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**Influence of different introduction methods of initial imperfection
on compressive behavior analysis of L-shaped welded steel column**

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KEYWORDS Finite element analysis, Single bevel butt joint, Initial imperfection, Load-bearing
capacity, Steel structure

ABSTRACT

The initial imperfection (initial deflection and residual stress) strongly influences the compressive behavior of welded steel structural members. This study examined introducing methods of the initial imperfection for simulating the compressive behavior of welded L-shaped columns by finite element (FE) analysis. When the initial deflection and residual stress were introduced independently into the model, the compressive behavior of the L-shaped column did not reproduce the experimental result. This study proposed a continuous analysis method from the welding simulation to the loading simulation for reproducing the perfectly dependent initial deflection and residual stress. The proposed method accurately reproduced the experimental results.

20 1. Introduction

21 Welding is a commonly employed technique for connecting various components in the construction of
22 steel structures such as bridges and ships. Its widespread use can be attributed to its ability to work in
23 tight spaces, achieve strong joints, and offer design flexibility. However, welding can introduce
24 deformation and residual stress due to the temperature difference between the surface and interior of
25 structural members. Since welding is a highly complex process involving the interplay of factors such
26 as the heat input from the electrical arc, the melting and solidification of metal, as well as the
27 deformation and residual stress generated due to contraction, quantitatively predicting welding
28 distortion and residual stress is exceedingly challenging. [1] Additionally, when steel structures are
29 subjected to compressive loads during their subsequent use, the welding-induced deformation can act
30 as an initial deflection, which has a significant impact on the stiffness of the structural members [2].
31 Furthermore, compressive residual stress can also significantly affect the load-bearing performance of
32 these members [3].

33 To assess the impact of initial imperfections on the load-bearing capacities of steel structural members,
34 numerous numerical analyses have been conducted. In traditional numerical analysis using finite
35 element (FE) simulation, geometric and material initial imperfections are typically considered
36 independently. For example, when taking into account the initial deflection, sine waves are often used
37 as a representative deflection mode [4]. A rectangular distribution is commonly employed as a
38 simplified model when incorporating welding residual stress [5, 6]. Based on review paper [7],

39 methods for introducing simplified models of initial imperfections still refer to research results from
40 decades ago. While various mathematical expressions are used to describe initial imperfection patterns
41 depending on the specific scenario [8, 9], it is essential to recognize that in actual welding processes
42 during the assembly of steel structural members, welding deformation and residual stress are inherently
43 related. This raises questions about the validity of treating them as separate and distinct factors in the
44 analysis.

45 That is to say, treating initial imperfections separately in numerical analysis can result in unbalanced
46 forces and diminished simulation accuracy. To tackle this problem, the authors have undertaken an
47 investigation into the possibility of conducting continuous analysis throughout both the welding and
48 loading processes. The goal is to achieve highly precise simulations by accounting for the
49 interconnected nature of these initial imperfections. The proposed continuous simulation method was
50 put into practice on L-shaped corner-welded steel columns, and a series of numerical analyses were
51 carried out to assess its effectiveness.

52 In a prior study [10], it was demonstrated that the compression behavior of a cruciform column can be
53 faithfully replicated through continuous simulation encompassing both the welding and compressive
54 loading processes. However, certain aspects remain unexplored. Firstly, the extent to which this
55 method improves analysis accuracy in the welding process needs to be understood. Secondly, while
56 this method is applicable to cruciform column specimens, its applicability to other types, such as corner
57 joint weld bead specimens, has not been verified. Additionally, the comparison of different methods

of introducing initial imperfections was carried out using the shell element model [11]. However, due to the limitations inherent to shell elements, residual stress values were obtained only at the inner and outer surfaces of the plates. Thus, whether the method based on above residual stress value exhibits superiority over traditional analysis methods in delivering more precise predictions when initial imperfections are introduced independently still needs to be established.

Hence, in this study, we aimed to confirm the load-bearing capacity by examining the variations between different methods of introducing initial imperfections with varying precision under various conditions. These conditions include scenarios where welding deformation and welding residual stress were considered independently as the initial condition (simplified distribution model) and cases where all welding consequences were factored into the initial conditions during the compressive loading analysis. This allowed us to assess the extent to which continuous analysis of both the welding and loading processes enhances analysis accuracy, and the appropriateness and expansion of applications of the approach of introducing the simplified distribution model used in previous studies [11].

71

2. Experimental procedure

2.1 Specimen

The specimens utilized in this study were L-shaped corner-joint welded steel structural columns, as depicted in Fig. 1. The reason why we chose this specimen is the simple structure with one weld line for investigating its basic mechanical behavior. Furthermore, a relatively simple model is expected to

77 better serve as an example to demonstrate the methodology and findings during this study. The flanges
78 had a thickness of 25 mm, while the L-shaped column had a thickness of 12 mm. All the plates were
79 fabricated from SM400B, in line with the JIS G3106 specification. Welding wire specified by JIS
80 YGW12 with a diameter of 1.2 mm was used. The L-shaped section was created by performing gas
81 metal arc welding four times. Furthermore, prior to the 4-pass welding process, two flanges were
82 securely attached to the vertical plates through tack welding. This was done to guarantee the accurate
83 geometric shape of the entire structure. Fig. 2 illustrates the cross-section resulting from the four-pass
84 welding process, which was assumed to resemble a single bevel groove.

85 In one of the two specimens we examined, the four welding passes employed a voltage of an average
86 of 25.25 V and a current of an average of 192.50 A. Specifically, the following voltage and current
87 were utilized: 24 V and 200 A, 25 V and 190 A, 26 V and 190 A, and 26 V and 190 A, respectively.

88 The welding speed during these four passes on the two vertical plates varied: 3.88 mm/s, 5.00 mm/s,
89 5.62 mm/s, and 5.81 mm/s, which also means the average welding speed during the welding of the two
90 vertical plates was 4.95 mm/s. Co-directional welding sequence for each weld pass was followed. The
91 cooling process lasted for 661 s, 623 s, and 631 s after the first three welding passes, respectively. The
92 cooling process for the last welding pass continued until the specimen body returned to room
93 temperature. Table 1 provides a list of the mechanical properties of the materials used for each
94 specimen, including values obtained from the mill sheet and catalog.

95 The slenderness parameter, denoted as λ , was calculated for the two vertical plates using Eq. (1) while

96 considering them as projection panels is 0.45 [6]. Where, σ_y is the yield stress (295 N/mm²), E is
 97 Young's modulus (205,000 N/mm²), and ν is Poisson's ratio (0.3). The breadth of plate, b is 88 mm
 98 and the thickness of plate, t is 12 mm. The buckling coefficient of a projection panel, k is 0.425.

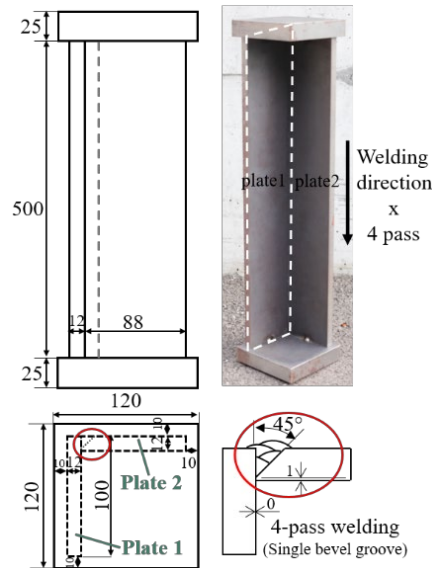


Fig.1 Experimental specimen overview

99

Table 1 Steel material information

	Chemical composition (mass %)					Mechanical properties		
	C	Si	Mn	P	S	Yield Strength	Tensile Strength	Elongation
	(x100)	(x100)	(x100)	(x1000)	(x1000)	(N/mm ²)	(N/mm ²)	(%)
Base plates	10	21	129	11	2	287	423	35
Vertical plates	12	22	103	20	5	295	440	36

Weld metal *	2-15	50-100	125-200	<30	<30	460	540	28
--------------	------	--------	---------	-----	-----	-----	-----	----

*Catalog values are given in parentheses.

$$\lambda = \sqrt{\frac{12(1-\nu^2)}{\pi^2 k}} \sqrt{\frac{\sigma_Y b}{E t}} \quad (1)$$

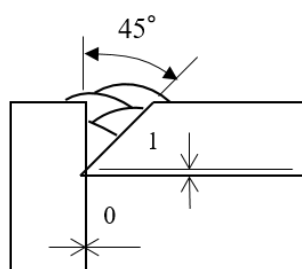
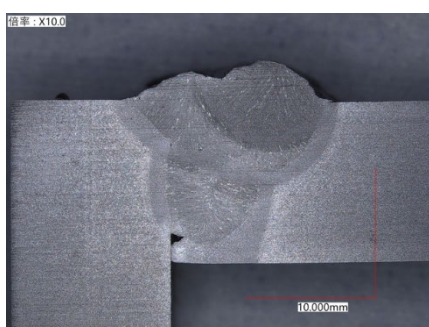


Fig. 2 Welded cross section (Single bevel groove)

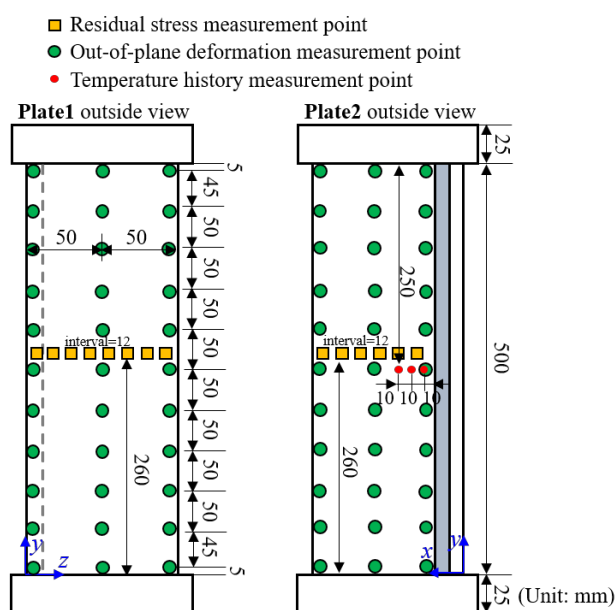


Fig. 3 Measurement location on specimen

2.2 Measurement

As depicted in Fig. 3, the two vertical plates are identified as 'plate 1' and 'plate 2'. To monitor temperature changes during welding, three thermocouples were attached to the surface of plate 2 at its center along the height direction ($y = 250$ mm).

109 The out-of-plane deformations in both plate 1 and plate 2 resulting from the welding processes were
110 measured by a dial gauge. Measurement points included the free edges and locations near the weld
111 bead on each plate, as well as the center point between the weld bead and the free edges. These
112 measurement points are illustrated in Fig. 3 and were situated at $y = 5, 50, 150, 200, 250, 300, 350,$
113 $400, 450,$ and 495 mm along the height direction (y -direction).

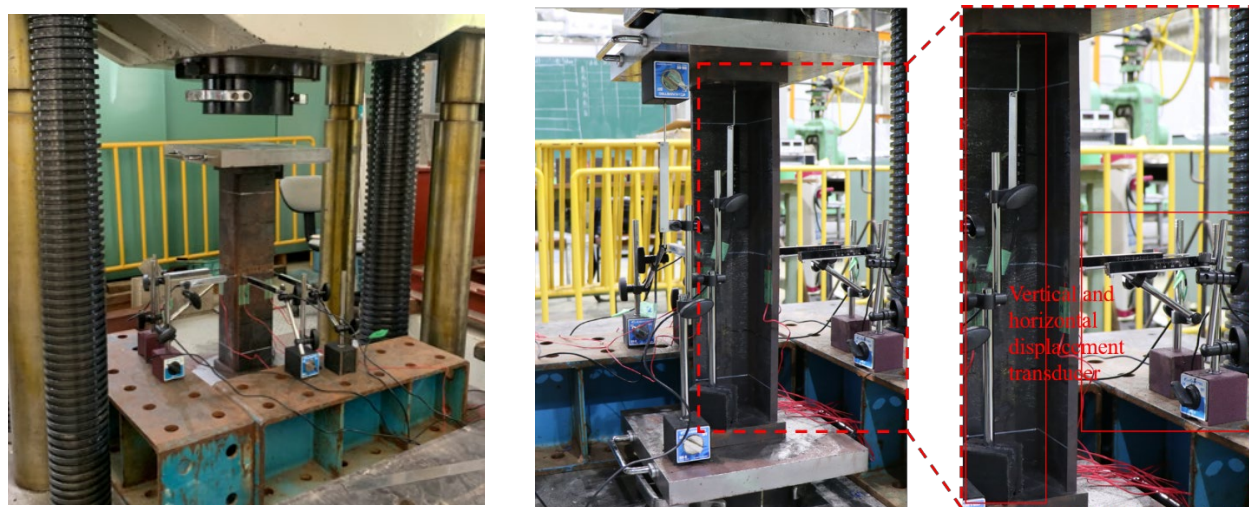
114 For assessing welding residual stresses, an X-ray diffractometer (specifically, the μ -X360s by Pulstec
115 Industrial Co., Ltd.) was utilized. Prior to conducting residual stress measurements, electrolytic
116 polishing was carried out at each measurement location on every specimen. Due to equipment
117 limitations, measuring the welded zone on the plate 2 joint side proved challenging. Consequently, the
118 welding residual stress data were obtained by measuring 8 mm from the weld bead on plate 2 ($x = 32$
119 mm), as well as 10 mm above the vertical center of the plate ($y = 260$ mm), as indicated in Fig. 3.
120 Stress components in the column's height direction (y -direction) were measured, as this component
121 significantly influences the load-bearing performance of the welded column.

122

123 2.3 Compressive loading experiment

124 Compressive loading experiments were conducted on two specimens. A static loading universal testing
125 machine was used to apply a gradual and monotonic compressive load along the axial direction of the
126 specimens. Once the maximum load was reached, the load was slowly released. The setup of the
127 loading experiment is illustrated in Fig. 4(a). To measure the vertical displacement, two displacement

transducers were positioned between the upper and lower flanges as shown in Fig. 4(b). Additionally, two displacement transducers were placed in contact with the surfaces of plate 1 and plate 2 to measure horizontal displacement of the height center of the vertical plates also as depicted in Fig. 4(b). Moreover, two strain gauges were affixed to each height center of the plate 1 and plate 2 free edge surfaces to check the loading balance to plate 1 and plate 2.



(a) Compressive experimental setup

(b) Out-of-plane deformation measurement setting

Fig. 4 Compressive experimental overview

133

134 3. Analysis procedure

135 3.1 Basic setting on analytical model through solid elements

136 The thermal elastic–plastic analysis was conducted using the commercial software ABAQUS 6.14.

137 Coupled temperature and displacement functions were chosen to accurately simulate the welding

138 process. Fig. 5 illustrates the finite element simulation model, assembled with eight-node solid

elements, designed to replicate both the welding and loading procedures of the experimental specimen. The mesh size in the direction perpendicular to the weld line between the vertical plates is approximately 10.0 mm. The thickness direction on each flange plate was divided into 5 layers, while both vertical plates were divided into 4 layers, which indicated that the mesh size in the flange thickness direction was 5.0 mm, and in the vertical plate thickness direction was 3.0 mm. Previous research [12] has shown that enhancing the mesh accuracy in the welded and adjacent areas, such that the number of meshes in the thickness direction is twice the current amount, only reduced the temperature data errors of each point to around 0.5% and the distribution of welding residual stress errors of each point to within 1.4% after welding simulation. This implied that there were not significantly different consequences between the higher-precision meshed model and the current meshed model. However, the higher-precision meshed model requires approximately five times longer to compute in welding simulation than the current meshed model. For the above reasons, the current mesh sizes are considered reasonable. Consequently, the mesh division depicted in Fig. 5 was deemed suitable for the analysis. The section shape of the four-pass heat input elements corresponding to the weld bead as shown in Fig. 6, which was designed based on the shape of the Fig. 2 actual weld bead. Correspondingly, the welding analysis based on birth–death element was applied on every 10.0 mm unit.

The analytical conditions of welding process are listed in Table 2. The von Mises yield criterion and the isotropic hardening rule were used. To prevent plates movement during the welding process, four

158 metal constraints were introduced to symbolize the metal left behind by tack welding between flanges
159 and vertical plates prior to simulating the formal four-pass welding. This not only ensured the vertical
160 alignment of the vertical plates during the four-pass corner welding process, but also made uncontacted
161 gaps between the flanges surface and the vertical plate edges by tack welding were simulated.
162 Consequently, in our analysis model, an artificial 0.1 mm gap was provided at the boundary of each
163 vertical plate edge and corresponding flange except for the elements symbolizing tack welding metal,
164 as shown in Fig. 5(b).

165 The analysis model employed 'Hard' contact conditions between their surfaces to control their normal
166 interaction behavior and to ensure that the vertical plates did not become embedded in the base plate
167 (flanges) during the compression analysis. Furthermore, the model incorporated a friction coefficient
168 of 0.5 to govern the tangential interaction behavior. A rigid-body displacement was fixed as the
169 mechanical boundary condition. Within the analytical model, the thermal interaction behavior included
170 heat transfer to the air from the outer surface of the model. By this comprehensive approach, accurate
171 and reliable consequences during the whole analysis were achieved.

172 In accordance with prior research [13, 14], the stress-strain relationships for each material were
173 displayed in Fig. 7, further material properties and physical constants are shown in Fig.8. Additionally,
174 these material properties and physical constants were validated the effectiveness by previous research
175 on welding simulation issues [15].

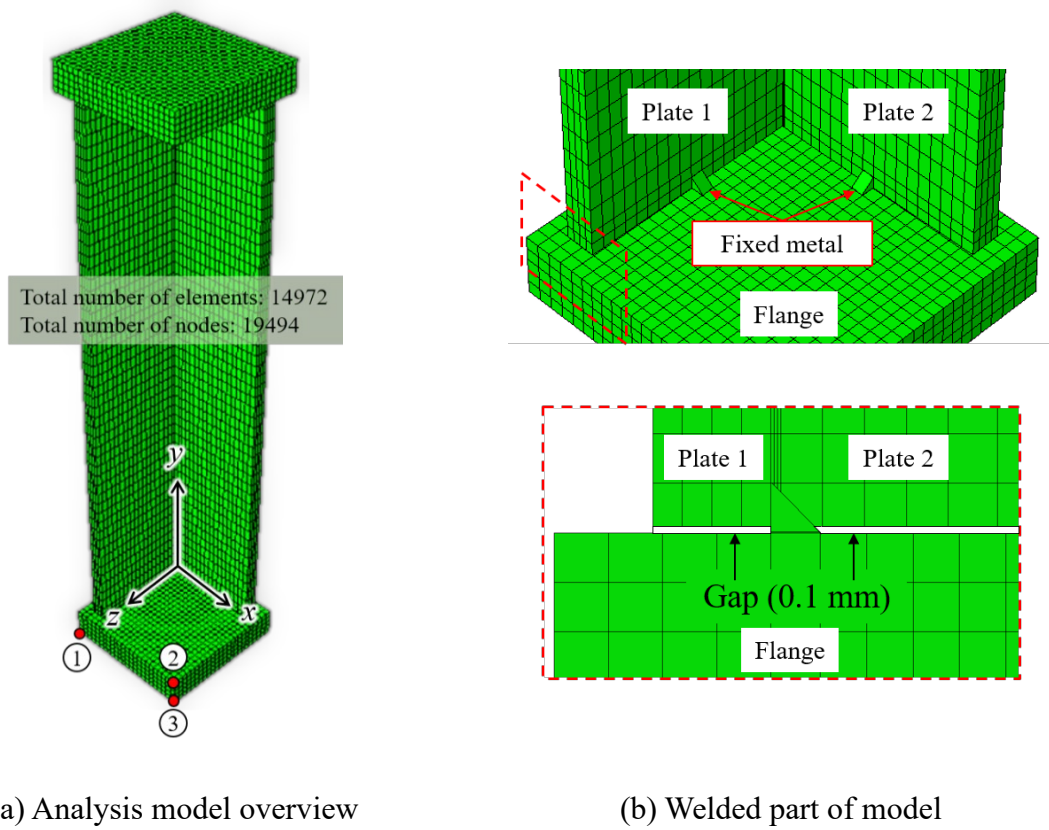


Fig. 5 Meshed model using solid element

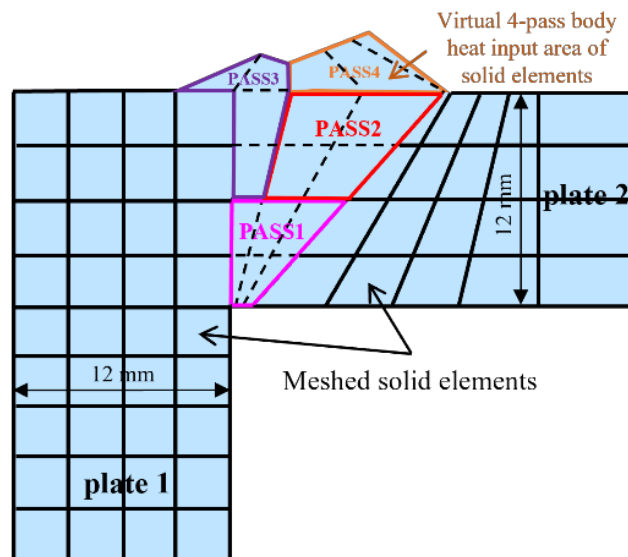


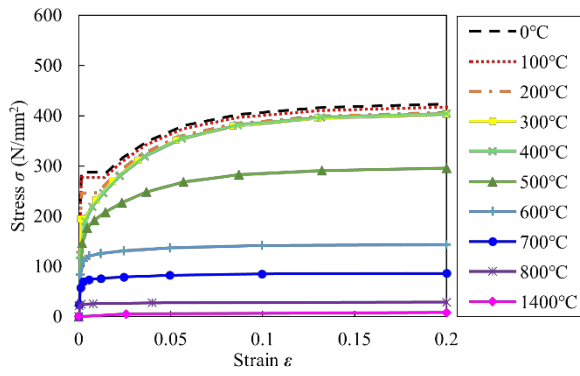
Fig. 6 Sectional view of heat input area in analytical model

Table 2 Analysis conditions of model using solid element

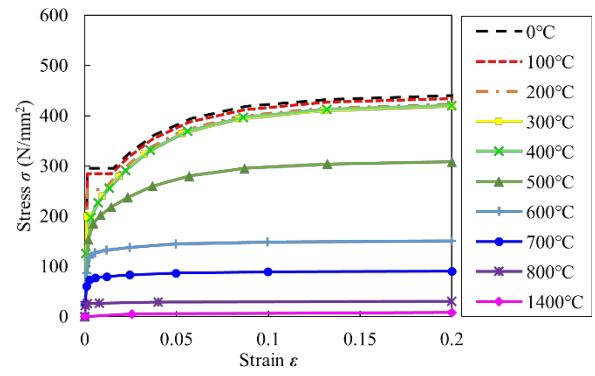
Analysis conditions setting	Specific description
Element type	8 node reduction integral solid element
Mechanical boundary conditions	x -direction displacement: Fix at ① y -direction displacement: Fix at ①, ②, ③ z -direction displacement: Fix at ①, ②
Thermal boundary conditions	Surface heat transfer
Weld line direction mesh size	Flange-plate 1 and plate 2: 10.0 mm (where close to base metal is 5 mm)
Physical characteristic value	Temperature-dependent type
Hardening rule	Isotropic hardening rule
Heat input method	Body heat flux
Heat source generation and transfer	Element birth function, moving heat sources
Supplementary conditions	Consider geometric non-linearity

178

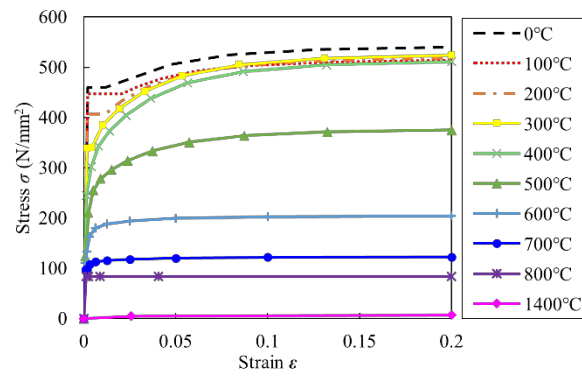
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(a) Flange (Base plate)



(b) Vertical plate



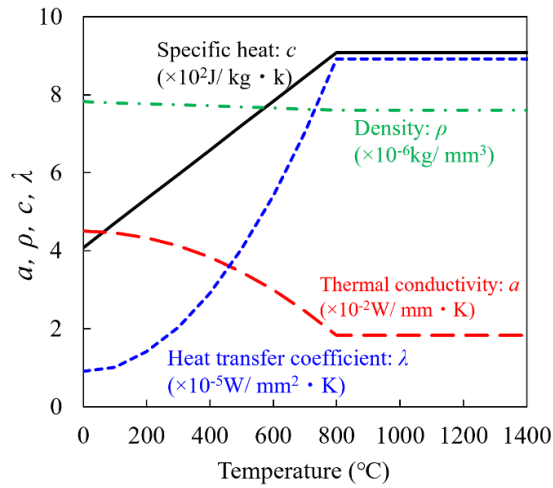
(c) Welding metal (JIS Z 3312 YGW12)

Fig. 7 Stress-strain curve of steel materials

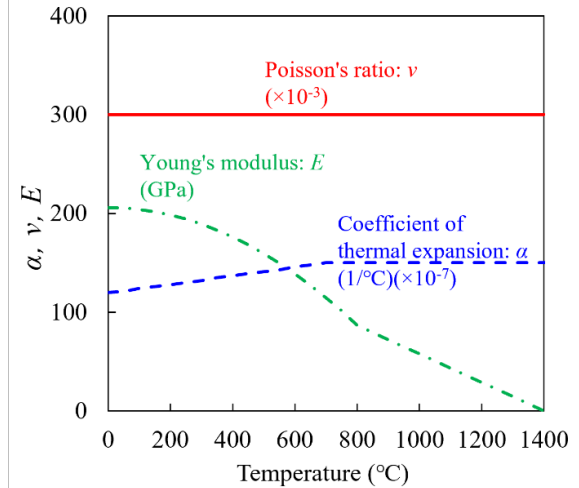
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181

182



(a) Temperature dependence of physical constants



(b) Temperature dependence of mechanical properties

Fig. 8 Material properties and the physical constants

183

184 3.2 Analysis simulation model

185 In this research, two different analytical models were designed, each employing distinct methods for
 186 introducing initial imperfections. The first model, referred to as the 'W model', involved the replication
 187 of the entire welding process through finite element thermal elastic–plastic analysis. Therefore, the
 188 initial letter W of welding is used to refer to this model. The other model, termed the 'R model',
 189 selectively excluded consequences other than welding deformation and welding residual stress from
 190 the consequences generated by the finite element thermal elastic–plastic analysis of the welding
 191 process, using them as initial imperfections. Correspondingly, the initial letter R of residual stress is
 192 used to refer to this model.

193 Welding process was simulated in the W model to obtain all associated consequences successfully.

194 Subsequently, by inverse analysis, welding imperfections with a self-balanced status that did not

195 conflict with the original analysis consequences were obtained effectively to the W model. Following

196 this, initial imperfections for the R model were introduced by extracting a subset of consequences

197 obtained through the welding process by W model. A schematic diagram as shown in Fig.9 illustrates

198 this concept briefly.

199 More specifically, by replicating the coordinates of every node obtained after the welding process from

200 the W model to the R model, the same welding out-of-plane deformation, including the initial

201 deflection, was accurately set as the initial deformation in the R model. Building upon this introduction

202 method, welding residual stresses on each element of the W model were also completely replicated to

203 each corresponding element of the R model. By this way, the R model not only replicated the welding

204 deformation from the W model but also replicated the residual stresses of every element obtained after

205 the welding process in the W model as its initial stresses.

206 By this approach, the influence of the welding deformation and residual stress, as well as the presence

207 or absence of other consequences such as plastic strain and hardening history, on the load-bearing

208 capacity during the subsequent analysis was allowed to confirm. Also, compared with the method of

209 using traditional calculation formulas to introduce welding deformation and residual stress [4-9],

210 whether this more accurate method of extracting accurate welding deformation and residual stress after

211 the welding process is more effective can be confirmed.

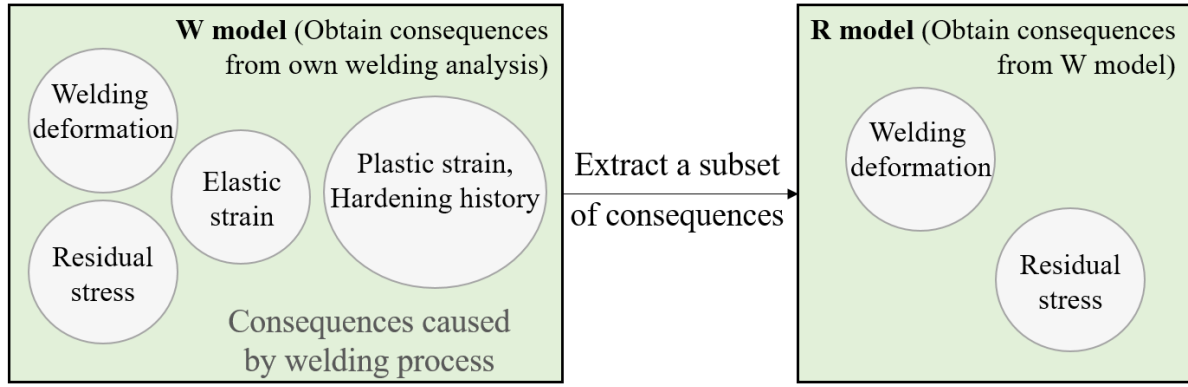


Fig. 9 Initial imperfection introduced method of R model

212

213 3.3 Adjustment of initial deflection

214 In order to accurately replicate the welding-induced out-of-plane deformation obtained from
 215 experimental data, the initial out-of-plane deformation of the analysis model was precisely adjusted
 216 using a calculation method based on the inversion analysis technique [10, 16]. To provide a concise
 217 overview, the following steps were involved.

218 The nodes on the free edges were adjusted first since their expected deformation was the largest. For
 219 the coordinates of these nodes, as shown in Fig. 10(a) using plate 1 as an example. Firstly, the out-of-
 220 plane deformation observed in the experimental measurements was interpolated as w_e using the Akima
 221 interpolation method [17] as the analysis out-of-plane deformation target. Subsequently, the out-of-
 222 plane deformation increment d caused by the heat input in the welding simulation was derived from
 223 the analysis consequences as shown in Eq. (2). Finally, algebraic operations were applied to subtract
 224 the calculated out-of-plane deformation increment d in the simulation from the experimental out-of-

225 plane deformation w_e as shown in Eq. (3). By this process, the final deformation coordinates as shown
 226 in blue dotted line w_0' for each node of plate 1 free edge were adjusted to achieve a precise alignment
 227 between the experimental data and the analysis consequences. After adjusting the node coordinates at
 228 the free edge of plate 1, the nodes within the same XZ plane that have the same vertical coordinates
 229 were proportionally adjusted, as shown in Fig. 10(b). The coordinates of the nodes on plate 2 were also
 230 adjusted accordingly.

231 Furthermore, Python script (matplotlib, tkinter, numpy, pandas,
 232 scipy.interpolate.Akima1DInterpolator) for batch processing of nodes adjustment in this study was
 233 used. Once the CSV files of the welding deformation measured after the experiment, the INP file and
 234 the CSV file of the welding deformation after the relative first simulation of the model in Abaqus were
 235 prepared, adjusted Abaqus INP input file based on the calculations from the Python script was obtained.

$$d = w_a(x_a, y_a, z_a) - w_0(x_0, y_0, z_0) \quad (2)$$

$$w_0'(x_0', y_0', z_0') = w_e(x_e, y_e, z_e) - d \quad (3)$$

236

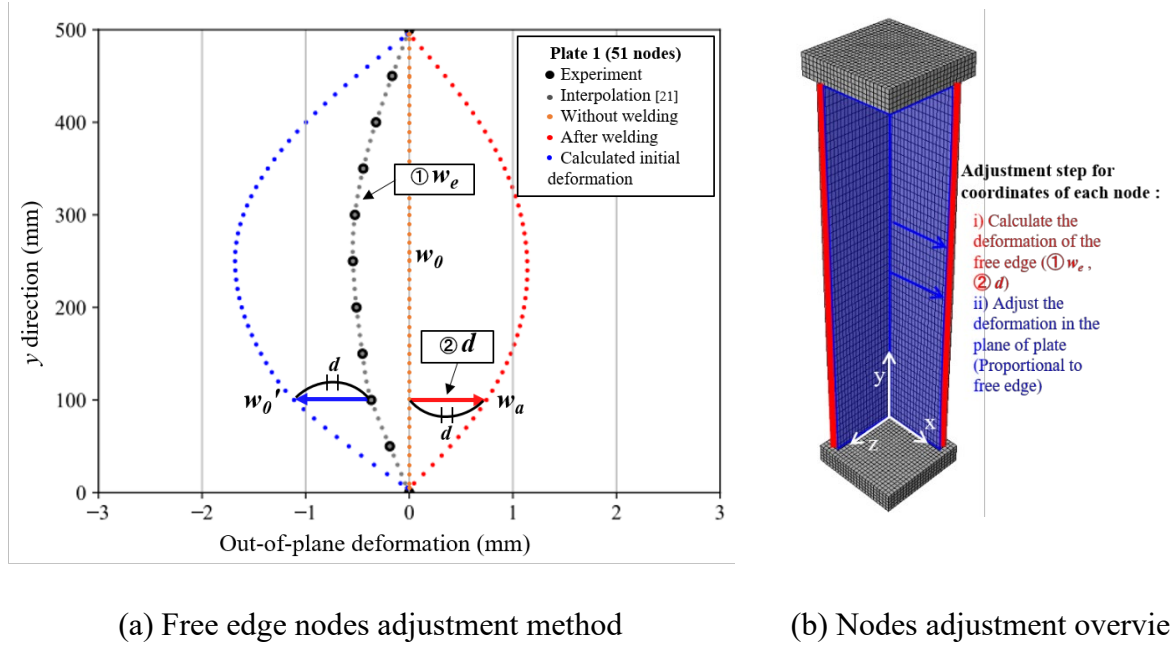


Fig. 10 Adjustment method for initial deformation

237

238 3.4 Welding process and welding temperature history

239 The section shape of the heat input element corresponding to the weld bead was based on the shape of
 240 the actual weld bead as shown in Fig. 6. A reasonable four-pass welding sequence section regarding
 241 the heat input area and shape for each welding pass was established.

242 Due to the minimal differences observed in experimental results of welding temperature history
 243 between the two specimens, the data of welding temperature history from one specimen was used for
 244 relevant calculations. The total heat input for each welding pass was calculated using Eq. (4), with the
 245 voltage E , current I , and speed v determined according to the experimental conditions. Also, thermal
 246 efficiency η played a key role in these calculations. The body heat flux was applied to the weld bead
 247 elements by considering the step-by-step movement and generation of the heat source using the

248 element birth function. In addition, for each element, thermal load is expressed as shown in Eq. (5). In
 249 this equation, S denoted the cross-sectional area of each heat input element, and l represented the length
 250 of each heat input element.

251 Given that the energy calculations relied on factors such as cross-sectional area, current, voltage, and
 252 heated volume, it was essential to adjust the thermal efficiency coefficients to accommodate variations
 253 in voltages, currents, and heated volumes for each welding pass. Typically, thermal efficiency in arc
 254 welding falls within the range of 65% to 90% [18-20]. By setting the thermal efficiency to 0.8, 0.6,
 255 0.6, 0.8 for each welding pass of the analytical model, the experimental temperature histories were
 256 accurately reproduced as shown in Fig. 11. The temperature error remained within 10% throughout the
 257 entire welding process.

258

$$Q = \frac{\eta EI}{v} \quad (4)$$

$$q = \eta \times \frac{EI}{Sl} \quad (5)$$

Q : Heat input (J/mm)

η : Thermal efficiency

E : Welding voltage (V)

I : Welding current (A)

v : Welding speed (mm/s)

q : Meshed element heat input (J/mm³)

S : Cross-sectional area of the meshed element (mm^2)

l : Length of the meshed element (mm)

259

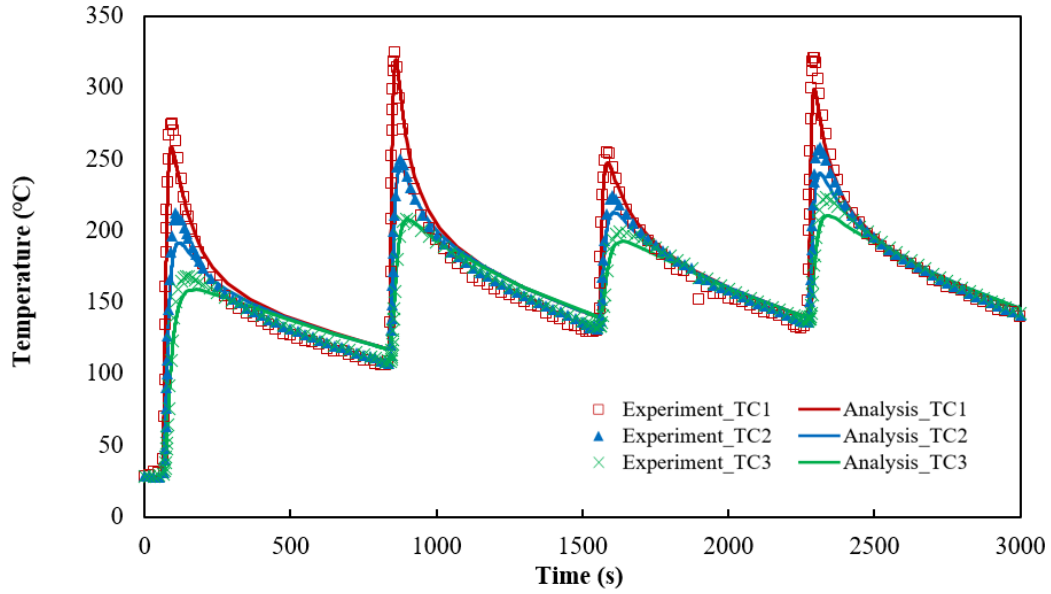


Fig.11 4-pass temperature histories at thermal couple locations predicted by FE model

260

261 3.5 Out-of-plane welding deformation (initial deformation)

262 The measurement points for out-of-plane welding deformations are depicted in Fig. 3. The out-of-
263 plane deformation data obtained at the 11 measurement points located at the free edge of each plate
264 were selected as the representative, since the overall deformation trend of each vertical plate can be
265 better shown. Among them, the experimental data presented in Fig. 12 are derived from the
266 corresponding measurements obtained for each plate of a single specimen. The standard deviation is
267 calculated from both two specimens. The magnitude of deformation was within 0.7 mm of each 12

mm vertical plate for each model, slight deformation attributable to welding was confirmed. At the same time, the amounts of deformation of the free edges of each vertical plate between the experimental results and the analytical consequences were compared. The experimental results were accurately replicated within the analytical model, and the maximum error percentage of the out-of-plane deformation consequences of the analytical model compared with the experimental results was 9.81%.

When the W model successfully replicated the out-of-plane deformation resulting from welding process, the identical out-of-plane deformation consequences were introduced in R model.

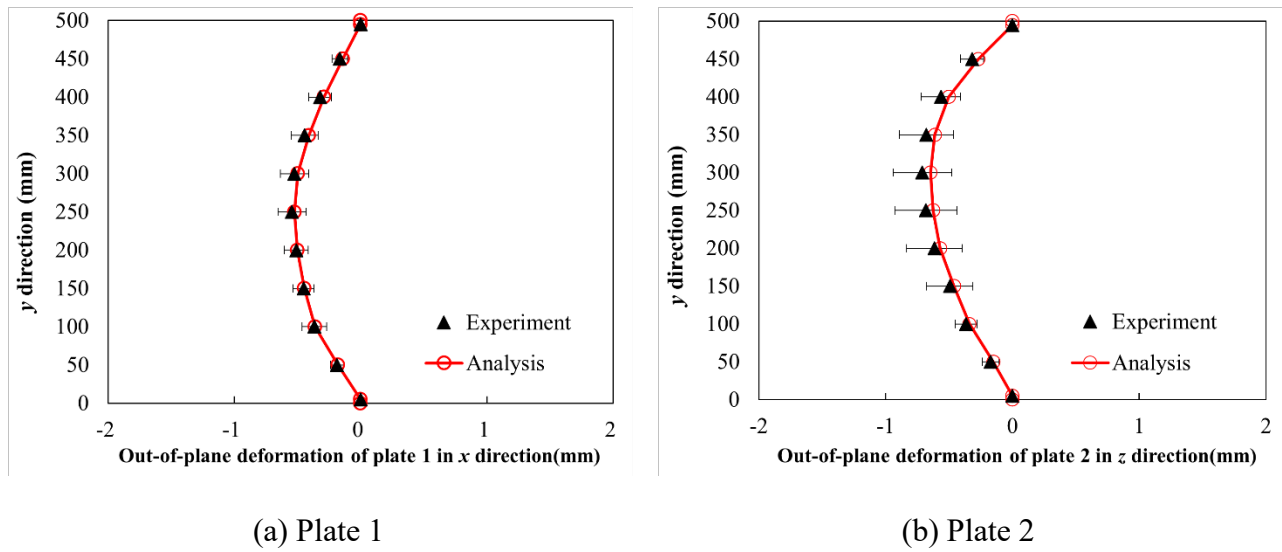


Fig. 12 Welding out-of-plane deformation

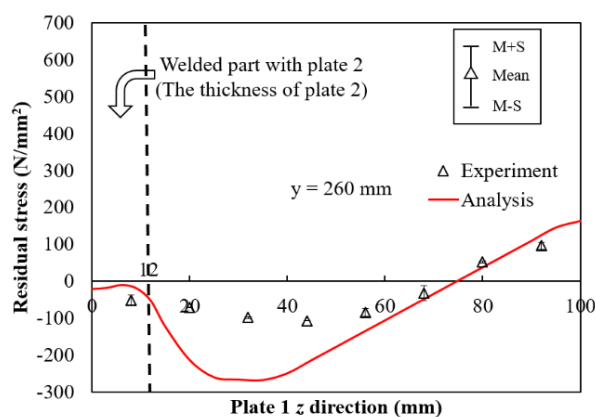
3.6 Residual stress introduced method on each model

In this analysis, the primary focus lies in assessing the influence of varying initial imperfections within different analysis methods. In many common simulation practices that omit the welding step, welding

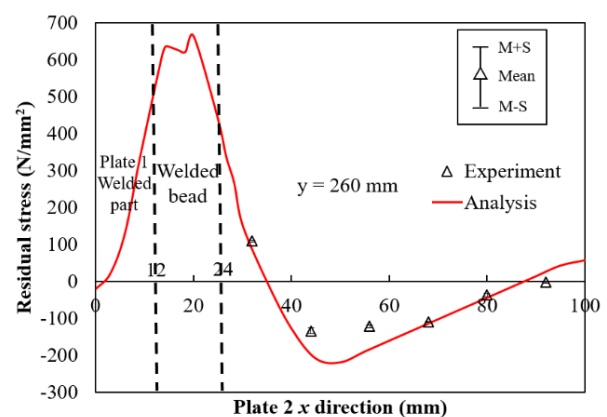
280 residual stress is directly introduced into the model as the initial imperfections. However, using a
281 sinusoidal function to introduce simplified welding deformations [4] and a rectangular distribution
282 model to introduce simplified welding residual stresses [5, 6] often makes the finite element model
283 unable to reach a self-balanced state. Therefore, this study incorporates the residual stresses from each
284 element of the W model, obtained during the thermal elastic plastic analysis of welding, into the
285 corresponding elements of the R model for discontinuous simulation (performing load-compressive
286 simulation only). This approach can be used as a high-precision alternative to using a sinusoidal
287 distribution to represent welding deformation and a rectangular distribution to represent residual stress.
288 Consequently, a comparison can be made between the analytical consequences of the W model, which
289 conducted continuous analysis of welding and load-compression, and the consequences of the R model
290 that introduced initial imperfections and solely performed load-compressive simulations. Considering
291 the characteristics of solid elements, it was possible to examine six stress components, with three of
292 them representing normal stresses in the x , y , and z directions within the in-plane domain. Following
293 above approach, this introduction method effectively established the initial residual stress within each
294 element of not only the W model but also the R model at the beginning of the loading process.

295 Fig. 13 illustrates the distribution of normal stress in the y direction serving as a representative example
296 since the y direction is the main important loading-bearing direction. It shows the initial welding stress
297 within each node of the analysis model for both plate 1 and plate 2 at a specific height ($y = 260$ mm),
298 which was the same as the experimental measurement location. In the range of 20–50 mm on plate 1,

299 there are certain discrepancies between the experimental results and the analytical consequences
 300 regarding the distribution of residual stresses. These discrepancies occurred because the actual
 301 specimens were constructed with four-pass welds overlapping each other. Viewing from the
 302 comprehensive perspective of the entire four-pass welding process, the corresponding positions
 303 experienced a redistribution of residual stresses due to a single thermal cycle after each pass was
 304 completed. The inability of the numerical analysis to accurately capture the stress relaxation after each
 305 welding pass [21], which leads to significant accumulated errors, was identified as one of the reasons
 306 for the inconsistency between the experimental results and the analytical predictions. However, the
 307 overall trend in the residual stress distribution is consistent. Therefore, when considering the overall
 308 difference in the whole specimen and model, the agreement between the experimental results and
 309 analytical consequences remains acceptable. In addition, by comparing the stress distribution between
 310 the W model and the R model, the initial stresses in both models were precisely consistent before the
 311 application of compressive loading can be confirmed.



(a) Plate 1



(b) Plate 2

Fig. 13 Initial residual stress distribution

312

313 3.7 Compressive loading analysis

314 Following the simulation of the welding process using thermal elastic–plastic analysis on the W model,
315 a uniform unidirectional compressive load was applied to the analytical models. Fig. 14 and Table 3
316 detail the geometrical boundary conditions for the compressive loading analysis. The displacement in
317 the y -direction was fixed at the lower of the bottom flange in each model. The load was applied by
318 imposing forced displacement along the negative y -direction onto the upper surface of the top flange.
319 To prevent large torsion of the top and bottom flanges during the loading process, horizontal
320 displacement was restricted at one point on each of the top and bottom flanges in both the x and z
321 directions. The stress–strain relationship utilized was interpolated from the relationship illustrated in
322 Fig. 7, and it corresponded to a room temperature condition of 28.7°C , which was consistent with the
323 experimental temperature conditions.

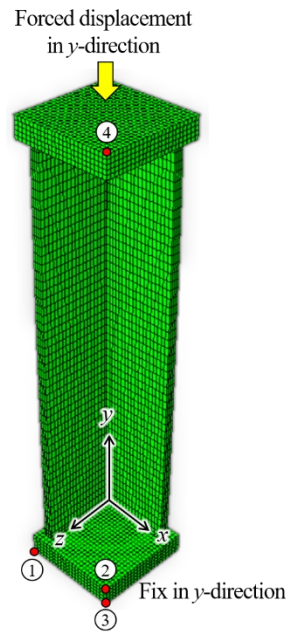


Fig. 14 Elastic-plastic finite displacement analysis model

Table 3 Geometrical boundary condition in loading process

Different directions	Fixed method
x -direction displacement	Fix at ①, ②, ③, ④
y -direction displacement	Bottom flange constrained Forced displacement on upper flange (-10 (mm))
z -direction displacement	Fix at ②, ④

325

326 4. Result and discussion

327 4.1 Load-bearing capacity

328 The relationships between load and vertical displacement, as observed in both the experiments and

analysis, are depicted in Fig. 15. Remarkably, for each analytical model, the elastic stiffness values were in good agreement with the experimental values, and their elastic stiffness values were all in the range of 660-710 kN/mm. However, compared to the experimental results and the analytical consequences of the W model, the consequences of the R model did not enter the plastic deformation stage under the corresponding load. The maximum loads recorded in the experiments were approximately 706.93 kN and 708.05 kN. In contrast, the maximum loads in the W model and R model were approximately 701.00 kN and 666.74 kN, respectively. This implied that the analysis errors between the W model and the experimental mean, as well as between the R model and the experimental mean at maximum load, were -0.9% and -5.8%, respectively, compared with the experimental mean. The load–vertical displacement curves of the W model analytical consequences, due to its continuous simulation, exhibited excellent agreement with the experimental results. Consequently, through thermal elastic–plastic analysis of the welding process, it is evident that the temperature history, out-of-plane deformation, and residual stress can be replicated with a remarkable degree of accuracy when compared to welded experimental specimens. However, based on the deformation and load–displacement relationships, despite the fact that the R model introduced the same welding residual stress (with a higher level of accuracy compared to traditional simple calculation methods) as the W model, it did not faithfully replicate the mechanical behavior and underestimated the maximum load. That might be the accumulated strain and the other generated consequences during the welding process that also played an important role but were not

introduced into the R model before the loading compressive process, which influenced the status of the model and furthermore impacted its maximum load capacity.

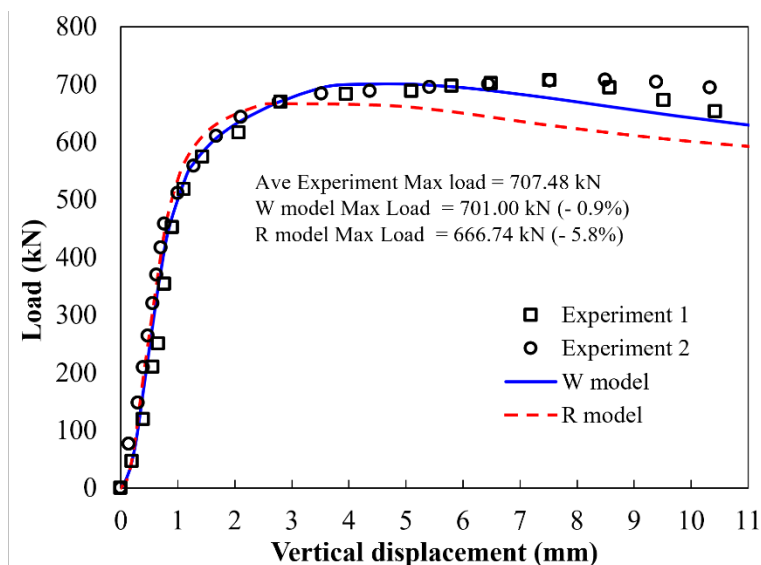


Fig. 15 Load and vertical displacement curve

350

351 4.2 Deformation behavior

The deformation behavior observed in the experiment can be successfully replicated across both two types of models under the different initial imperfections introduced. The deformation modes are visually represented by the load and horizontal displacement curve in Fig. 16, which was derived by extracting data at the midpoint of the free edge between the models and the experimental specimen. Because only the one of the experimental specimen was used as the initial welding deformation reference for the inversion analysis calculation, the data of another specimen was removed from this figure.

In both models, the largely deformed locations and the direction of the deformation were same to those

360 experimental specimens. Specifically, the magnitude of horizontal deformations under the maximum
 361 load capacity on each plate of the W model which with continuous simulation were 4.43 mm and 1.44
 362 mm, the R model which with both the welding deformation and welding residual stress introduced
 363 were 1.14 mm and 0.91 mm, while the magnitude of horizontal deformations under the maximum load
 364 capacity of experimental specimen 1 were 6.14 mm and 1.33 mm. The R model did not enter the plastic
 365 deformation stage under the corresponding load, whereas the W model's performance across the entire
 366 range of horizontal displacement closely matched the experimental data. This indicates that the W
 367 model exhibited favorable consistency with the experimental results in the aspect of horizontal
 368 displacement.

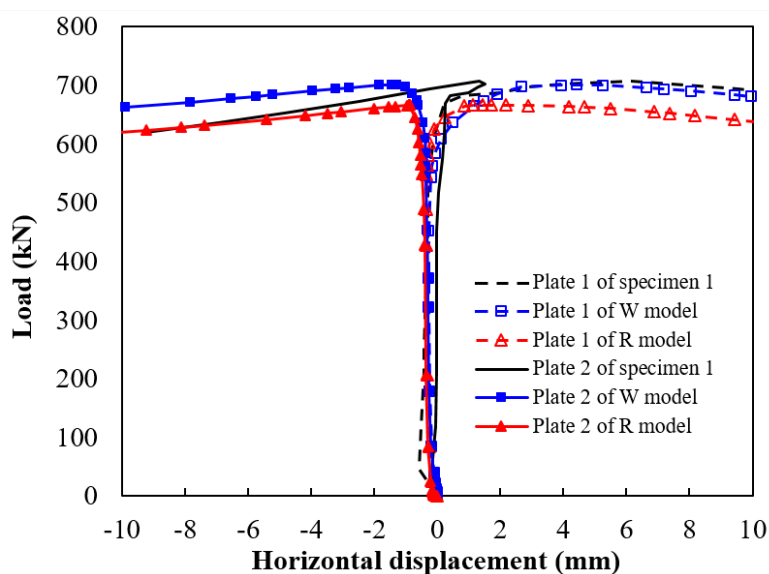


Fig. 16 Load and horizontal displacement curve

369

370 4.3 Stress and strain history

371 Fig. 17(a) illustrates the measurement points at specific nodes within a finite element analysis, where

the measurement locations for both plate 1 and plate 2 are all at the midpoint of the free edges, with five points selected along the thickness direction for each plate. This setup allows the analysis of stress and strain histories at critical points of the structure, as these points may experience the most significant changes in hardening history throughout the compressive loading process.

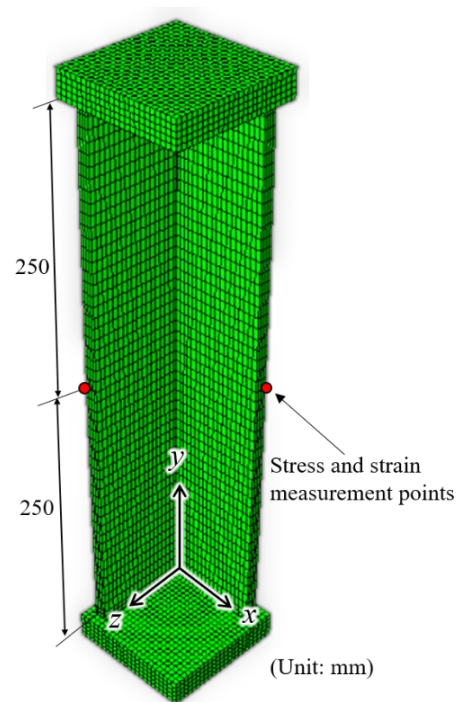
Figs. 17(b) and 17(c) show the relationship between stress and plastic strain at the average of five measurement points in the loading direction (y -direction) for both plate 1 and plate 2, respectively. It's noteworthy that the figures concerning the W model include cumulative stress and strain from both the welding and loading processes. In contrast, the figures related to the R model only include stress and strain from the loading process, as they did not include welding analysis. That is to say, at the start of the compressive loading simulation, although the W and R models have the same stress values, the strain for both plates in the R model starts at zero, whereas in the W model, it does not.

Specifically, during the compressive loading process, in the W model, the stress on plate 1 changed from an initial value of -58.61 N/mm^2 to a maximum of -288.68 N/mm^2 , while the strain changed from -0.00048 to -0.00312 . In the R model, the stress on plate 1 shifted from an initial -58.61 N/mm^2 to a peak of -287.43 N/mm^2 , and the plastic deformation increased from 0 to -0.00225 . For plate 2 in the W model, the stress shifted from an initial 0.127 N/mm^2 to a maximum of -280.17 N/mm^2 , with strain changing from -0.00109 to -0.00241 . In the R model, the stress on plate 2 moved from 0.127 N/mm^2 to a peak of -287.43 N/mm^2 , and the strain increased from 0 to -0.00124 . Thus, in this process, compared to the W model, the R model exhibited stress increment errors of -0.55% and 0.58% for

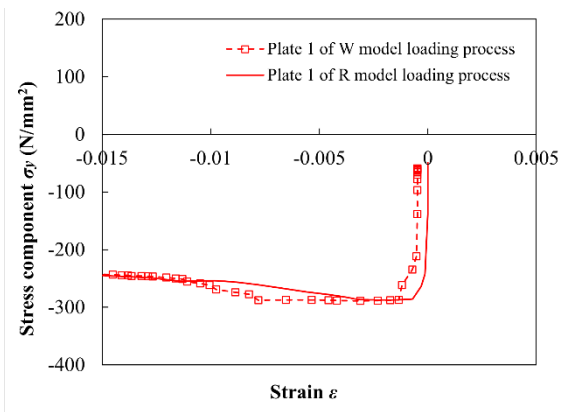
391 plate 1 and plate 2, respectively, and strain increment errors of 1.54% and -3.98% for plate 1 and plate
392 2, respectively. Although both plates in both models show classic signs of plastic deformation followed
393 by strain hardening, the R model generally exhibits an earlier hardening phase, particularly noticeable
394 in plate 2.

395 Furthermore, in the W model, the stress continuously decreased after compression. However, in the R
396 model, the stress values for both plates initially increased slightly upon compression, before
397 subsequently decreasing. The observed differences are due to the fact that the R model only
398 theoretically replicated the residual stress values but failed to fully simulate the changes in mechanical
399 properties experienced by the W model. In the W model, since an actual welding simulation was
400 conducted, changes in the microstructure during welding and cooling, such as grain reorganization or
401 the internal release of residual stresses, might be accurately modeled. This allows the steel material to
402 respond more uniformly and continuously to stress during the compressive loading process. However,
403 for the R model, even though the initial residual stresses introduced were the same as those in the W
404 model, the absence of a simulated actual welding process caused the release and redistribution of
405 residual stresses under external forces to differ from those in the W model. Uneven stress distribution
406 caused the absolute stress values to decrease before increasing during the early stages of loading. As a
407 reference, the stress-strain relationship curves of the W model in the loading direction (y -direction)
408 for both plate 1 and plate 2 during the welding simulation process are shown in Figs. 17(d) and (e). It
409 can be seen from the figures that the W model shows stress redistribution as early as the welding

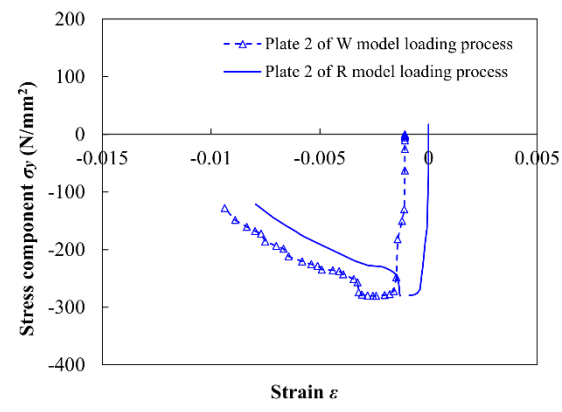
410 simulation stage.



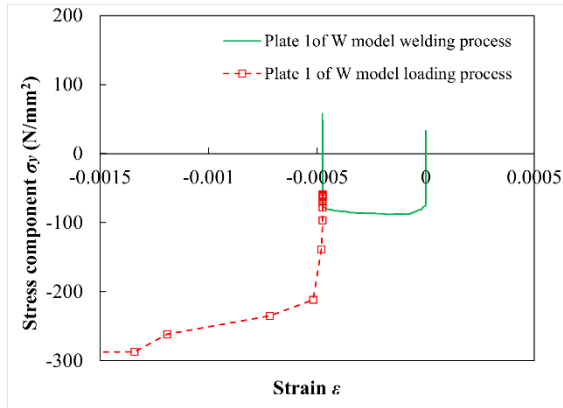
(a) Measurement location for stress and strain in finite element analysis



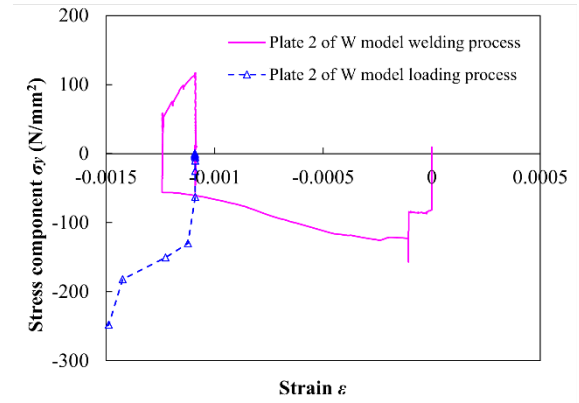
(b) Loading process for plate 1



(c) Loading process for plate 2



(d) Plate 1 in the W model



(e) Plate 2 in the W model

Fig. 17 Stress and strain curve

411

412 4.4 Yield state and stress components

413 The stiffness decreased sharply from the load of approximately 500 kN on all analytical models, which
 414 was also observed in the experiments, as shown in Fig. 15. Based on this, model yield states in different
 415 loading periods by element of each model were checked and shown in Fig. 18 when blue represents
 416 elasticity and red represents plasticity. As the figure shown, before reaching the maximum load
 417 capacity, a considerable number of elements in the vertical plates next to the weld bead, as well as
 418 some elements close to the weld bead, exhibited irreversible plasticity in the W model. In contrast,
 419 minimal to no elements displayed plasticity in the R model.

420 When both models were subjected to their maximum loads, a substantial number of plastic elements
 421 manifested on the upper side of plate 1, and a small number of plastic elements manifested on the
 422 lower side of plate 2 in the R model. At the same time in the W model, a greater number of elements

undergoing plastic deformation. The deformation mode observed in plate 1 was closely resembled that of plate 1 in the R model, which also means that the plate 1 of the W model amplifies the deformation trend of the plate 1 of the R model. Similar deformation trends also occurred on plate 2 of both models. In plate 2 of the W model, not only did numerous elements on the upper side experience plastic deformation, but a significant number of elements on the lower side also underwent plastic deformation. Correspondingly, a small number of elements in the plate 2 of the R model undergo plastic deformation at the same position. Additionally, during the unloading stage, both models exhibited similar trends in plastic deformation. These observations highlighted the distinct differences in the extent and distribution of plastic deformation among these two models, illustrated the effects of welding residual stress on the elastic–plastic state.

Notably, for the L-shaped corner-welded specimen examined in this study, welding residual stress has a notable impact by in the form of tensile stress to enhance the maximum load capacity of the specimen. Besides, by checking analysis consequences, although there was not a substantial difference in the initial distribution patterns of the three principal stresses between the W model and the R model, as the loading process proceeded, stress distribution became different, and the maximum load also became different. This divergence might be attributed to the fact that, in addition to the main factor of residual stress, other factors such as accumulated strain still play a role in influencing the maximum load capacity of the model.

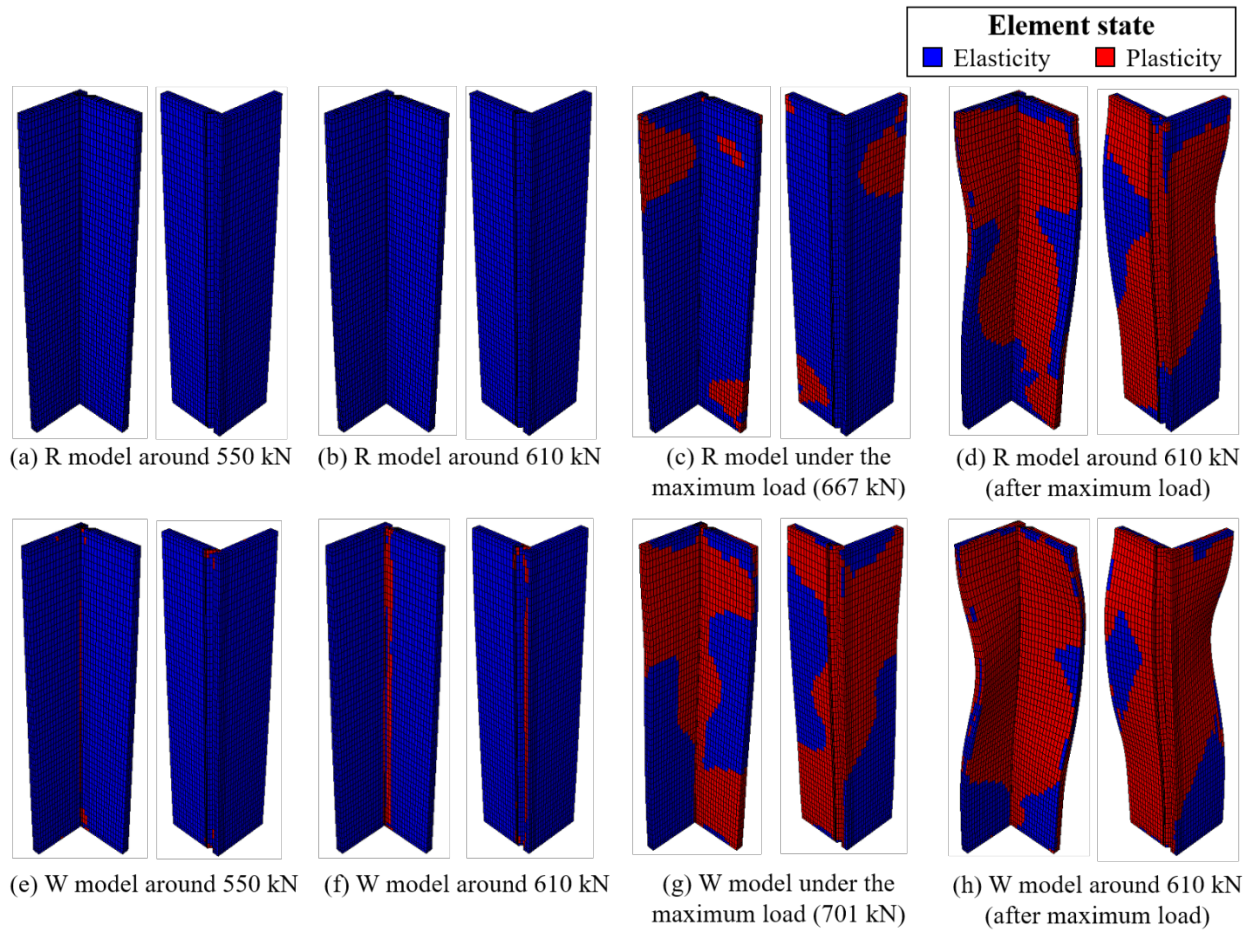


Fig. 18 Yield state by element (loading to unloading process)

441

442 5. Conclusions

443 A series of experiments and analyses were conducted to investigate the accuracy of the load-bearing
 444 capacity when introducing different initial imperfections by different analysis methods for steel
 445 structural members. The main findings of this study are summarized as follows.

- 446 (1) A single-bevel corner joint welding experiment was conducted using a steel L-shaped column. The
 447 experiment was simulated by thermal elastic-plastic analysis using three-dimensional solid
 448 elements. The temperature history obtained from the experiment was reproduced using W analysis

models. The out-of-plane welding deformation of the free edge was forcibly reproduced by adjusting the initial deformation in the W model, and then used as one of the initial imperfections introduced in the R model. The welding residual stress obtained from the experiment was completely replicated in the W model by thermal elastic–plastic analysis, and then was introduced into the R model as another initial imperfection. Based on this introduction method, the two comparison models had the same welding deformation and welding residual stress.

(2) A monotonic static compressive loading experiment was performed on the L-shaped corner-welded column. After conducting the welding simulation using thermal elastic–plastic analysis on the W model, and also after introducing the initial imperfections on the R model, the compressive loading experiment was simulated continuously on both two models. The reproducibility of the experiment was low when only the subset of consequences as initial imperfections, for instance, the R model. In contrast, when the welding process and compressive loading process were continuously simulated in the same model, such as the W model, the consequence of the load-displacement relationship in the analysis was in good agreement with the experimental results.

(3) This study focuses on the significance of considering the impact of introducing different initial imperfections through different analysis methods on the accuracy of maximum load capacity predictions. Different from the common impression, such as previous studies, that welding residual stress will reduce the maximum bearing capacity of the specimens, in the case of the L-shaped corner-welded specimen subjected to 4-pass co-direction welding, the maximum load-bearing

capacity was actually enhanced by welding tensile stress. This highlights the complexity of the relationship between initial imperfections and maximum load-bearing capacity, which might vary depending on different welding joint methods.

Future studies will extend to bridge structural components using other welding methods, with the aim of reproducing actual bridge structures by combining various types of joints to confirm how these welding combinations influence the maximum load-bearing capacity under the different initial imperfections. In addition, for complex welding and loading conditions, verification of more advanced numerical methods is required to capture these subtle differences. At the same time, finite element simulation methods that could shorten computational time while ensuring accuracy in terms of load-bearing capacity will also be explored.

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