ratios for curled specimens in two different steel materials was found to be higher than those (0.54) for specimens with no curling due to a larger strength reduction of stainless steel connections by curling compared to carbon steel connections.

In addition, it is believed that the occurrence of curling has an influence on the change of stress distribution in connection plate, namely, stress distributions, obtained from both surfaces of curled specimens at same location, are different and tensile or compressive region of stress gets changed into opposite stress as out-of-plane deformation gets larger. It is also observed that the stress distribution of stress concentration part and the subsequent structural behavior of thin-walled bolted connections may be different from the mechanical properties of different steel materials; carbon steel and stainless steel. Therefore, since mechanical properties of steel materials may affect the ultimate behaviors of structural members, it is necessary to investigate the current design codes taking account of the steel materials specified by structural usage with the comparison of the design equations according to the difference of steel material.

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