MEASUREMENT METHOD FOR WELDING RESIDUAL STRESS IN STEEL I-SHAPED GIRDER WITH THICK FLANGE AND ITS INFLUENCE ON LOAD-CARRYING CAPACITY FOR BENDING

Takeshi MIYASHITA¹, Naofumi INABA², Shigeyuki HIRAYAMA³, Cuiping LIU⁴
and Masatsugu NAGAI⁵

¹Member of JSCE, Associate Professor, Dept. of Civil and Environmental Eng., Nagaoka University of Technology
(1603-1 Kamitomioka, Nagaoka, Niigata 940-2188, Japan)
E-mail: mtakeshi@vos.nagaokaut.ac.jp

²Member of JSCE, Tokyo Branch, Central Nippon Expressway Co. Ltd.
(4-3-1, Toranomon, Minato-ku, Tokyo 105-6011, Japan)
E-mail: n.inaba.aa@c-nexco.co.jp

³Member of JSCE, Highway Technology Research Center (3-10-11 Toranomon, Minato-ku, Tokyo 150-0001, Japan)
E-mail: s.hirayama@tecmed.or.jp

⁴Member of JSCE, Research and Development Center, Nippon Koei Co. Ltd.
(2304 Inarigahara, Tsukuba, Ibaragi 300-1259, Japan)
E-mail: a7614@n-koei.co.jp

⁵Member of JSCE, Professor Emeritus, Dept. of Civil and Environmental Eng., Nagaoka University of Technology
(1603-1 Kamitomioka, Nagaoka, Niigata 940-2188, Japan)
E-mail: nagaimasatsugu@gmail.com

Along with the spread of steel bridges with I-shaped girders, the use of thick steel plates has been increasing in recent years. It is feared that residual stress in the thick plate affects the girder's load-carrying capacity, yet residual stress measurement data are insufficient. Consequently, the load-carrying capacity curves used in the Japan Highway Bridge Specifications are based on old data. In this study, a test specimen that simulates the welding section between the main girder web and thick flange is elaborated; the residual stress distribution is also measured in the flange plate width and thickness direction using a mechanical cutting method. In the plate thickness direction measurement, accuracy of the measurement is sacrificed in order to propose a simple and easy measurement method. It is found that the slope of stress distribution in the plate thickness direction increases as the thickness of the plate increases. Then, considering a three-dimensional equilibrium of residual stress, the intermediate support of an existing bridge is modeled. From the elasto-plastic finite element analysis, it is confirmed that the residual stress in the thick plate does not affect the load-carrying capacity for the bending of steel girders.

Key Words : *thick steel plate, residual stress, welding, steel girder bridge, load-carrying capacity*

1. INTRODUCTION

Recently, the use of thick steel plates as a structural material has been increasing in different fields. In the civil engineering field, since the revision of the Specifications for Highways Bridges¹⁾ in 1996, the maximum limit of steel bridges' plate thickness has been increased to 100mm; and as background to the rational design of I-shaped girders bridges, there are a large number of bridges constructed with a flange

plate thicker than 50mm.

The load-carrying capacity curve described in the design standards is based on old data. Consequently, the measurement data obtained from thick plates included in this curve are practically null. In order to increase the competitiveness of steel bridges, the idea of using plates with thickness superior to 100mm, as used in Europe, has been pondered. However, the available information about the load-carrying capacity and residual stress of struc-

Fig.1 T-shaped specimens (Unit: mm).

Fig.2 Band sawing machine.

Table 1 Data of T-shaped specimens.

Type			A					B				
Name of specimens			A1	A2	A3	A4	A5	B1	B2	B3	B4	B5
Flange	Thickness	mm	23	30	50	70	88	23	30	50	70	88
	Steel type	-	SM490YB		SM520C-H			SM490YB		SM520C-H		
	Yield stress	MPa	453	456	397	410	365	453	456	397	410	365
Web	Thickness	mm	20					20				
	Height	mm	110					610				
	Steel type	-	SM490YB					SM490YB				
	Yield stress	MPa	449					449				
Weld leg length		mm	7	8	10	12	14	7	8	10	12	14
Number of specimens	Plate width dir.	-	1	1	1	1	1	1	1	1	1	1
	Plate thickness dir.	-	1	1	1	1	1	1	1	1	1	1

tures that possess thick plates is not sufficient.

Although it has been conventionally known that residual stress affects the load-carrying capacity of steel girders²⁾, until now, only thin plates have been studied. Due to this fact, the residual stress distribution has been set as a constant in plate thickness direction³⁾. However, in the case of thick steel plates, it is thought that residual stress distribution varies due to the influence of welding heat, cooling process after rolling, and gas-cutting process. Since the measurement process is difficult and time-consuming, the available measurement data are scarce⁴⁾⁻⁷⁾. In particular for welding joints, a research based on residual stress measurements in plate width direction, suggests that in the case of thick plates, due to its thickness, a difference in residual stress between the flange's top and bottom surfaces occurs, and the residual stress is distributed in the plate thickness direction⁷⁾. However, the authors only know about the existence of references 8) and 9) related with welding residual stress distribution measurements in plate thickness direction.

In reference 6), the influence of residual stress in the load-carrying capacity of a steel girder is examined based on residual stress distribution measurements in the plate thickness direction of a thick steel plate. However, it considers the residual stress originated by the rolling and manufacturing process, not the residual stress originated by the welding. Thus, the influence of welding residual stress on steel girder with thick steel plates is not clear.

In this research, the object of study is a steel I-shaped girder with thick plate. Research objectives are as follows:

- 1) To grasp the residual stress distribution in thick steel plates with welding joints.
- 2) To perform an analytical analysis of the influence of residual stress on load-carrying capacity for bending of steel I-shaped girders.

For research objective 1), a thick steel plate is jointed by welding to a steel plate, creating a T-shaped specimen, which simulates the flange and web sections. Residual stress in the welding line direction distributed in the width and thickness di-

Fig.3 Position of strain gauge (Type: plate width dir.).

rection is measured using a mechanical cutting method. For residual stress measurement in the plate thickness direction, the released residual stress is deemed to have reached its maximum value when the specimen is cut in a perpendicular plane to the welding direction. Sacrificing measurement accuracy, a measurement method simpler and easier than the method in reference 9) is described.

For research objective 2), the influence of residual stress on load-carrying capacity for bending of a steel I-shaped girder is examined. Concretely, an existing bridge's intermediate support is modeled considering the residual stress distribution obtained from research objective 1); and based on an elasto-plastic finite element analysis, its ultimate strength is obtained.

2. RESIDUAL STRESS MEASUREMENT

(1) Introduction

In order to elaborate on a specimen that simulates the flange and web junction of an existing bridge, a thick steel plate is welded to a steel plate of the same grade, resulting in a T-shaped specimen. Then, the T-shaped specimens are cut into small-width specimens, and the residual stress is measured. The re-

Fig.4 Cutting procedure of plate width dir. specimens (Type A).

sidual stress of particular interest in this study is the stress in welding line direction distributed in the plate width and thickness direction.

(2) Mesurement outline

a) Test specimen

Figure 1 shows the manufactured T-shaped specimens, and their dimensions are shown in Table 1. Depending on specimen height, there are two types of specimens: Type A, with web height of 110 mm; and Type B, with web height of 610 mm. These specimens are prepared to determine the influence of web height on residual stress distribution specimens. Flange width is set as 800 mm, a value near the flange width of the existing bridge; and web thickness is set as 20 mm, constant along the specimen. This is the averaged value of the main girder web thickness corresponding to the bridge of study.

In this study, in order to understand flange thickness influence on residual stress distribution, from the minimum flange thickness (23 mm) to the maximum flange thickness (88 mm) used in the bridge of study, five different flange thicknesses were selected: 23 mm, 30 mm, 50 mm, 70 mm, and 88 mm. Combining Type A and Type B, there are 10 types of specimens. Because the residual stress measurements were made in plate width and thickness directions, in total, 20 test specimens were

manufactured. The specimens' steel type, weld leg length and yielding point are shown in **Table 1**.

The welding method used is carbon-dioxide arc welding, welding current is 240 A, welding voltage is 32 V, welding speed is 37 cm/min, welding position is flat, welding material is a 1.2 mm diameter flux-cored wire, and heat input is 12500 J/min.

b) Measurement method

In this measurement, the focus was on residual stress in the welding line direction. Residual stress measurement was carried out based on mechanical cutting (stress release method). Strain gauges for general use measuring 1 mm in length were collocated in the measuring locations. The released strain and opposite sign strain caused by the cutting procedure were multiplied by Young's modulus to obtain the residual stress. Cutting operation was made using a band sawing machine as shown in **Fig.2**. In order to prevent specimens from being affected by heat resulting from the cutting procedure, a non-contact thermometer was used to measure the temperature; always checking that temperature did not exceed the maximum value of the gauge's temperature compensation range (80 °C).

3. RESIDUAL STRESS MEASUREMENT IN FLANGE WIDTH DIRECTION

(1) Measurement method

Before cutting the test specimens, strain gauges were attached. **Figure 3** shows the position of the strain gauge. Each specimen was cut along the welding line direction, obtaining 100mm width specimens. From the cutting procedure, three Type A and 1 Type B specimens were obtained. The reason for the three Type A specimens was to check measurement repeatability. Then, as shown in **Fig.4**, from Cutting 1 to Cutting 12, specimens were cut into small pieces alternately. However, in the case of Type B, after Specimen Cutting 3 (**Fig.4**), the web height was reduced to 110mm. Residual stress final value was calculated based on the strain amount of change from strain before cutting and strain after each cutting procedure.

(2) Measurement results

The left column of **Fig.5** shows the residual stress measurement results in flange width direction. Here, measurement results obtained from flange's top and bottom surfaces of specimens Type A and Type B are shown. The horizontal axis shows the measurement location on the flange's top and bottom surfaces; $\pm 400\text{mm}$ represents flange end, and 0mm represents

flange center. It was assumed that an uniform residual stress was introduced in the flange end due to the heat resulting from the cutting procedure, and the data corresponding to the edge surface center were set as the values corresponding to the flange end. Since the value in the center part of the flange's top could not be measured directly, this value was calculated from a linear extrapolation between two points immediately adjacent to the flange center part.

Based on the measurement results, it was determined that the discrepancy between the residual stress distribution corresponding to the flange's top and bottom surfaces of specimens Type A and Type B was small. About the whole residual stress distribution tendency, it was found that in the flange's top surface, tension stress was distributed in the flange end and welding part areas; compression stress was also distributed in the middle part of the outstanding plate. These results are similar to previous measurement results³⁾.

In the flange's bottom surface, it was found that when flange thickness increased, tension stress in the flange center changed into compressive stress. Reference 7) also mentions that when plate thickness increases, tension stress in flange center changes into compressive stress.

(3) Modeling of residual stress distribution

Here, in order to simplify the introduction of residual stress into the finite element analysis carried out in Chapter 5, the modeling of measured residual stress distribution was conducted.

Residual stress reached the steel material yielding stress level due to the thermal effects resulting from the welding procedure. Because of this, the value adopted in the flange's top surface center was the maximum value obtained between Type A and Type B. Then, when the plate thickness was greater than 50 mm, the minimum stress location slightly shifted from the flange's lower surface center; and the distribution lost its symmetry. In order to obtain the minimum stress in the flange's bottom surface, the distribution form was modified. Finally, using the left-half of Type B flange (measurement location: -400mm to 0mm) data, which did not present any local variation in its distribution, a symmetric residual stress distribution with respect to the flange center was determined.

The right column of **Fig.5** shows the modeled residual stress distribution obtained from the procedure described above. Horizontal axis $\bar{x}$ shows the non-dimensional value obtained by dividing the measurement location by flange width. Vertical axis σ/σ_y shows the non-dimensional value obtained by

(a) Measurement ($t = 23$ mm)

(b) Modeling ($t = 23$ mm)

(c) Measurement ($t = 30$ mm)

(d) Modeling ($t = 30$ mm)

(e) Measurement ($t = 50$ mm)

(f) Modeling ($t = 50$ mm)

(g) Measurement ($t = 70$ mm)

(h) Modeling ($t = 70$ mm)

(i) Measurement ($t = 88$ mm)

(j) Modeling ($t = 88$ mm)

Fig.5 Measurement results of residual stress and modeling (Type: plate width dir., t : plate thickness).

Fig.8 Cutting procedure of plate thickness dir. specimens (Conventional method).

Fig.9 Cutting procedure of plate thickness dir. specimens (Proposed method).

Fig.10 Position of strain gauge (Type: plate thickness dir.).

Type A specimens with 23 mm and 88 mm. After cutting the specimen and reducing its width to 50 mm, the cutting procedure described in **Fig.8** was carried out. First, in order to improve its workability, the flange was cut at a distance of 50 mm from the weld toe (Cutting 1). The other side of the flange side was also cut at a distance of 50 mm from the weld toe (Cutting 2). Then, 23 mm and 88 mm thick specimens were cut in the plate thickness direction, parallel to the flange's surface, obtaining two and five divisions, respectively (Cutting 3). Here, thickness t shown in **Fig.8** was reduced from 23 mm to 11.5 mm; and from 88 mm to 17.6 mm. After this, notches were placed in the welding line and perpendicular direction on the brink of the strain gauge attached to the steel plate obtained after the cutting procedure.

Notch length was determined by the sequential confirmation of strain gauge value; and it was set in a position where the variation disappeared. Thereafter, strain gauges were attached to the newly generated flange surface. After this, the procedure from Cutting 3 to Cutting 5, and the gauge attachment process were repeated.

b) Proposed method

The Proposed Method is described in **Fig.9** and explained as follows:

- Gauge Attachment 1: Similar to the procedure described in **Fig. 8**, after cutting the T-shaped specimen, its width was reduced to 50 mm, and a strain gauge was attached to the center part, between the web and the flange's bottom surface.

Fig.11 Measurement of residual stress (Type A: plate thickness t dir., red square: position of strain gauge).

Fig.12 Measurement of residual stress (Type B: plate thickness t dir., red square: position of strain gauge).

Fig.13 Comparison of measurement methods (r : plate thickness).

- Cutting 1: The cutting procedure in the plane parallel to welding line direction did not have a big influence on residual stress in the welding line direction. In other words, it was assumed that the stress released quantity would not reach its maximum value, and the flange corresponding to the weld leg end was cut in the vertical direction. This assumption is called Assumption 1.
- Gauge Attachment 2: To improve work efficiency, the other side of the flange corresponding to the weld leg end was also cut in the ver-

tical direction.

- Cutting 3 - Cutting 4: The strain gauge brink was cut in a plane perpendicular to the welding line direction. It was assumed that residual stress in welding line direction was the maximum stress released. This assumption is called Assumption 2.
- Cutting 5 - Cutting 8: Finally, specimen was cut into smaller specimens.

In the next section, each cut event data is analyzed, and the mentioned process for Assumptions 1 and 2 is verified. Then, after comparing the measurement

Fig.14 Repeatability of proposed measurement (t : plate thickness).

data obtained from the Conventional and Proposed Methods, the validity of the Proposed Method is examined.

(2) Measurement results

a) Measurement result for each cut event

Measurement results corresponding to the Proposed method are shown in **Fig.11** and **Fig.12**. Results of Cutting 5 to Cutting 8 procedure described in **Fig.9** were omitted because stress variation was small. Then, web and flange measurement location differed, so these results are displayed separately. Strain gauges position is represented with a red square. The values of the flange's top and bottom surfaces were calculated extrapolating the two measured points immediately adjacent to this part.

Figure 11 and **Fig.12** show that, when Cutting 3 and Cutting 4 procedures are carried out in the per-

pendicular plane to the welding line direction, the maximum residual stress in welding line direction is released. This fact confirms the validity of Assumption 2. Additionally, the amount of stress released during the cutting process in a parallel plane to the welding line direction is small, confirming Assumption 1. Therefore, it can be said that the Proposed Method fulfilled the assumptions presented in previous sections.

Then, comparing the measurement results from Type A and Type B with different web heights, it is found that a tension residual stress is introduced into the Type A specimen web upper end due to the gas cutting process.

b) Comparison of measurement methods

Figure 13 shows a comparison between the measurement results of both methods. These results were focused on 23 mm and 88 mm thickness Type A

specimens. It should be noted that, for the Proposed Method, a weld bead was located in the flange's top surface, so it was not possible to attach the corresponding strain gauges in this place. To calculate this value, the two points immediately adjacent to this part were measured and extrapolated. This value is represented by a dotted line in the figure. The flange's bottom surface is illustrated in the same way.

A difference between the measurement results of both methods was found. This was due to the difference in the number of measured points and measured procedures. Notwithstanding, comparing both measurement results showed that their general tendencies were almost the same.

c) Repeatability of measurement results

Figure 14 shows the residual stress measurement results in the thickness direction for each plate thickness of specimens Type A and Type B using the Proposed Method. In this figure, only the flange distribution is shown. Except for the 30 mm thickness specimen case, residual stress distribution coincides in most cases for the Type A and Type B specimens. The discrepancy found in the 30 mm thickness specimen might have been due to welding heat quantity or cutting speed. However, the reason was not clear.

The residual stress introduced in the welding vicinity might have reached a value near the yielding point, but measurement results showed that residual stress in the welding area was lower than that of the yielding point. This was because one part of residual stress was released when the large scale T-shaped specimen was cut into 50 mm width specimens. Considering the released part of residual stress, measurement results were corrected. These corrected results are shown in **Fig.14**.

In the next section, an analysis of the residual stress released during the cutting procedure is carried out, and the obtained results are compensated. In order to simplify residual stress introduction into the finite element analysis, a three-dimensional equilibrium of residual stress is considered, and then, the corresponding residual stress distribution is modeled.

(3) Modeling of residual stress distribution

a) Stress distribution compensation method

The residual stress released during the cutting procedure of T-shaped specimen into the specimens used to measure residual stress was examined for Type A plate width direction specimens. As shown in **Fig. 3**, the plate width direction specimens were selected because before cutting the specimens, the

specimen strain gauges were attached in two points in the web vicinity, and welding leg value could be obtained from a linear extrapolation of measurements in the plate thickness direction.

Based on **Fig.4**, the cutting procedure of the T-shaped specimen into specimens for residual stress measurement is described below.

- Cutting 1: T-shaped specimen width was reduced from 1000 mm into 250 mm in welding line direction.
- Cutting 2: One side of 250 mm width specimen was cut 75 mm, so its width was reduced into 175 mm.
- Cutting 3: The other side of the 175 mm width specimen was cut 75 mm. Finally, a 100 mm width was obtained.

Figure 15 shows the residual stress variation in the welding line direction corresponding to the flange center for each cut. For each cut process, the released residual stress level in the flange's top and bottom surfaces is practically the same. Because the number of measurement points in this study was limited, when the specimen used for residual stress measurement was elaborated, it was assumed that the black straight line shown in **Fig.15** represents the released residual stress, and the measurement results shown in **Fig.14** will be compensated.

Figure 16 shows the compensated results of **Fig.14** using the process described before. Horizontal axis $\bar{x}$ shows the non-dimensional value obtained by dividing residual stress σ by yielding stress σ_y . Vertical axis z shows the non-dimensional value obtained by dividing measurement position by plate thickness. The dotted line represents the stress correction amount obtained from **Fig.15**. Result before compensation is the averaged value from **Fig.14**. The flange's top and bottom surface values were calculated extrapolating the two measured points immediately adjacent to this part. **Table 2** sorts out the values corresponding to the flange's top and bottom surfaces, previously shown in **Fig.16** and in the left column of **Fig.5**. Although results corresponding to the top surface presented a little difference among them, this difference is deemed acceptable since there was an error resulting from the residual stress modeling, already mentioned in Chapter 3.

It is desirable to simplify the residual stress distribution form as much as possible when it is modeled and analyzed by finite element analysis. Because of this, based on **Fig.16**, residual stress in the plate width direction shown in **Fig.5** is interpolated in the plate thickness direction. The shape function corresponding to 23 mm thickness plate is a constant value, and the one corresponding to other thickness

Fig.15 Repeatability of proposed measurement (t : plate thickness, Blue line: Cutting 1, Red line: Cutting 2, Green line: Cutting 3, Black line: 1000 mm to 100 mm width).

plate is a straight line. This is because, based on results obtained in this research and Reference 7), when plate thickness exceeds 30 mm, a residual stress variation is produced in the flange's bottom surface. Additionally, comparing the distribution described in Reference 10) and the residual stress distribution in the plate thickness direction obtained from analysis results using the eigen strain method, it was found that both distributions were approximately a straight line. For this reason, this shape function is deemed adequate.

b) Three-dimensional stress equilibrium

The flange's cross-section residual stress distribution was determined in the previous section. Considering a three-dimensional stress equilibrium inside the cross-section, a final residual stress distribution is modeled here. When equilibrium is considered, the width of the compression stress area in the width direction is established as a parameter.

Figure 17 shows the residual stress distribution model for each plate thickness. Black solid line shown in the left figure represents the modeled residual stress distribution. The three-dimensional residual stress distribution is shown in the right figure. Here, $\bar{z}$ represents the non-dimensional value obtained by dividing the measurement position by plate thickness.

For the 23 mm thickness specimen, residual stress distribution in the plate thickness direction was set as constant, and a two-dimensional stress equilibrium was considered. The obtained residual stress distribution is shown in **Fig.17(a)**. Orthogonal projection on $\bar{z} = 0$ in the right figure of **Fig.17(a)** is shown in the left figure of **Fig.17(a)**.

Except for the 23 mm thickness specimen case, residual stress distribution in the thickness direction was set as a linear variation function. Here, it is necessary to consider a three-dimensional stress

Fig.16 Residual stress distribution in the thickness direction after compensation (t : plate thickness).

equilibrium. As shown in the left figure of **Fig.17**, blue line and red line points located in $\bar{z} = 1$ and $\bar{z} = 0$ planes are connected by a straight line in the $\bar{z}$ direction, and they move along $-0.5 \leq \bar{z} \leq 0.5$ range. The width of compression area is determined when the volume surrounded by the surface generated by the straight line, $\bar{z} = 0$ plane, $\bar{z} = 1$ plane, and $\sigma/\sigma_y = 0$ plane becomes zero. Since distribution in width direction is symmetric, thus only $\bar{x} \geq 0$ range is considered. The derived formula used in this research to calculate this volume is described in the Appendix.

Figures 17(b)-17(e) show the residual stress distribution obtained from the model for all plate thickness except for the 23 mm thickness specimen. Characteristic points of the distribution are summarized in **Table A1** located in the Appendix. The next chapter describes the introduction of the obtained residual stress distribution into an elasto-plastic fi-

Table 2 Comparison of residual stress on top and bottom surfaces of flange.

Thickness (mm)	σ / σ_y			
	Model (Fig. 5)		Measurement (Fig. 16)	
	Top	Bottom	Top	Bottom
23	0.74	0.45	0.77	0.43
30	0.66	0.10	0.84	0.30
50	0.84	-0.20	0.89	0.03
70	0.97	-0.23	1.12	-0.28
88	0.94	-0.32	1.15	-0.18

nite element analysis corresponding to the flange of a steel I-shaped girder.

(a) $t = 23$ mm

(b) $t = 30$ mm

(c) $t = 50$ mm

(d) $t = 70$ mm

(e) $t = 88$ mm

Fig.17 Modeling of residual stress in thick steel plate (t : plate thickness).

Fig.18 Analytical model (Unit: mm).

Table 3 Cross-sectional dimensions and material properties.

Member	Dimensions (mm)	Steel type	Yield stress (MPa)
Upper flange	750 × 50	SM520C-H	355
Web	31 × 2950	SM490YB	355
Lower flange	850 × 88	SM520C-H	355
Stiffener	50	SM570	450

Fig.19 Residual stress distribution in web³⁾.

5. INFLUENCE OF WELDING RESIDUAL STRESS OF A THICK STEEL PLATE IN LOAD-CARRYING CAPACITY FOR BENDING OF A STEEL GIRDER

In this chapter, an intermediate support of an existing bridge is modeled, and the influence of welding residual stress on its load-carrying capacity for bending is examined based on elasto-plastic FEA. The distribution shape introduced in this model is the one obtained in Chapter 4, which considered a three-dimensional stress equilibrium.

(1) Analytical model and its outline

Figure 18 shows an analytical model created considering the characteristics of an intermediate support of an existing bridge. An intermediate support was selected because the maximum plate thickness used in this section of the lower flange was 88 mm. Also, to avoid the influence of local buckling in the analysis, instead of the 30 mm thick vertical stiffener used in existing bridge, a 50 mm thick vertical stiffener was used. Additionally, nodes located in the welding section were stiffly jointed to represent the groove welding between the web and stiffener. Table 3 shows the cross-section dimensions and material properties of the model. Flexural yielding is the final state corresponding to the analytical model. Yielding moment M_y and full plastic moment M_p are 60,370 kN m and 80,264 kN m, respectively.

The analysis software used in this study was Diana

9.4.2. For the analysis, 20-node three-dimensional solid elements (CHX60) were used. Considering symmetry conditions, a half model was created. With respect to elements division, the upper flange was divided into 20 parts in the width direction; lower flange was divided into 22 parts in the width direction; web was divided into 16 parts in the height direction; and two divisions in the thickness direction. In the girder longitudinal direction, girder was divided into 57 divisions. However, in sections where stress variation was big, as the vicinity of loading points and girder ends, elements were subdivided more finely. Additionally, nodes were provided in sections where there was variation in residual stress distribution. The number of nodes and elements in this model were 42,017 and 7,552, respectively.

The stress–strain relationship of structural steel was set up as a bilinear model of a perfect elasto-plastic body. Young's modulus and Poisson ratio were set as 200 GPa and 0.3, respectively. In addition, the steel plate that simulated the loading plate was set up as an elastic body. However, in this study, initial deflection was not considered. In order to evaluate residual stress influence, the plate's initial deflection was not considered in this study.

Two analysis cases were considered in this study:

- Model NR: This case did not consider residual stress distribution.
- Model AC: This case considered residual stress distribution.

From measurement results shown in Fig.17 (c) to

Fig.20 Load-displacement diagram (NR: without residual stress, AC: with residual stress).

Fig.21 Stress counter (Mises stress, Unit: MPa).

17 (e), for 50 mm and 88 mm plate thickness specimens, a modeled residual stress distribution is introduced into flange's top and bottom surfaces. Maximum tension residual stress in the flange's top and bottom surfaces is 0.80 and 0.94 times the yielding point, respectively. In the web plate, a trapezoidal-shaped residual stress distribution, as shown in Fig.19, is assumed³⁾. The σ_{wy} shown in the figure represents web plate yielding stress. In the analysis, this residual stress is introduced to each node as an initial stress, and then the equilibrium is considered. After this, as shown in Fig.18, a uniform displacement δ is given in the girder middle part.

(2) Analysis results

Figure 20 shows a load-displacement diagram for each analysis case. Vertical axis M represents the bending moment at girder center, calculated after the applied load is obtained from the total reaction forces at supports. Horizontal axis δ is the displacement in loading direction corresponding to point D, which is shown in Fig.18. Yielding moment M_y and full plastic moment M_p are shown in the same figure. In

Table 4 Vertical displacement.

Model	δ_y (mm)	δ_p (mm)
NR	16.965	32.962
AC	17.367	36.706

Model NR, M_p becomes the ultimate strength, so it can be said that the analysis model and analytical method are adequate.

Yielding strength in Model AC decreased 0.32% compared with the strength obtained in Model NR. This was due to the residual stress introduced into the model, Model AC yields, and its stiffness was reduced in an early stage compared with that of Model NR. However, this reduction was only a small quantity, and regardless of the presence or absence of residual stress, after reaching the full plastic moment M_p , the deformation continued without decreasing moment M . From the above, it can be said that residual stress distribution influence in load-carrying capacity for bending is small.

Figure 21 shows the Mises stress counter when yielding moment M_y is reached in Model NR and

Fig.A1 Projection onto $\bar{z} = 0$.

Fig.A2 Section at $\bar{x} = \bar{x}$.

Model AC. Then, **Table 4** summarizes the displacements in loading direction δ_y and δ_p when M_y and M_p are reached. From **Table 4**, it is concluded that when residual stress is considered, stiffness is reduced, thus δ_y and δ_p are slightly bigger, although this difference is small.

6. CONCLUSIONS

Recently, as background of rational design of I-shaped girders bridges, there has been a large number of bridges constructed with flange plates thicker than 50mm. Although it is feared that residual stress in thick plates affects the load-carrying capacity of steel girders, the residual stress measurement data are insufficient. Consequently, the load-carrying capacity curve used is based on old data. In this study, a test specimen that simulated the welding section between the main girder web and thick flange was elaborated; residual stress distribution was measured in the flange width and thickness direction. Based on these measurement results and using an elasto-plastic finite element analysis, the influence of residual stress on load-carrying capacity for bending of a steel I-shaped girder was examined. This research can be summarized as follows:

- (1) Influence in welding residual stress due to web height of T-shaped specimen was small compared with the influence due to flange plate thickness.
- (2) For residual stress measurements in flange width direction, there was a discrepancy between measurement results from the flange's top and bottom surfaces when flange plate thickness increased. This discrepancy originated when plate thickness exceeded 30 mm, and when the plate thickness was greater than 50 mm, residual stress

in the flange's bottom surface changed into compressive stress. This means that when flange thickness becomes thicker, welding residual stress is distributed in the plate thickness direction.

- (3) For residual stress measurements in plate thickness direction, it was assumed that the released residual stress resulting from the mechanical cutting procedure reached its maximum value when the specimen was cut in a perpendicular plane to the welding direction; thus, a measurement method with better workability than the method described in Reference 9) was proposed. Based on measurement results, the adequacy of the assumptions made in this study was verified. After comparing both measurements methods, it was confirmed that the tendency of both methods was almost the same.
- (4) It was confirmed that one part of residual stress was released when the T-shaped specimen was cut into small specimens used to measure the residual stress. Thus, using the stress value released due to the cutting procedure, a compensation method was showed.
- (5) A welding residual stress distribution for thick steel flanges was determined based on measurement results, and after considering a three-dimensional equilibrium of stress in the plate width and thickness direction.
- (6) Determined residual stress distribution was introduced into a finite element analysis, where an intermediate support of an existing bridge was modeled. The influence of residual stress on its load-carrying capacity for bending was examined. In this research, it was confirmed that residual stress distribution influence on load-carrying capacity for bending was small. However, only one case was examined, thus, in

Table A1 Characteristic points in **Fig. 17** (Residual stress distribution model, t : plate thickness).

(a) $t = 23$ mm			(b) $t = 30$ mm			(c) $t = 50$ mm		
$\bar{x}$	σ / σ_y		$\bar{x}$	σ / σ_y		$\bar{x}$	σ / σ_y	
	Top	Bottom		Top	Bottom		Top	Bottom
-0.50	0.40	0.40	-0.50	0.37	0.37	-0.50	0.62	0.62
-0.43	-0.10	-0.10	-0.44	-0.09	-0.03	-0.46	-0.11	-0.01
-0.07	-0.10	-0.10	-0.26	-0.07	-0.04	-0.16	-0.11	-0.01
0.00	0.74	0.74	-0.16	-0.06	-0.06	-0.11	-0.04	-0.04
0.07	-0.10	-0.10	-0.11	-0.01	-0.10	-0.06	0.13	-0.09
0.43	-0.10	-0.10	-0.06	0.15	-0.12	0.00	0.80	-0.20
0.50	0.40	0.40	-0.03	0.36	-0.11	0.06	0.13	-0.09
			0.00	0.66	0.10	0.11	-0.04	-0.04
			0.03	0.36	-0.11	0.16	-0.11	-0.01
			0.06	0.15	-0.12	0.46	-0.11	-0.01
			0.11	-0.01	-0.10	0.50	0.62	0.62
			0.16	-0.06	-0.06			
			0.26	-0.07	-0.04			
			0.44	-0.09	-0.03			
			0.50	0.37	0.37			

(d) $t = 70$ mm			(e) $t = 88$ mm		
$\bar{x}$	σ / σ_y		$\bar{x}$	σ / σ_y	
	Top	Bottom		Top	Bottom
-0.50	0.64	0.64	-0.50	0.77	0.77
-0.41	-0.10	-0.10	-0.38	-0.04	-0.25
-0.11	-0.10	-0.10	-0.11	-0.04	-0.25
-0.06	0.05	-0.13	-0.06	0.17	-0.25
0.00	0.97	-0.23	0.00	0.94	-0.32
0.06	0.05	-0.13	0.06	0.17	-0.25
0.11	-0.10	-0.10	0.11	-0.04	-0.25
0.41	-0.10	-0.10	0.38	-0.04	-0.25
0.50	0.64	0.64	0.50	0.77	0.77

the future, it is necessary to accumulate more data.

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APPENDIX

The derived formuladiscussed in Chapter 4, which considers a three-dimensional equilibrium is mentioned. As shown in **Fig.A1**, points σ^+ and σ^- for $\bar{z} = 1$ and $\bar{z} = 0$ planes are connected by a straight line in z -direction, and move along the $\bar{x}_1 \leq \bar{x} \leq \bar{x}_2$ range. The volume surrounded by the surface generated by the straight line, $\bar{z} = 0$ plane, $\bar{z} = 1$ plane and σ/σ_y is calculated.

Straight lines σ^+ and σ^- corresponding to **Fig.A1** can be expressed as:

$$\bar{\sigma}^+ = a^+ \bar{x} + b^+ \quad (1a)$$

$$\bar{\sigma}^- = a^- \bar{x} + b^- \quad (1b)$$

where

$$a^+ = \frac{\bar{\sigma}_2^+ - \bar{\sigma}_1^+}{\bar{x}_2 - \bar{x}_1} \quad (2a)$$

$$b^+ = \bar{\sigma}_2^+ - a^+ \bar{x}_2 \quad (2b)$$

$$a^- = \frac{\bar{\sigma}_2^- - \bar{\sigma}_1^-}{\bar{x}_2 - \bar{x}_1} \quad (2c)$$

$$b^- = \bar{\sigma}_2^- - a^- \bar{x}_2 \quad (2d)$$

Then, the solid body considered in this study is cut in the $\bar{x} = \bar{x}$ plane, and the resulting figure is shown in **Fig.A2**. Here, the gray part represents solid body cross-section. Here, the obtained volume is ex-

pressed as:

$$V = \int_{x_1}^{\bar{x}_2} \left(\int_0^1 \bar{\sigma} d\bar{z} \right) d\bar{x} \quad (3)$$

Then, straight line σ in **Fig.A2** is expressed as:

$$\bar{\sigma} = \left(\bar{\sigma}^+ - \bar{\sigma}^- \right) \bar{z} + \bar{\sigma}^- \quad (4)$$

Therefore, substituting equation (4) into equation (3), and sorting out the terms, the obtained volume can be expressed as:

$$V = \frac{1}{2} \left\{ \frac{1}{2} (a^+ + a^-) (\bar{x}_2^2 - \bar{x}_1^2) + (b^+ + b^-) (\bar{x}_2 - \bar{x}_1) \right\} \quad (5)$$

Using this formula, the volume is determined for each piecewise as shown in **Fig.17**, and the width of the compression stress area is determined when the total volume becomes zero.

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