Mechanical Behaviors of Structural Members Welded under Loading†

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Abstract

In case of repairing or strengthening of a structure in-service condition, welding has to be made on a member under loading.

Some experiments and thermo-elasto-plastic calculations were carried out to analyze mechanical behaviors of structual members under such conditions.

KEY WORDS: (Mechanical Properties) (Residual Stress) (Deformation) (Repair) (Strengthening)

1. Introduction

There are many steel girder bridges in service which suffer damages, such as deformation and crack by increase of vehicle load, and corrosion. To repair the damaged members, we usually try to increase the effective areas of damaged parts, so that splice or cover plates will be furnished. There are two methods to stiffen a damaged member, that is bolt connection and welding. It is pridicted that bolt connection method decreases the net area of member by drilling so that stress condition may be severe. For this reason, field weldings are often adopted for strenghening. This field welding differs from ordinary welding in respect to stress conditions, and contains several unknown factors such as effect to mechanical properties, residual stress and deformation of welded joints.

It is the purpose of this paper to investigate the above mentioned points. First, plates under tensile loading were welded, and tensile specimen and charpy V-notch sub-size specimen were cut off from welded part. Mechanical properties of welded joint and distribution of residual stress are discussed. Then H-shaped beams under bending were welded on tensile and compressive regions respectively to examine their deformation and residual stress. Thermo-elasto-plastic analysis was carried out to the model of plate under tensile loading in order to compare with the experimental results, and stress behavior under welding accompanied by loading is discussed.

2. Experiments

2.1 Plate under tensile loading

2.1.1 Experimental procedure

Four type basic welds were selected in respect to combination of welding and loading conditions, which were shown in Fig. 1, that is;

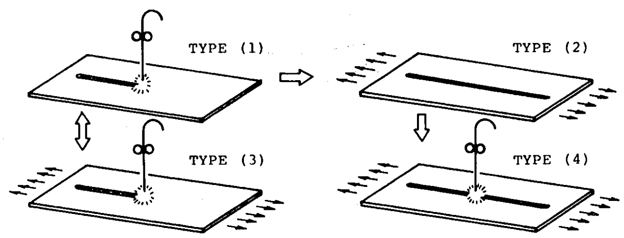

Fig. 1 Combination of Weld and Load

- Type (1) ; As-welded
- Type (2) ; Loaded to allowable tensile stress after welding
- Type (3) ; Welded under loading to allowable tensile stress
- Type (4) ; Welded to as-welded plate under loading to allowable tensile stress

Test plate (150 mm x 300 mm x 6 mm) was SS41 (JIS-G-3101) mild steel with SR-treatment of 620°C. They were welded with micro-wire submerged arc welding. Test plate for mechanical properties specimen was welded in 5 mm x 3 mm trench, that for residual stress measurements was welded as bead-on-plate. Test plates were loaded to 14 kg/mm^2, equivalent to allowable tensile stress, by TRC testing machine which possessed a function of electro-hydro-servo-mechanism, and the load was always kept constant.

2.1.2 Mechanical properties of weld metal

Two tensile specimens and three 2 mm-V-notch charpy sub-size specimens were cut off from each of Type(1)–(4).

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Table 1 Summary of Tensile and Impact Test

TYPE	Yield Stress kg/mm2	Tensile Strength kg/mm2	Elongation %	Reduction of Area %	Ab.Energy at 0°C kg·m	ASTM A-593-72 kg·m (ft·lb)
(1)	(32.7) (31.5) 32.1	(48.2) (47.8) 48.0	(26) (24) 25	(50) (50) 50	(0.95) (1.01) 0.97 (0.95)	1.66 (12)
(2)	(32.2) (32.5) 32.4	(48.4) (49.0) 48.7	(28) (23) 26	(43) (40) 42	(1.26) (1.33) 1.19 (0.98)	2.28 (17)
(3)	(33.9) (33.9) 33.9	(49.4) (49.4) 49.4	(29) (24) 27	(40) (40) 40	(0.95) (1.23) 1.02 (0.89)	1.79 (13)
(4)	(34.7) (34.5) 34.6	(49.1) (48.7) 48.9	(30) (27) 29	(44) (45) 45	(1.39) (1.35) 1.37 (-)	2.70 (20)

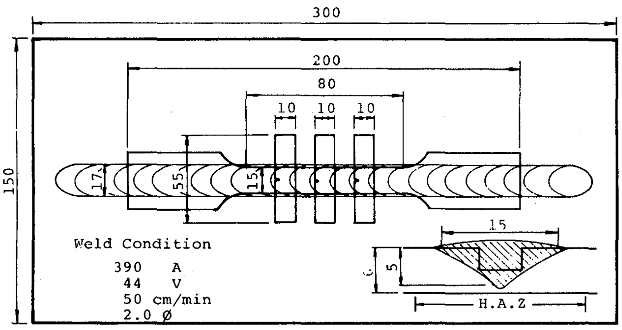


Fig. 2 Picking Position of Specimens

Fig. 2 shows their positions. Table 1 shows summary of test results. Last column of this Table was modified value by ASTM A-593-72. From these results on tensile strength and yield strength, there was little difference between them. Results on charpy absorbed energy scattered a little, but those of Type (2)–(4) are greater than those of Type (1). On Type (4), second welding improved their toughness because of their fine-grained micro-structure.

From a series of these results, it is considered that mechanical properties of weld metal welded under loading are not debased below the original properties.

2.1.3 Residual stress

Residual stresses were messured by the released strain due to slit-like cutting between wire strain gauges (gauge length 2 mm) put on the plate. Fig. 3 shows results of logitudinal residual stresses. In this figure, the result of plate welded under 25 kg/mm^2 is added as Type (5), and yield strength of weld metal and base metal are represented as (W.M) and (B.M) respectively. Out of plane bending moment worked to plate before strain release owing to one side bead-on-plate welding with 50 kg/mm^2 tensile strength welding wire. So that, on obverse the stress indicated sharp peak, while on reverse the peak was dull.

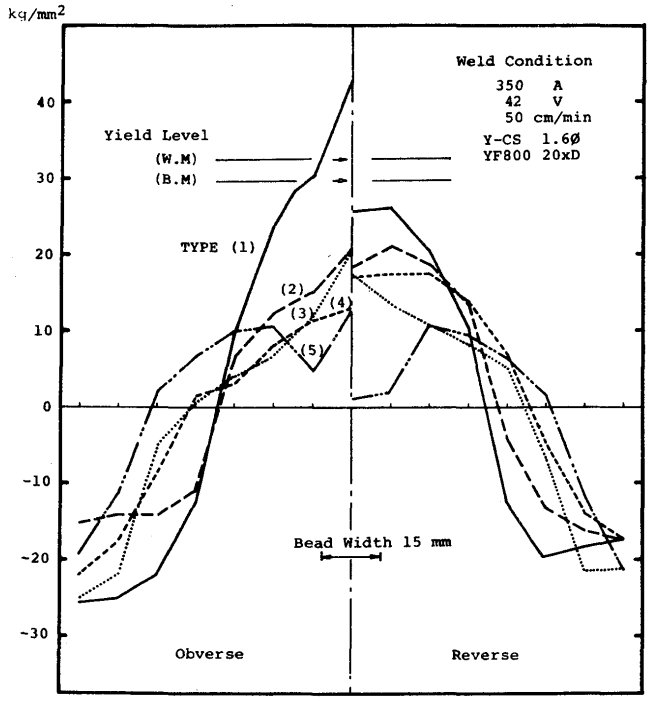


Fig. 3 Ditribution of Residual Stress

However, as to Type (3) which was welded under tensile loading, it was condidered that yield strength of base metal was reduced by weld heat input and plastic elongation by both weld and load grew to some degree so that difference between results of obverse and reverse was smaller than the others. Fig. 4 shows the distributions of averages of obverse and reverse side of each Type. It can be said that applied stress was relaxed in regard to peak stress and that distributions of residual stresses were changed owing to interactions of deduction of yield strength and welding temperature distribution. In the case of Type (5), base plate were generally yielded and elongated to strain hardening region. This was confirmed

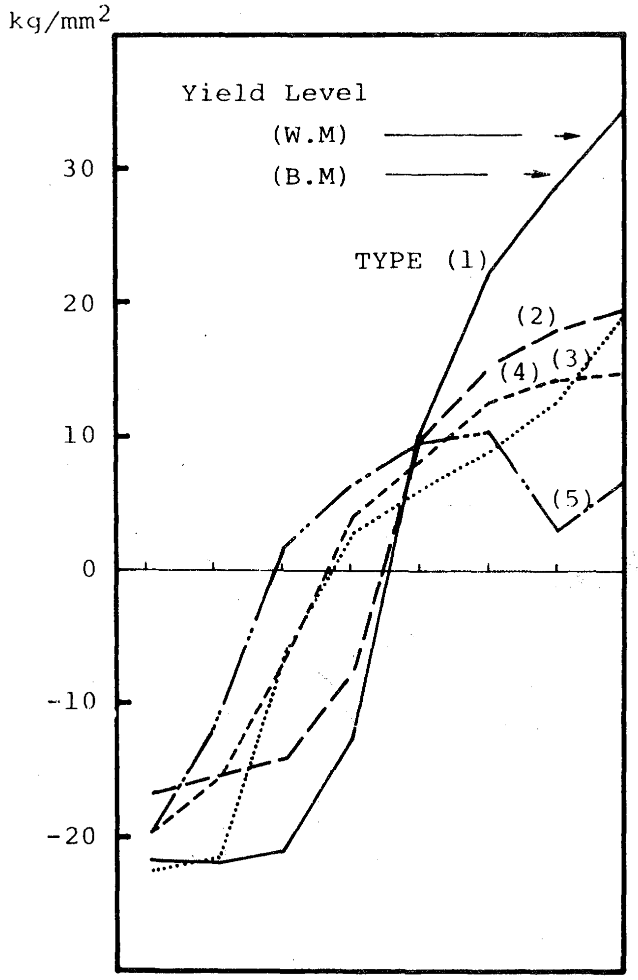


Fig. 4 Distribution of Residual Stress (mean value)

by the fact that total elongation of base plate was reached to 3.5% after weld and residual stress on reverse side had peak of +10 kg/mm^2 apart from bead in spite of zero stress measured near bead. Considering the mechanical properties of weld metal, it is predicted that on the case of welding to loaded plate, at first, base plate deforms to some degree, then weld metal being stressed gradually as it cools down, while elongation of base plate does not effect to mechanical properties of weld metal.

2.2 H-shaped beam under bending

2.2.1 Experimental procedure

Test materials were H-shaped (100 mm x 100 mm x 6 mm x 8 mm, JIS G 3194) SS41 mild steels. Fig. 5 shows experimental procedure and conditions. Beam was loaded to working stress ± 14 kg/mm^2 in both upper and lower flange. Fillet weld or bead-on-plate weld was done to the uniform moment region with micro wire submerged arc welding. Test was carried out by a universal testing machine without servomechanism so that load was kept constnat as possible by manual control of its hydro-valve Small steel balls was set both sides of flange (gauge length 50 mm) before welding, after welding changes of distance of those small balls were read by using contact type strain gauge. Thus strains of both flanges were gotten. Residual stress was gotten by measuring strain release method. Above measurements were carried out to compare welding to tensile flange with welding to compressive flange. Beam was loaded to keep stress constant until all positions of specimen cooled down to room temperature after welding. Second weld was done after unloading. Weld wire of 1.6 mm in diameter was used to low heat input and that of 2.0 mm in diameter to high heat input. Twelve data were gotten to the combination of load and weld conditions.

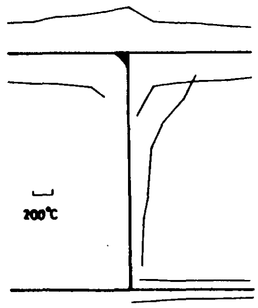
2.2.2 Residual stress and deformation

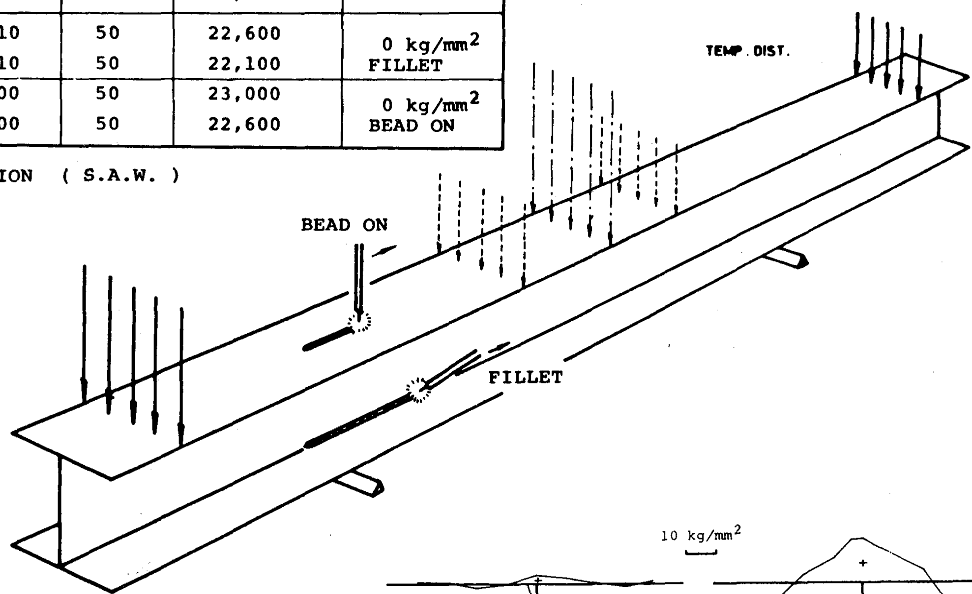
Fig. 6 shows the results of residual stress measurement. In as-rolled beam, the residual stress was so low that stress relief treatment was not done. Residual stress on No. 6, as-welded, distributed to +28 kg/mm^2 as highest value to −18 kg/mm^2 as lowest value. In the case of No. 2', welded on tensile flange under loading, stress equivalent to applied stress +14 kg/mm^2 was relaxed on the bead of tensile flange. On the case of No. 3' which was welded to compressive flange, compressive residual stress equivalent to applied stress −14 kg/mm^2 was also relaxed, on web there was considerable compressive residual stress. On the case of welding to compressive region, thermal expansion was disturbed more strictly than that of welding to tensile region, for this reason residual stress was not relaxed so much.

Fig. 7 shows longitudinal strain of both upper and lower flanges. As strains were distributed uniformly in uniform moment reagion, it was considered average values as representatives. Fig. 7 also contains strain by fillet welding to tensile flange as dotted line because difference between No. 5' and No. 6' was not negligible. Fig. 8 shows strain change according to time sequences which produced strain by load, strain by welding, strain by reduction of yield strength and Young's modulus accompanied with weld heat input. Strain change made the deformation of beam clearly understandable. From these results, it is clear that deformation due to welding to compressive region is much greater than that due to welding to tensile region because strong interactions between inherent shrinkage and reduction of yield strength and Young's modulus.

SPECIMEN	VOLTAGE V	CURRENT A	SPEED cm/min	HEAT INPUT J/cm	STRESS
NO.1	42	285	70	10,300	+14kg/mm² BEAD ON
NO.1'	38	290	75	8,800	
NO.2	49	385	50	22,600	
NO.2'	47	395	50	22,300	
NO.3	46	400	50	22,100	-14kg/mm² FILLET
NO.3'	45	410	50	22,100	
NO.4	38	290	70	9,400	
NO.4'	36	290	70	8,900	
NO.5	46	410	50	22,600	0 kg/mm² FILLET
NO.5'	45	410	50	22,100	
NO.6	48	400	50	23,000	0 kg/mm² BEAD ON
NO.6'	47	400	50	22,600	

WELDING CONDITION (S.A.W.)





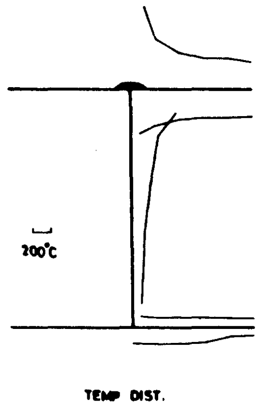


Fig. 5 Experimental procedure and condition

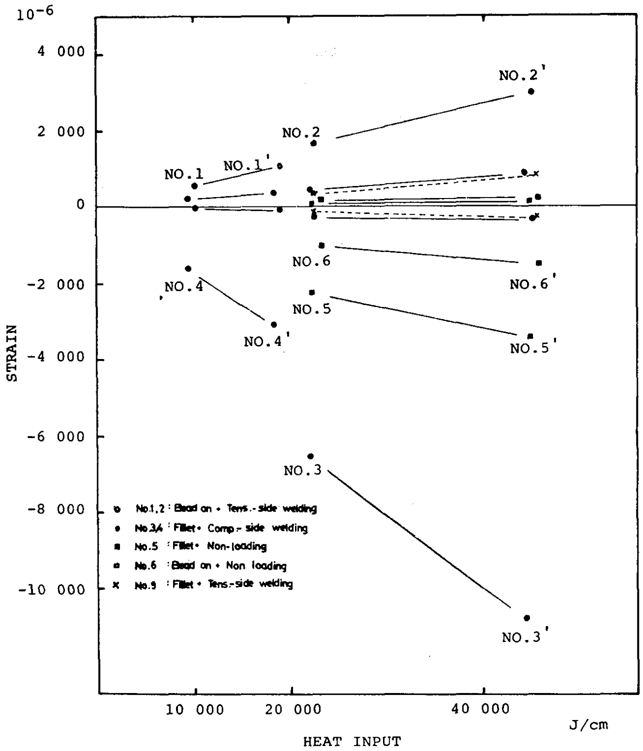


Fig. 7 Strain of upper and lower flanges after welding

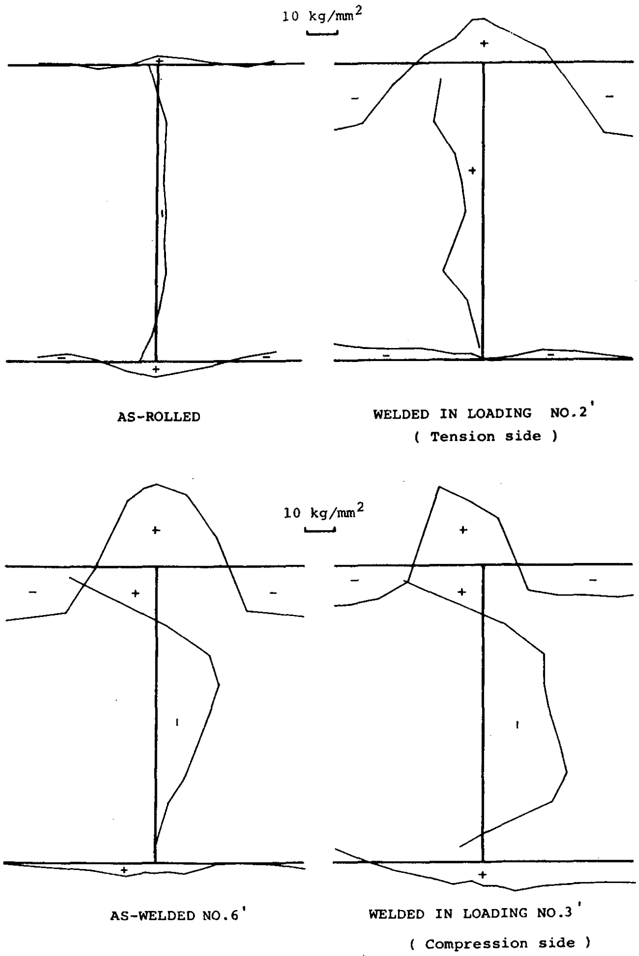


Fig. 6 Distribution of Residual Stress

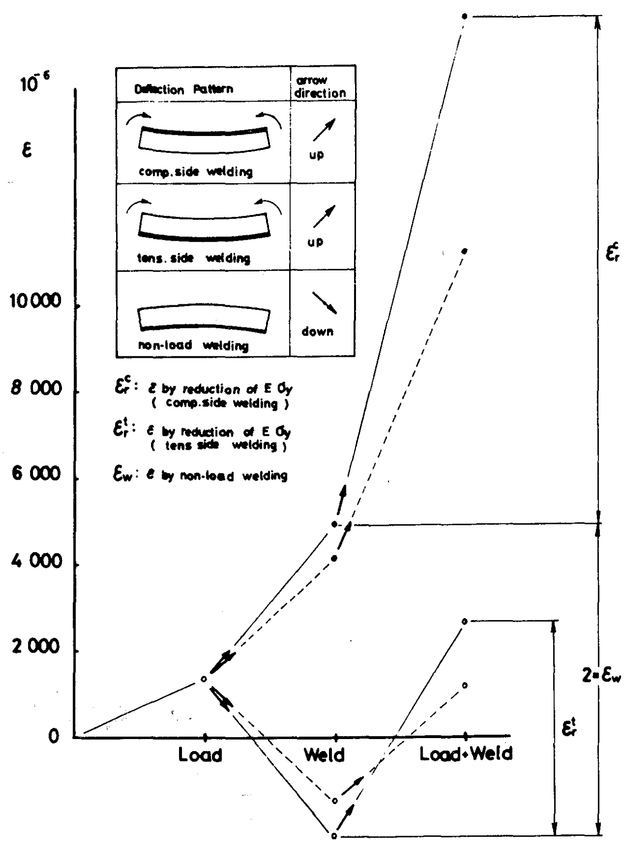


Fig. 8 Strain change by load, weld and reduction of "E", "σ_y"

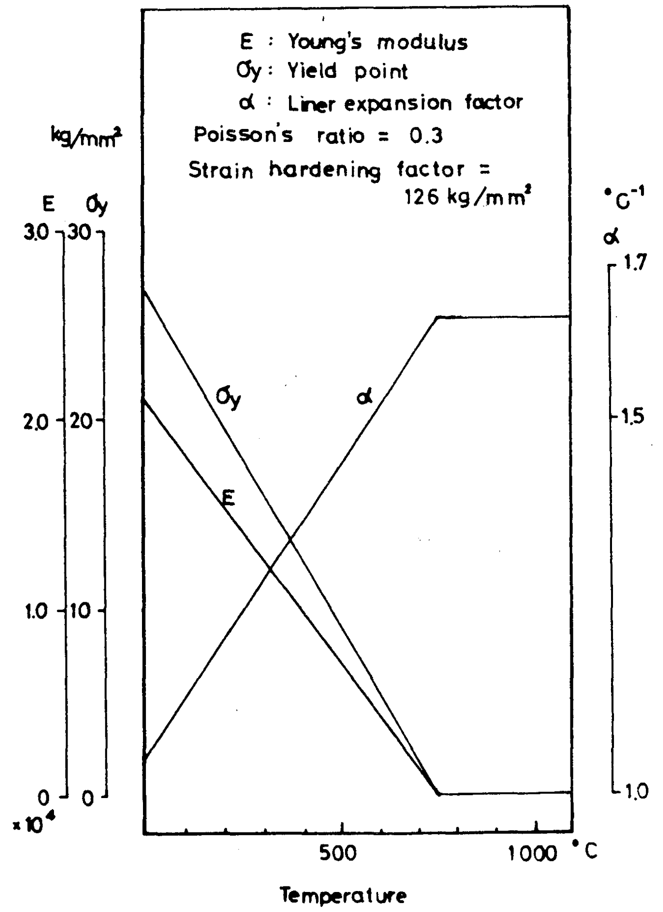


Fig. 10 Material Properties

3. Thermo-elasto-plastic calculations

3.1 Calculation method

Thermo-elasto-plastic calculation with finite element method was carried out to investigate transitional behaviors concerning the welding under tensile loading. In thermo-elasto-plastic calculation, momentary line heat source was assumed to welding area so that thermal distribution on plate was gotten by heat conduction theory. Fig. 9 shows finite element's mesh of the model. Material properties were assumed as Fig. 10. By coupling heat conduction theory with elasto-plastic theory, residual stress on the plate was computed. In this numerical computation, uniform displacement was forced to the edge of model to produce the longitudinal stress of 14 kg/mm^2, equivalent to allowable tensile stress for bridges.

3.2 Discussions

Fig. 11 shows the calculated stress distribution of residual stress with experimental results. They show good coincidence. It can be seen that elastic strain was released uniformly over the cross section by unloading. Fig. 12 shows the process that stress and yield strength change after welding. In welded beads zone it was always yielded. At the position of 18 mm apart from welded beads center, the stress decreased from applied stress (14 kg/mm^2) to

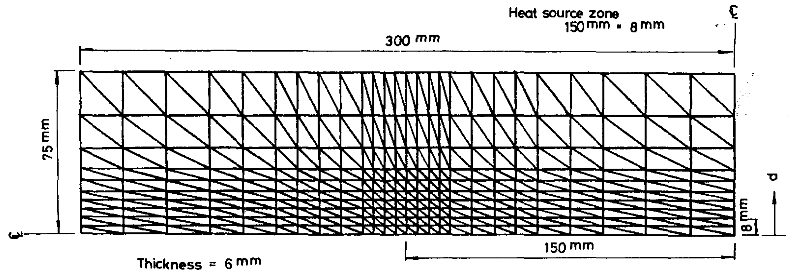
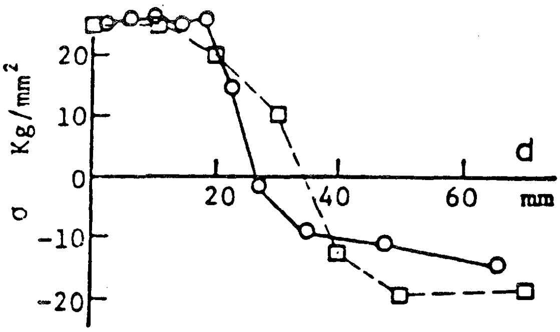
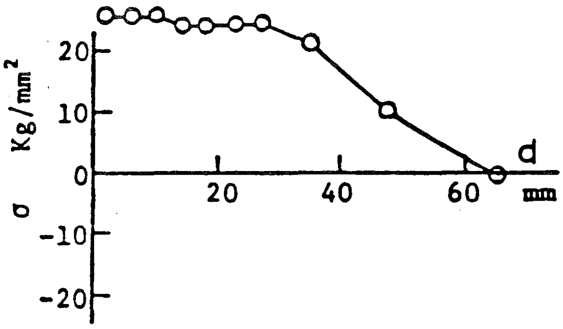


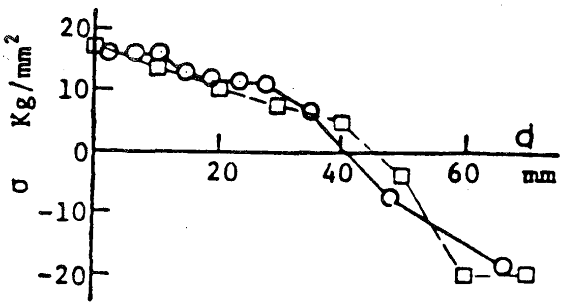
Fig. 9 Mesh Divisions



(a) as-welded



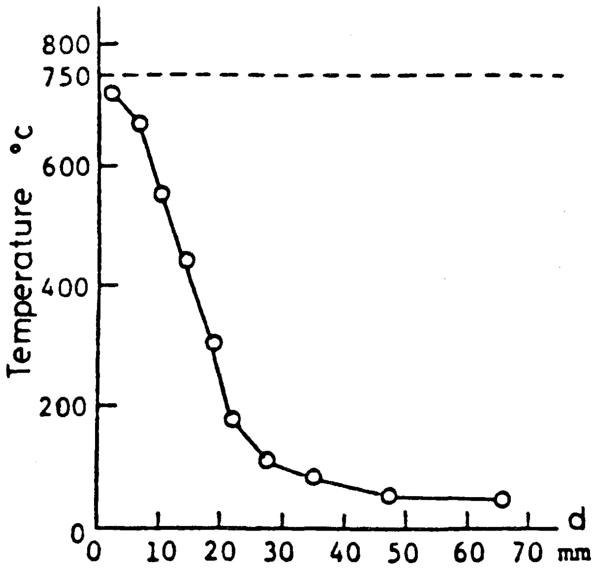
(b) after weld under load



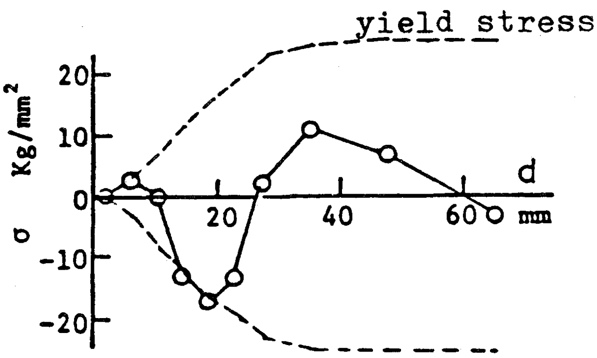
(c) unload after weld

—□— experiment
—○— analysis

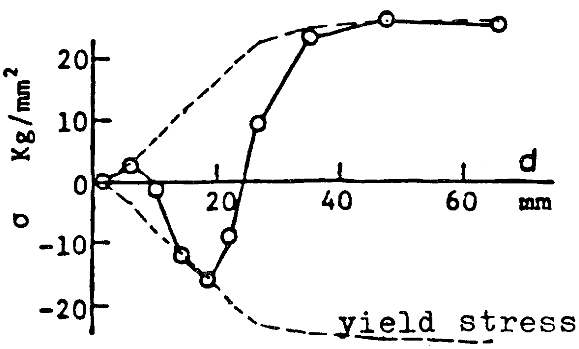
Fig. 11 Distribution of Residual Stress



(a) Temperature



(b) non-loading



(c) loading

Fig. 13 Temperature and Stress after weld 8.7 seconds past

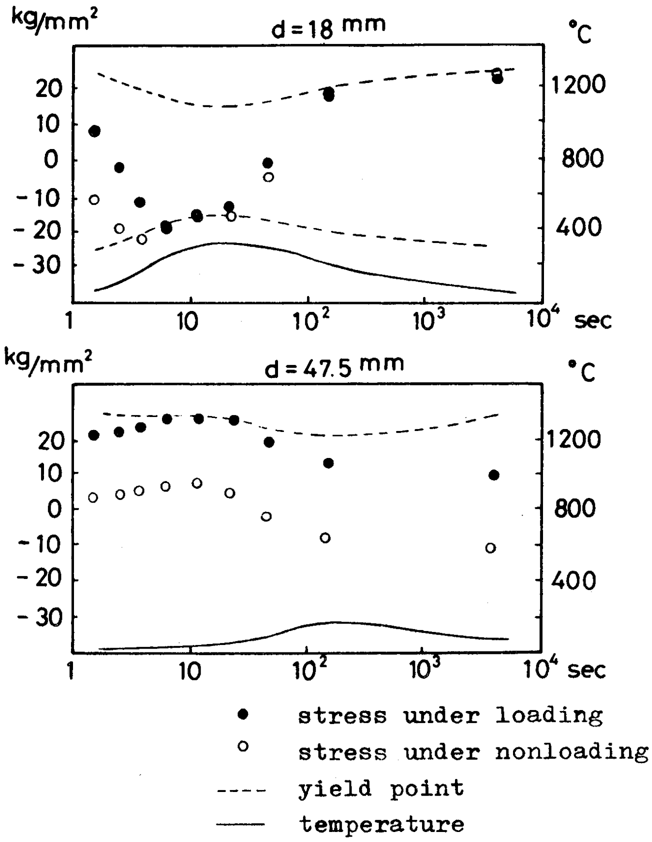


Fig. 12 Stress Change after Heating

compressive yield point abruptly and reversed to tensile gradually, following the tensile yield strength's path to lead to 24 kg/mm^2 at the end. After compressive yielding, it did not differ from the case of non-loading. At the position of 47.5 mm apart from welded beads center, the stress increased to 25 kg/mm^2 and the decreased to 10 kg/mm^2. There might be a period that side edge was over stressed for stress redistribution. Fig. 13 shows temprature and stress in plate 8.7 seconds after welding. In case of non-loading, about 15% of the plate was yielded, while in the case of loading, about 60% of plate was yielded. This means that the area of yielded region of the plate welded under loading is larger than that of welded without loading.

4. Summary

The effects of welding to loaded members were studied on mechanical properties, residual stress and deformation with experiments and numerical calculations. The results are summarised as follows;

(1) Mechanical properties, such as yield strength, tensile strength and charpy absorbed energy, are not debased by welding.

(2) Residual stress is reduced by the amount of applied stress by unloading.

(3) Deformation by welding to compressive member is large, so it will not be recommendable to weld compressive members.

(4) In case of welding to tensile member the area of yielded region become larger for transitional stress redistribution.

In conclusion it can be said that one must be careful of residual stress for welding to tensile members and of deformation for welding to compressive members.

Acknowledgement

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