Title	Experimental Study on Brittle Fracture with Plastic Strain at Cruciform Butt Joints (Report I) : Effect of Properties of Weld Metal(Mechanics, Strength & Structure Design)
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Citation	Transactions of JWRI. 1997, 26(2), p. 81-88
Version Type	VoR
URL	https://doi.org/10.18910/11123
rights	
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Experimental Study on Brittle Fracture with Plastic Strain at Cruciform Butt Joints† (Report I)

−Effect of Properties of Weld Metal−

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Abstract

In The Great Hanshin-Awaji Earthquake Disaster, "the general yield brittle fractures" were observed in beam-column connections of steel building frames. It is considered that the mechanical properties of weld metal have a substantial effect on the fracture.

In this paper we describe bi-axial loading test results using cruciform butt specimens welded by three types of welding consumable. The specimens are modeled on a cruciform joint by taking out the part of the beam-flange to column-flange connection. The purpose of this paper is to examine the effect of the mechanical properties of weld metal on fractures.

The main results are summarized as follows. 1) In the case of the ductile weld metal, it presented a brittle fracture-surface at -40°C but the elongation is equal to or greater than that at room temperature that presented a ductile fracture-surface. But in the case of the ductile weld metal, the elongation fell to less than 1/2 mainly because the brittle fracture occurred after the plastic deformation. 2) The fracture-surface appearance only depends on the specimen temperature and not on the mechanical properties of the weld metal (The mechanical properties mean the absolute values of the elongation in the tensile test and Charpy absorbed energy in this paper). The elongation value in the bi-axial tests tends to become large and the fracture-surface also tends to appear ductile with specimen temperature rising. 3) It follows that the specimen that has the larger Charpy absorbed energy has the larger elongation in the bi-axial test, even if the elongation values by tensile tests are equal.

KEY WORDS: (Damage due to Earthquake) (Steel Structures) (Welded Joints)(Cruciform Joints) (Brittle Fracture)(Bi-axial Loading)

1. Introduction

In The Great Hanshin-Awaji Earthquake Disaster (January 17, 1995, magnitude of 7.2 on the Richter scale), fractures were observed in beam-column connections of steel building frames. In steel buildings, the beam-column connections are usually made by welding. These parts have the largest load, so that they become the most important part in the frame. These fractures are divided two types, either due to insufficient strength or to brittle fracture. The former type was found in comparatively older buildings. It is assumed that these were welded according to the old design standards.

However the latter type of damage occurred in connections welded according to the present design standards. It was ascertained by marks of local buckling, peeling of paint or mill scale and Luders's lines, that these fractured after large deformations. In this context, these are regarded as "general yield brittle fractures", because they fractured at stress concentration points or discontinuous points of shape after absorption of seismic energy. As the fracture was maybe caused by the hardness of metal, so it differs from "the low stress brittle fracture", which hardly absorbs seismic energy. More studies are needed about the influencing factors of general yield brittle fracture and about the energy absorption capacity required for these structures. [1)-5)]

As **Figure 1** shows diagrammatically, typical

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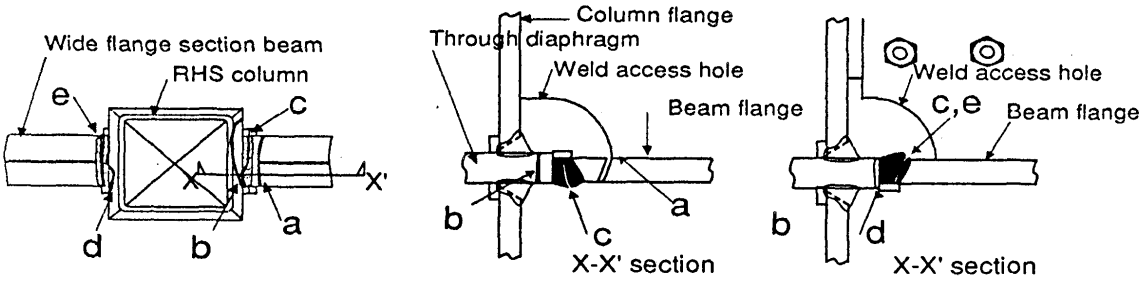
Transactions of JWRI is published by Joining and Welding Reseach Institute of Osaka University, Ibaraki, Osaka 567, Japan.



(a) Shop Welding Type *(b) Site Welding Type*

Fig.1 Typical modes of brittle fracture in beam-column connections[3)]

modes of brittle fracture in beam-column connections are divided as follows.

(Mode-A) Brittle fractures in the base metal at beam-flanges, starting from the toe of the weld access hole (scallop) in the web.(**Fig.2**)

(Mode-B) Brittle fractures in the base metal, heat-affected zone or weld metal of welded connections, starting from the backing strip or the end tab. (**Fig.3**)

It is considered that the mechanical properties of the base metal and the detail of the scallop, the backing strip and the end tab have substantial effects on the Mode-A and Mode-B forms of fracture. It was reported that the plastic deformation capacity of beam-column connections became large following improvement of detail of the scallop.[6)]

As well as the above influencing factors, it can be considered that the mechanical properties of the weld metal have substantial effects in Mode-B. In this paper we describe bi-axial loading test results using cruciform butt specimens welded by three types of welding consumable. The purpose of this paper is to clarify the effect of the mechanical properties of weld metal on fractures.

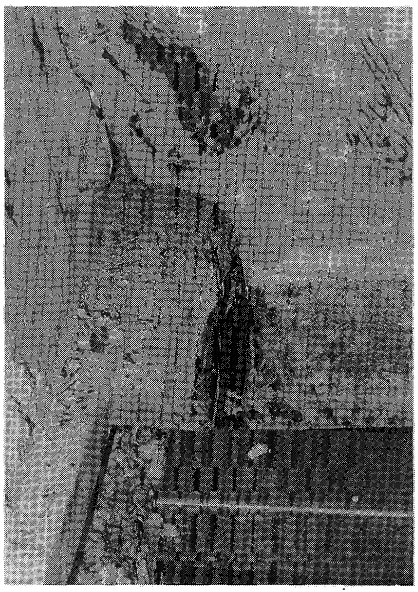


Fig.2 Brittle fracture in base metal from the toe of the scallop[2)]

2. Experimental details

2.1 Shape of the specimen

The specimen for the bi-axial loading test is shaped as shown in **Fig.4** and modeled on a cruciform joint by taking out the part of the beam-flange to column-flange connection. In the specimen, butt welds are at the crossover point of flanges which appears to be the most critical zone for fracture. Single bevel groove and full penetration are used to make the cruciform butt weld. After welding, excess weld metal is removed and the width of the weld part is narrowed from 40mm to 30 mm. Moreover an artificial notch (Width:0.2mm, Depth:2mm) is added in the thickness direction as an initial defect by the electric wire-cut. The detail of weld zone is shown in **Fig.5**.

2.2 Experimental parameters

The mechanical properties of the weld metal and

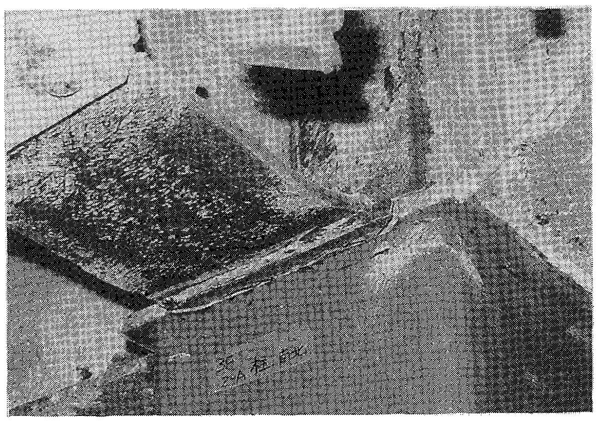


Fig.3 Brittle fracture at heat-affected zone[2)]

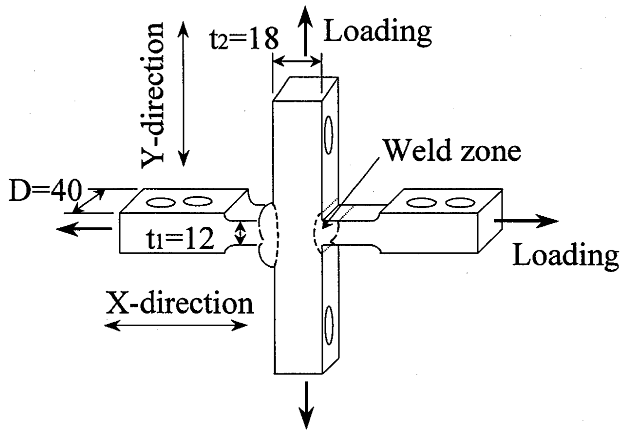


Fig.4 A conception shape of the cruciform butt specimen

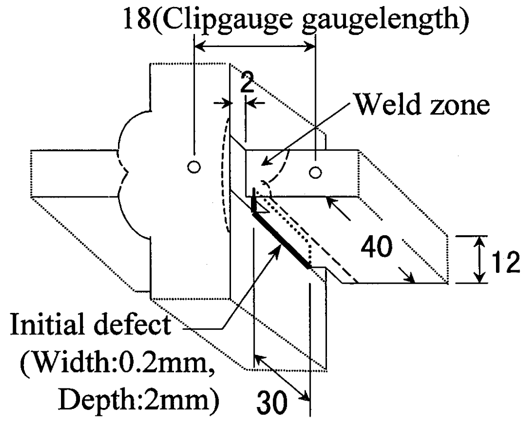


Fig.5 Detail of weld zone and measuring points

temperature of the specimen are varied in this experiment.

2.2.1 The mechanical properties of Weld metals

Three types of weld metal are used in this experiment. The Y-series specimens are welded by CO_2 shielded gas wire (JIS Z 3312 YGW11), the D-series specimens are welded by covered electrode (JIS Z 3211 D4301) and the S-series specimens are welded by self-shielded wire (JIS Z 3313 YFW-S50GX). The minimum value of Charpy observed energy is provided for YGW11 and D4301 (47J at 0°C), but not provided for YFW-S50GX in JIS. (JIS: Japan Industrial Standard)

Table 1, **Figure 6** and **Figure 7** show tensile test results and Charpy impact test results for each weld metal. JIS Z 2201 No.14 test pieces (diameter:10mm) were used for the tensile test and JIS Z 2202 No.4 test pieces for the Charpy impact test. All test pieces were cut from deposited weld metal.

In the results of tensile tests, the Y-series and the D-series show large elongation values (over 30%) whereas the S-series are lower (about 16%). The values of yield and tensile stress increase in the order the S-series, the D-series and the Y-series. In each series, the value of the yield and tensile stress at –40°C becomes about 10% larger than that at room temperature.

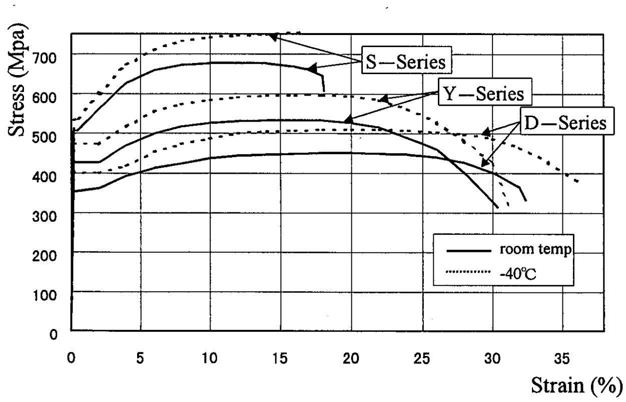


Fig.6 Stress-strain curve by the tensile test

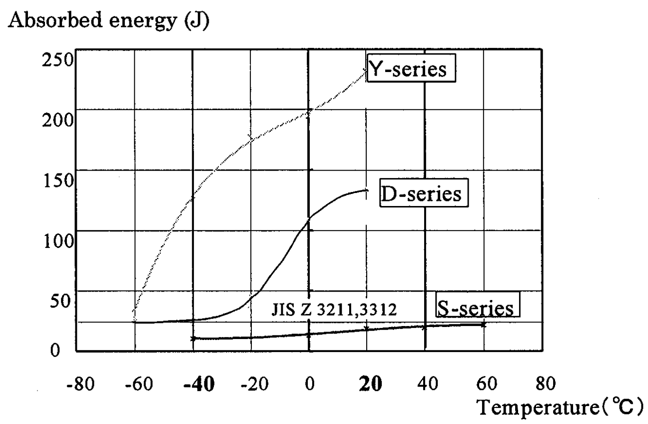


Fig.7 The comparison of Charpy absorbed energy

Table 1 Results of the tensile test and Charpy Impact test

	Tensile test								Charpy impact test Absorbed energy(J)						
	-40℃				Room Temp.										
	σ_y (MPa)	σ_u (MPa)	ε_f (%)	ϕ (%)	σ_y (MPa)	σ_u (MPa)	ε_f (%)	ϕ (%)	-60℃	-40℃	-20℃	0℃	+20℃	+40℃	+60℃
Y-series	483	608	31	70	437	541	31	74	35	126	178	195	232	—	—
D-series	392	504	34	56	343	448	30	59	28	25	46	109	134	—	—
S-series	526	749	16	17	500	683	17	28	—	11	—	13	19	20	22

The Charpy absorbed energies of the Y-series are over 100J, either at room temperature or –40°C. The D-series are over 100J at room temperature but equal to or less than 27J at –40°C. The S-series are less than 27J in all ranges from -40°C to +60°C. The value of 27J is a minimum that is required for steels for welded building structures in JIS.

From these material test results, the mechanical properties of weld metals are summered as follows.

Room Temp. (Lower Temp.)

Y-series

Large (Large) elongation in tensile test
Large (Large) Charpy absorbed energy

D-series

Large (Large) elongation in tensile test
Large (Small) Charpy absorbed energy

S-series

Small (Small) elongation in tensile test
Small (Small) Charpy absorbed energy

2.2.2 Temperature of specimens

Experiments were done at room temperature and lower temperature. The value of the lower temperature was chosen as –40°C from the results of charpy impact test to meet these requirements as follows.

Y-series

absorbed energy at room temp. > 100J
absorbed energy at low temp. > 100J

D-series

absorbed energy at room temp. > 100J

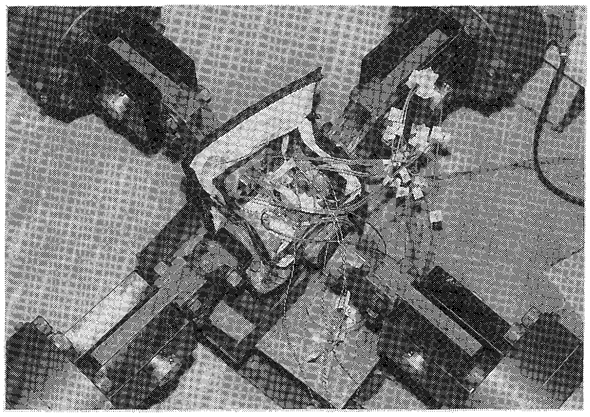


Fig.8 The bi-axial loading machine and a specimen
(examined at lower temperature)

Table 2 Results of bi-axial tensile test (Y-Series)

Specimen No.	Temp. (℃)	Load (kN)		Disp. of clip gauge (mm)		Fracture surface (Brittle surface ratio)	Weld defect
		Max.	Fracture	Max. load	Fracture		
YMR-1	25	200.34	200.01	2.15	2.43	Ductile(0%)	No
YMR-2	25	210.93	209.93	3.01	3.41	Ductile(0%)	No
YML-1	-40	217.96	217.22	3.01	3.85	Brittle(100%)	No

Table 3 Results of bi-axial tensile test (D-Series)

Specimen No.	Temp. (℃)	Load (kN)		Disp. of clip gauge (mm)		Fracture surface (Brittle surface ratio)	Weld defect
		Max.	Fracture	Max. load	Fracture		
DMR-1	25	168.65	168.48	1.08	1.25	Ductile(0%)	Lack of fusion
DMR-2	25	128.75	Max.	1.04	Max.	Ductile(0%)	Lack of penetration
DML-1	-40	198.69	Max.	2.26	Max.	D→B(20%)	No
DML-2	-40	174.77	174.48	1.58	1.71	D→B(50%)	Lack of fusion

Table 4 Results of bi-axial tensile test (S-Series)

Specimen No.	Temp. (℃)	Load (kN)		Disp. of clip gauge (mm)		Fracture surface (Brittle surface ratio)	Weld defect
		Max.	Fracture	Max. load	Fracture		
SMR-1	30	195.92	195.01	1.73	2.08	Ductile(0%)	No
SMR-2	29	187.25	Max.	2.12	Max.	D→B(65%)	No
SM0-1	0	182.66	Max.	1.15	Max.	D→B(90%)	No
SM0-2	0	184.51	Max.	1.74	Max.	D→B(95%)	Lack of penetration
SM2-1	-20	177.04	Max.	0.92	Max.	Brittle(100%)	Lack of fusion
SML-1	-40	169.24	Max.	0.47	Max.	Brittle(100%)	No
SML-2	-40	187.39	Max.	0.94	Max.	Brittle(100%)	No
SML-3	-40	146.65	Max.	0.45	Max.	Brittle(100%)	Lack of penetration

absorbed energy at low temp. ≒ 27J

S-series

absorbed energy at room temp. ≒ 27J

absorbed energy at low temp. < 27J

To further clarify the effect of temperature, S-type specimens were also tested at –20°C and 0°C.

During the low temperature experiments the specimens were cooled by ethyl alcohol and liquid nitrogen kept at -40±2°C, -20±2°C or 0±2°C. Temperatures were measured by two points of thermocouple (C-C type) fixed on the specimen.

2.3 Loading and measuring method

The Bi-axial fatigue machine was used in the experiment. This machine has four jacks and can load in two directions at the same time.

First the specimen is subjected to tensile load (50% of yield strength of base metal) in the Y-direction and kept loaded, then continuously pulled in the X-direction until it fractured. It seems that this condition (stresses in both directions in tension) is the most severe for fracture. This stress condition corresponds to a beam-column connection subjected to the vertical vibration or the tensile force by the overturning moment during earthquake.

The displacements between the gauge-length 18mm, shown in Fig.5, were measured by two clip-gauges fixed to both sides of the specimen.

3. Results and discussion

Table 2-Table 4 show the results of the bi-axial tensile test. At fracture-surface in some of the specimen, weld defects were observed after the test. So in this paper, test results by specimens that have weld defects enough to affect the result are not discussed (hatched in the table).

All specimens fractured immediately after the maximum load but the fracture-surface and the elongation differed between experiments. Three types of fracture-surface, ductile fracture-surface, brittle fracture-surface and intermingled fracture-surface were observed. In the intermingled fracture-surface specimen, it seems that the brittle fracture occurred after developing the ductile crack (D⇒B: ductile ⇒ brittle). In **Fig.9-Fig.12**, symbol ○ means the ductile fracture-surface, ●

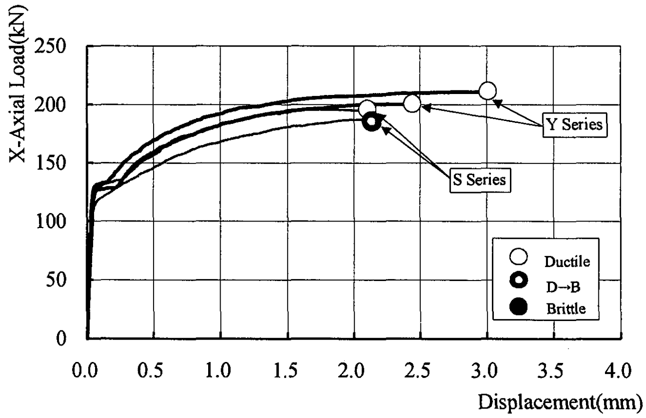


Fig.9 X-axial load-displacement relationship *(Room temp.)*

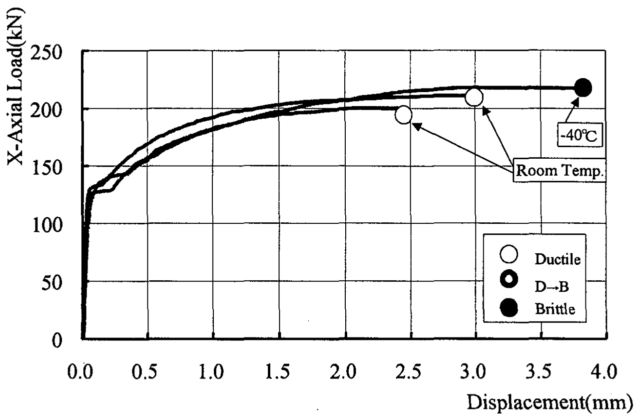


Fig.11 X-axial load-displacement relationship *(Y-series)*

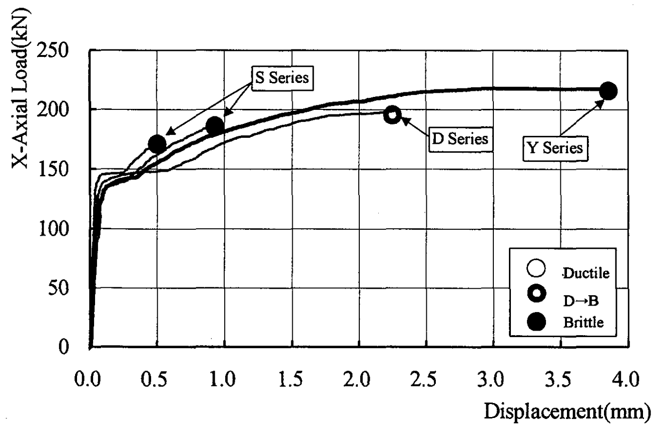


Fig.10 X-axial load-displacement relationship *(-40°C)*

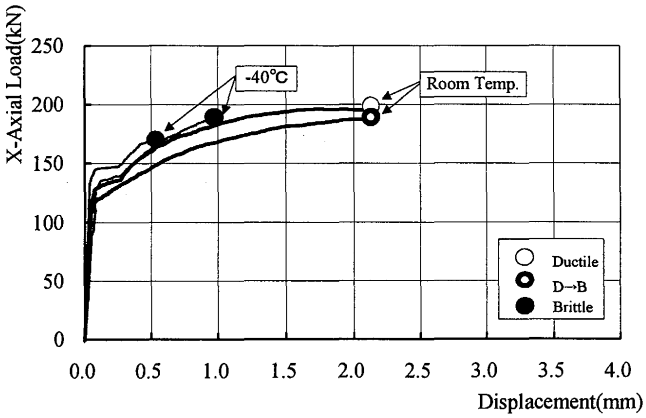


Fig.12 X-axial load-displacement relationship *(S-series)*

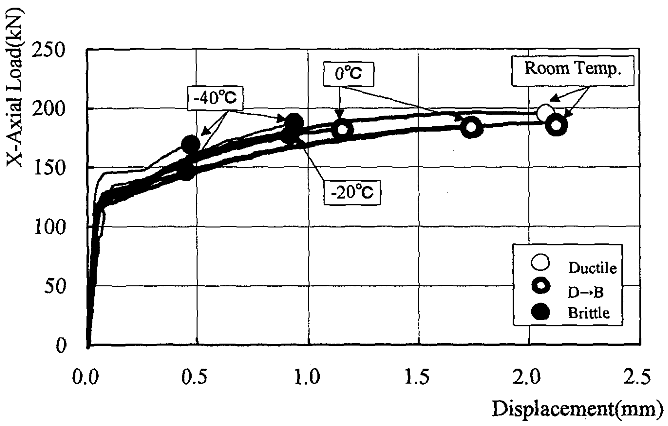


Fig.13 X-axial load-displacement relationship
(S-series, all temp.)

means the brittle fracture-surface and ◎ means the intermingled fracture-surface(D ⇒ B). **Figures 14-16** show the specimens that fractured with a ductile fracture -surface, with a brittle fracture-surface and with a intermingled fracture-surface. In the specimen with ductile fracture-surface, the crack run to 45° of Y-direction from the tip of the initial defect. But in the specimen with brittle fracture-surface, the crack run to the right-angled of Y-direction from the tip of the initial defect.

3.1 Influence of the weld metal

Load-displacement relationships of the Y-series and the S-series in case of the room temperature are shown in **Fig.9** and load-displacement relationships of the Y-series, the D-series and the S-series in case of -40°C are shown in **Fig.10**. The displacement in these figures is the average of two clip-guages' readings.

In the case of room temperature, mainly the ductility fracture-surfaces appeared in both of the S-series and the Y-series. On the other hand, mainly the brittle fracture-surfaces appeared in the case of -40°C.

Also, at room temperature the S-series had the large elongation that is approximately equal to the Y-series. On the other hand, at -40°C the S-series fractured at the small elongation after plastic deformation compared with the Y-series. The D-series had the elongation of the middle of the Y-series and the S-series at -40°C. In the tensile test, the elongation of the weld metal was almost equal in Y-series and D-series, but in the bi-axial test the Y-series had the large elongation than the D-series. It results that the specimen that has the larger Charpy absorbed energy had the larger elongation in the bi-axial test.

3.2 Influence of temperature of the specimen

Figure 11 and **Figure 12** show X-axis load - displacement relationships for the Y-series and the S-series to compare the elongations at room temperature and at -40°C.

In the Y-series, the fracture-surface at -40°C appeared brittle but the elongation is equal to or greater than that at room temperature which showed a ductile fracture-surface. On the other hand, in the S-series, the elongation fell to less than 1/2 mainly because the brittle fracture occurred after the plastic deformation.

In the Y-series, the maximum load at -40°C is bigger than the maximum load at room temperature. This is the same as the result of the tensile test. In the S-series, the maximum loads at -40°C are equal or less than that at room temperature. This seems again because of the brittle fracture occurring after the plastic deformation

Figure 13 shows X-axis load - displacement relationship of the S-series at -40°C, -20°C, 0°C and room temperature. The Charpy absorbed energies differ by only about 10J at all temperatures, the elongation values in the bi-axial tests tend to become large with rising specimen temperature. The fracture-surface also tends appear ductile with rising specimen temperature.

4. Conclusions

In this study the cruciform butt specimens that had initial defects were welded using three types of welding consumable metal and tested under bi-axial continuous load and at several temperatures. The results are summarized as follows.

(1) In the case of the weld metal with the large elongation in the tensile test and large Charpy absorbed energy, it presented a brittle fracture-surface at -40°C, but the elongation in bi-axial test is equal to or more than that at room temperature which presented a ductile fracture-surface. On the other hand in the case of the weld metal with small elongation in the tensile test and small Charpy absorbed energies, the elongation fell to less than 1/2 mainly because the brittle fracture occurred after the plastic deformation. As the Charpy absorbed energies differ only about 10J, the elongation value in the bi-axial tests tends to become large and the fracture-surface also tend to appear ductile as specimen temperature rises.

(2) At room temperature fracture with a ductile fracture-surface occurred, on the other hand at -40°C the fracture had a brittle fracture-surface appearance or the brittle fracture-surface appearance after the ductile crack developing occurred in all specimens. The fracture-surface appearance depends on specimen temperature and not on the properties of the weld metal (The properties mean the elongation

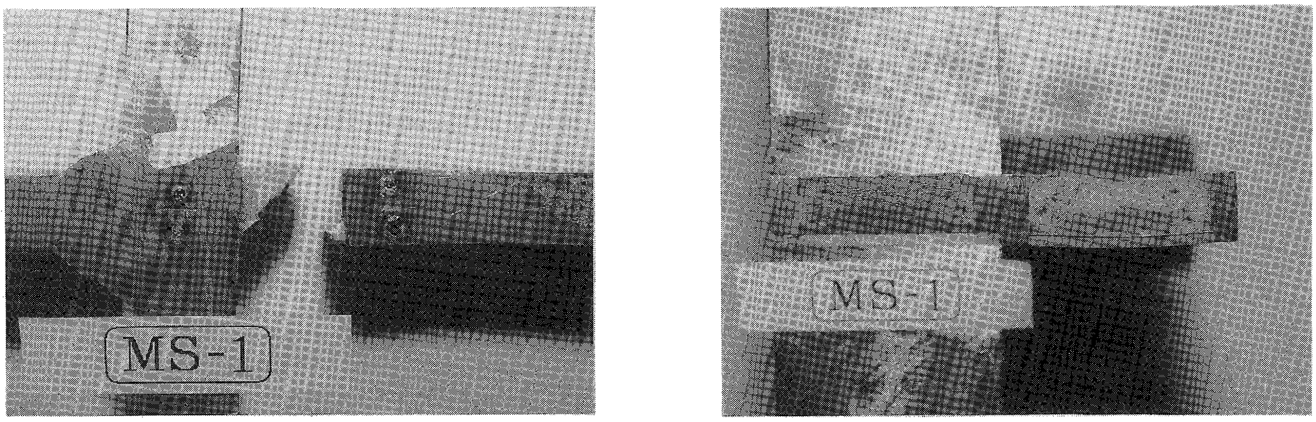


Fig.14 Specimen fractured with ductile fracture-surface

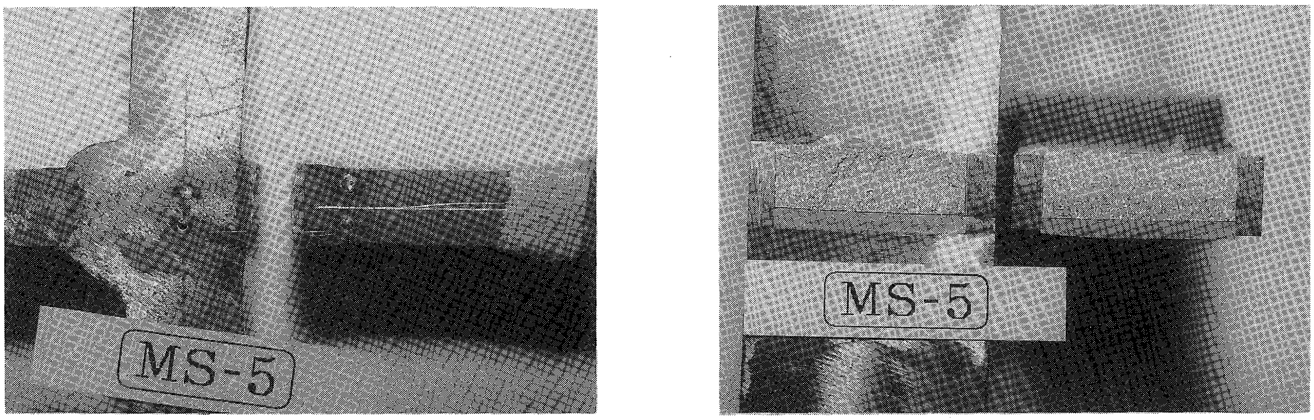


Fig.15 Specimen fractured with brittle fracture-surface

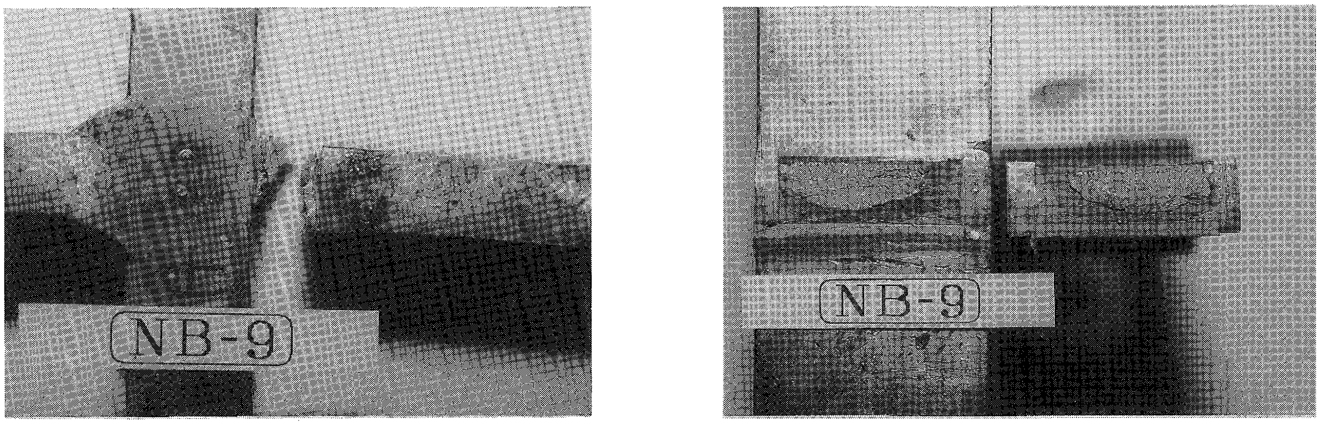


Fig.16 Specimen fractured with intermingled fracture-surface (D → B)

in the tensile test and Charpy absorbed energy).

(3) It follows that the specimen that has the larger Charpy absorbed energy has the larger elongation in the bi-axial test, even if the elongation values by tensile tests are equal.

Acknowledgments.

The author would like to thank Mr. Y.NAKATUJI for his help during the experiments. This study was financially supported in part by the Grant-in-Aid for Eencouragement Reserch (A) from the Ministry of Education, Science and Culture.

Reference

1) M.TOYODA: How Steel Structures Fared in Japan's Great Earthquake, Welding Journal, American Welding Society, December (1995), pp.31-42
2) Committee on Steel Building Structures, The Kinki-Branch of The Architectural Institute of Japan (AIJ): Reconnaissance Report on Damages to Steel Building Structure Observed from the 1995 Hyogoken-Nanbu (Hanshin/Awaji) Earthquake, 1995
3) Japanese Society of Steel Construction (JSSC): KOBE EARTHQUAKE DAMAGE TO STEEL MOMENT CONNECTIONS AND SUGGESTED IMPROVEMENT, JSSC Technical Report, No.39 (1997)
4) K.HORIKAWA and Y.SAKINO: Review of Damage in Welding Joints Caused by The Kobe Earthquake, Trans. of Welding Research Institute of Osaka University (JWRI), Vol.24 (1995), No.2, pp.1-10
5) K.HORIKAWA and Y.SAKINO: Damage due to Steel Structures Caused by the 1995 Kobe Earthquake, Structural Engineering International, J. Int. Ass. for Bridge and Structural Engineering (IABSE), Vol.6(1995), No.3, pp.182-183
6) Committee on Steel Building Structures, The Kinki-Branch of The Architectural Institute of Japan (AIJ): Full-Scale Test on Plastic Rotation Capacity of Steel Wide-Flange Beams Connected with Square Tube Columns, 1997 (in Japanese)
7) Y.SAKINO, K. HORIKAWA and H. KAWAZU: Experimental Study on Brittle Fractures with Plastic Strain at Butt Cruciform Joint: Preprint of the National Meeting of J.W.S., No.61, 1997, pp412-415 (in Japanese)