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Acceptable Size of Weld Defect in Steel Buildings

Tolérances dans les défauts de soudure d'ossatures métalliques

Zulässiges Ausmass von Schweissfehlern bei Bauwerken aus Stahl

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SUMMARY

The important factors which reduce the maximum strength of welded joints involving defects are determined by factorial experiments, and the regression equations for the maximum strength of cross and butt joints are derived as a function of these factors. Finally, a method for estimating the acceptable size of weld defect is proposed for both joints.

RÉSUMÉ

L'expérience laisse apparaitre les principaux facteurs influençant la résistance maximale des connections soudées présentant quelques défauts. Une formule donnant la résistance extrême des assemblages bout à bout et perpendiculaires est établie à l'aide de ces facteurs. Une méthode d'estimation des tolérances acceptables pour les défauts de soudure est proposée pour de tels assemblages.

ZUSAMMENFASSUNG

Der vorliegende Bericht beschreibt die wesentlichen Faktoren, die die Festigkeit von fehlerhaften Schweissnähten herabsetzen und stützt sich dabei auf systematisch angelegte Versuche und eine statistische Auswertung der Resultate. Auf dieser Grundlage wird eine Methode zur Abschätzung des zulässigen Ausmasses von Schweissfehlern bei Stumpf- und Stirnnähten vorgeschlagen.

1. INTRODUCTION

The main design force on steel buildings is quasi-static one such as seismic force and wind force. In order to estimate the maximum strength and the deformation capacity of joints involving weld defects subjected to quasi-static load, various factors such as the kind, location and dimensions of weld defect, the type and dimensions of the joints,the loading condition etc. should be considered.

In this paper, the influential factors are selected statistically by the factorial experiments (1) and then the regression equations estimating the maximum strength of cross and butt joints are obtained as a function of these influential parameters using the test results hitherto reported in Japan (2,3,4). And the acceptable size of weld defect is discussed for both joints.

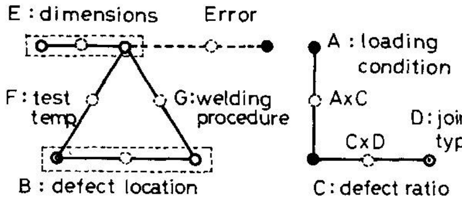
2. FACTORIAL EXPERIMENTS

2.1 Test Series I

2.1.1 Test Scheme

The experimental factors and the layout of the specimens into L 16 Orthogonal Array are shown in Fig. 1. The levels of the factors are as following;

- Loading Condition (A); The monotonic loading (Level 1) and the incremental cyclic reversal loading (Level 2) reflecting the severe earthquake condition, are adopted. The loading scheme of the latter is shown in Fig. 2.
- Defect Location (B); The defect kind is limited to lack-of-penetration defect and 4 levels shown in Fig. 1 are selected.
- Defect Ratio (C); The designed ratio of the nominal defective area to the gross sectional area is 3% (Level 1) and 6% (Level 2). The defect ratio is designed by varying the defect length, while the defect height is fixed to 20% of the thickness of the specimens.
- Joint Type (D); The cross joint (Level 1) and the butt joint (Level 2) are adopted as shown in Fig. 3.
- Dimensions of the Specimen (E); 4 levels are selected as shown in Fig. 1 considering the thickness of beam flange practically used.
- Test Temperature (F); Room temperature of about 293K (Level 1) and low temperature of 253K (Level 2) considering the cold region in Japan are adopted.
- Welding Procedure (G); CO_2 arc semi-automatic welding (Level 1) and manual arc welding (Level 2) which are usually used are adopted. Low alloy high strength steel which is designated as SM50 (specified minimum tensile strength by JIS is ${}_{b}\sigma_{ST} = 490\,N/mm^2$) is used for the base metal.



Levels of B and E (mm)

Level	1	2	3	4
B				
E (T)	12	19	25	32
E (W)	120	152	150	128

Fig. 1 Design of Experiment (Test Series I)

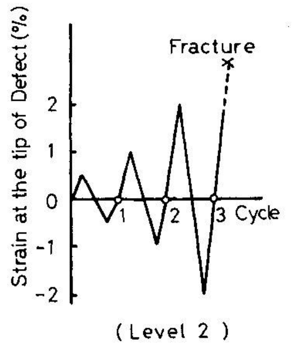


Fig. 2 Loading Condition

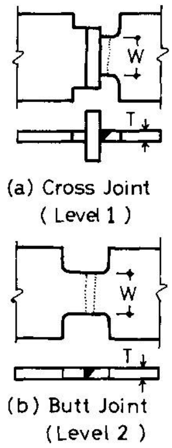


Fig. 3 Joint Type

2.1.2 Test Results

As the characteristic values for the maximum strength and deformation capacity of the joints, the following indexes are considered.

$$\frac{\sigma_B}{{}_b\sigma_B} = \frac{\text{nominal maximum stress of the specimen}}{\text{actual tensile strength of base metal at test temperature}}$$

$$\frac{{}_dEl_u}{{}_bEl} = \frac{\text{uniform percentage elongation at the maximum strength of the specimen}}{\text{percentage elongation of base metal at test temperature}}$$

As for the uniform percentage elongation of the specimens loaded by incremental cyclic reversal loading, the accumulated ones obtained by the method shown in Fig. 4 are adopted.

The results of the analysis of variance for the maximum strength index $\sigma_B/{}_b\sigma_B$ and the deformation capacity index ${}_dEl_u/{}_bEl$ are shown in Table 1 and the followings can be seen from this table.

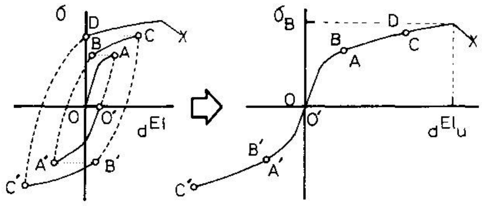


Fig. 4 Accumulating Method

- Maximum Strength
The contribution of the dimensions of the specimen is large and this factor is significant by 1% level. As seen in the result of point estimation shown in Fig. 5 a), the maximum strength shows a tendency to decrease as the dimensions of the specimen increases except for the case of Level 1 (T=12mm). This exception can be attributed to the fact that the specimens of Level 1 have buckled at compression side of loading. Although the defect location is significant by 5% level, a clear tendency cannot be seen. The maximum strength will be not influenced by the defect ratio of 3% to 6% range, though it can not be concluded definitely since the contribution ratio of the interaction is rather large.

	$\sigma_B/{}_b\sigma_B$	${}_dEl_u/{}_bEl$
A	-	-
B	11.9*	5.3
C	5.6	-
D	4.8	22.7*
E	38.1**	23.4
F	-	-
G	-	-
A×C	10.0	-
C×D	21.0	12.1
Er.	8.6	36.5

* : Significant (5% Level)
** : Significant (1% Level)
Er.: Error Term

Table 1 Contribution Ratio (Test Series I)

The contribution of the loading condition, the test temperature and the welding procedure can be negligible.

- Deformation Capacity
The contribution of the dimensions of the specimen and the joint type is large, and the latter factor is significant by 5% level. The results of point estimation of these factors are shown in Fig. 5 b) and c). As for the dimensions of the specimen, the deformation capacity decreases largely at Level 4 (T=32mm), and the effect of the difference of the joint type is also large. But the contribution of other factors is almost negligible.

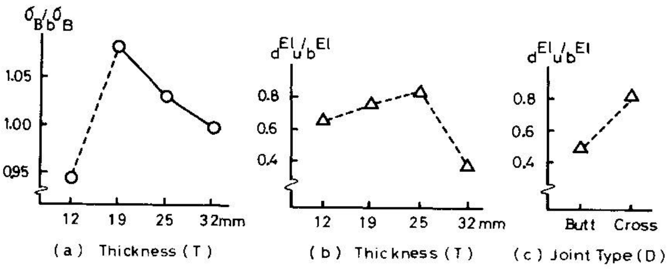


Fig. 5 Point Estimation for Influential Factors (Test Series I)

2.2 Test Series II

2.2.1 Test Scheme

The factors which are found to be necessary to research further from the results of the analysis of variance of Test Series I are as following;
- Defect Location (B); The defect kind is also limited to lack-of-penetration defect and 4 levels shown in Table 2 are selected laying emphasis on the cases of defects at the edge of plates.

- Defect Ratio (C); The levels in this series are 6% (Level 1) and 9% (Level 2). Reflecting on the results of Test Series I, the larger defect ratios are selected. The defect height is fixed to 5mm for T=19mm and 8mm for T=32mm.
- Joint Type (D); The cross joint (Level 1) and the butt joint (Level 2) are adopted again laying emphasis on the former.
- Dimensions of the Specimen(T,W); This factor is divided into two factors, i.e., the plate thickness(T) and the width(W) of the specimen. Two levels of these factors are T=19mm (Level 1), 32mm (Level 2) and W=100mm (Level 1), 300mm (level 2) respectively.
- Steel Grade (M); This factor is added in this series. The levels are SM50 (Level 1) and quenched and tempered high strength steel designated as SM58 whose ${}_{b}\sigma_{ST}$ is 568.4N/mm^2 (Level 2).

As for the factors whose contribution is small in Test Series I, the level is fixed to single, i.e., A=monotonic loading, F=room temperature, and, G= CO_2 arc semi-automatic welding. The layout of the specimens into L8 Orthogonal Array is shown in Table 2. This series consists of five subseries, but, the specimens are only 20 in number because another subseries can be constructed by changing half specimens of one subseries.

(a) Level of Factors

No.	B	C	D	M	T	W
1	1	1	1	1	1	1
2	4	2	1	2	1	1
3	1	1	1	2	1	2
4	4	2	1	1	1	2
5	1	2	1	1	2	1
6	4	1	1	2	2	1
7	1	2	1	2	2	2
8	4	1	1	1	2	2
9	4	2	2	1	1	1
10	1	1	2	1	1	2
11	4	1	2	1	2	1
12	1	2	2	1	2	2
13	2	1	1	1	1	1
14	2	1	1	2	1	2
15	2	2	1	1	2	1
16	2	2	1	2	2	2
17	3	2	1	2	1	1
18	3	2	1	1	1	2
19	3	1	1	2	2	1
20	3	1	1	1	2	2

(b) Layout of the Specimen

	Subseries (Sub.) (1)	(2)	(3)	(4)	(5)
Specimen No. 1	1	13	1	13	1
2	2	2	17	17	9
3	3	14	3	14	10
4	4	4	18	18	4
5	5	15	5	15	5
6	6	6	19	19	11
7	7	16	7	16	12
8	8	8	20	20	8

(c) Levels of Factor B

1	2	3	4

Remarks

Sub.	(1) - (4)	(5)
Level	D = 1	M = 1

Table 2 Design of Experiment (Test Series II)

2.2.2 Test Results

The results of the analysis of variance for the maximum strength index $\sigma_B/{}_{b}\sigma_B$ and the deformation capacity index ${}_{d}El_u/{}_{b}El$ are shown in Table 3 and the followings can be observed from this table.

- Maximum Strength
The contribution of the defect location is large in Subseries (1) and (3), but, negligible in Subseries (2) and (4) in case of cross joints. As seen in the results of point estimation of these subseries shown in Fig. 6 a), the effect

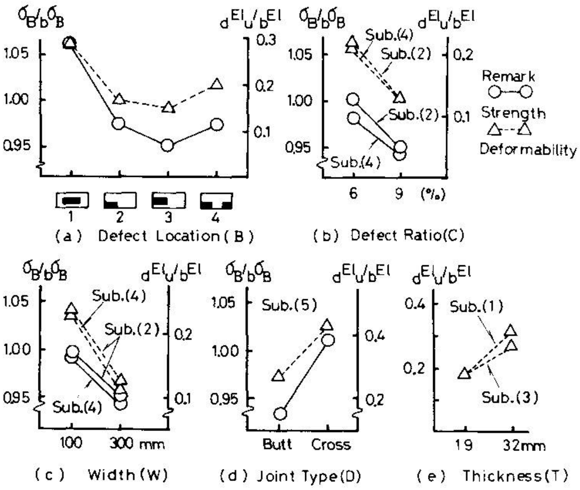


Fig. 6 Point Estimation for Influential Factors (Test Series II)

(a) Maximum Strength ($\sigma_B/{}_{b}\sigma_B$)

Sub.	(1)	(2)	(3)	(4)	Sub.	(5)
B	79.6**	-	92.1**	-	B	-
C	5.1	44.2*	-	21.5	C	-
M	-	-	-	-	D	32.2*
T	-	-	-	14.4	T	-
W	4.8	34.2*	-	21.5	W	46.4*
TxW	-	-	-	7.4	TxW	-
Er.	10.5	21.6	7.9	35.2	Er.	21.4

(b) Deformation Capacity (${}_{d}El_u/{}_{b}El$)

Sub.	(1)	(2)	(3)	(4)	Sub.	(5)
B	21.4	-	45.9*	-	B	-
C	-	18.5	-	17.1	C	-
M	-	23.5	-	4.7	D	-
T	46.9*	-	14.7	-	T	16.4
W	-	27.0	12.0	44.9*	W	63.7*
TxW	-	-	-	2.3	TxW	-
Er.	31.7	31.0	27.4	31.0	Er.	19.9

Table 3 Contribution Ratio (Test Series II)

of the edge defect is larger than that of the center one, but the effect of the defect location in the direction of thickness can be negligible. In case of butt joints, the effect of the defect location is indicated to be negligible by the results of Subseries(5).

From the results of Subseries (2) and (4) which consist of the specimens of cross joints and their defect location is at edge, the followings can be observed. The contribution of the defect ratio and the width of the specimens is large, and the maximum strength of the joints decreases with the increase of the defect ratio and the width of the specimens as seen in Fig. 6 b) and c).

The contribution of the joint type is large in case of Subseries (5). As seen in the results of point estimation (Fig.6 d)), the deterioration of the maximum strength of cross joints is smaller than that of butt joints. As for the steel grade, the contribution seems to be negligible throughout all subseries.

- Deformation Capacity

In case of cross joints, the contribution of the defect location, the defect ratio and the width of the specimens is large, and their results of point estimation are shown in Fig. 6 a),b) and c). Although the contribution of the joint type is non significant, the deformation capacity of cross joints is larger than that of butt joints as seen in Fig. 6 d). From above results, the deformation capacity correlates with the maximum strength when the joints are fractured in ductile manner.

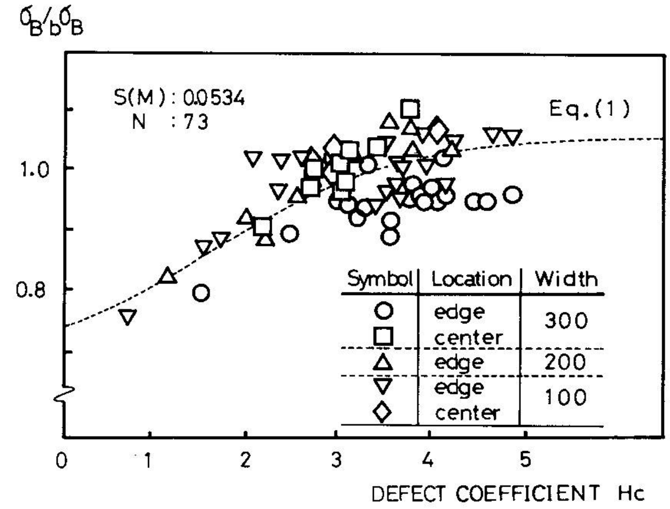


Fig. 7 $\sigma_B/{}_b\sigma_B$ versus H_c Relationship for Cross Joints

3. ESTIMATION OF THE ACCEPTABLE SIZE OF WELD DEFECT

3.1 Estimation of the Maximum Strength of the Joints Involving Weld Defect

3.1.1 The Maximum Strength of Cross Joints

- Regression Equation for the Maximum Strength of Cross Joints:

From the results of the experiments hitherto reported (2,3) and of the experiments in Chapter 2 whose welding procedure is CO_2 arc semi-automatic welding or manual arc welding, steel grade is SM50 or SM58, and, defect kind is lack-of-penetration, the regression equation for the maximum strength is obtained by the method of least squares as

$$M_c = \sigma_B/{}_b\sigma_B = (1.06\, e^{H_c} + 3.6)/(e^{H_c} + 5.4). \quad \ldots (1)$$

Where, $H_c = 1.3 \ln((W/l_s)^{0.7} \times (T/h_s)^{1.4})$ is the defect coefficient for cross joints, ls is the defect length measured from the fracture surface after testing, hs is the defect height measured. The ranges of the experiments are $0.1 \leqq l_s/W \leqq 0.76$ and $0.16 \leqq h_s/T \leqq 1.0$.

The relationship between the test results and the regression equation is shown in Fig. 7. As seen in this figure, the deterioration of the maximum strength of the joints whose width is W=300mm and defect location is edge is somewhat larger compared with that of other joints. This result coincides with the result of the factorial experiments.

- Other kind of defect and other welding procedure

a) Crack Defect

In the experiment(1), crack defect is induced in the weldment. The test results $\sigma_B/{}_b\sigma_B$ are shown in Fig. 8 by the marks **O** .

As seen in this figure, the deterioration of the maximum strength is larger compared with the case of lack-of-penetration defect. The crack defect of this experiment is hot crack induced naturally by welding the joint in high restraint as shown in Fig. 9 a). The procedure of making lack-of-penetration defect is as follows. After providing the special edge preparation which has a projection with specified size as seen in Fig. 9 b), groove welding is excuted.

b) Self-shielded Arc Semi-automatic Welding

The test results $\sigma_B/{}_b\sigma_B$ of the specimens of this welding procedure are shown in Fig. 8 by the marks □ and ■. The specimens marked with □ were fractured in ductile manner, while the specimens marked with ■ were fractured in brittle manner.

As seen in this figure, the deterioration of the maximum strength is remarkable compared with that of other welding procedures. This can be attributed to the poor toughness of weldment obtained by this welding procedure (3).

So, these cases should be regarded as out of scope.

3.1.2 The Maximum Strength of Butt Joints

- Regression Equation for the Maximum Strength of Butt Joints: From the results of the experiments hitherto reported (4) whose welding procedure is CO_2 arc semi-automatic welding or manual arc welding, the regression equation for the maximum strength is obtained by the method of least squares as

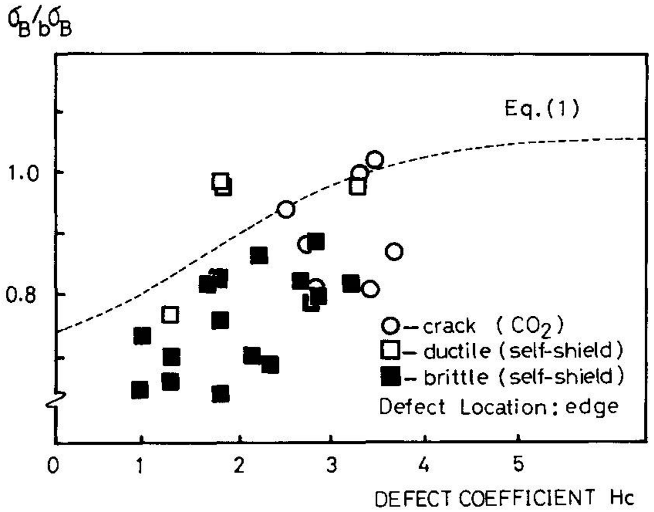
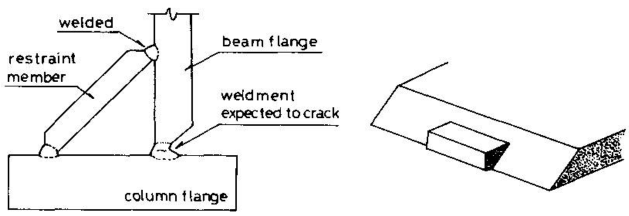


Fig. 8 Test Results of Cross Joints



(a) Crack Defect (b) Lack-of-Penetration Defect

Fig. 9 Method of Making Weld Defect

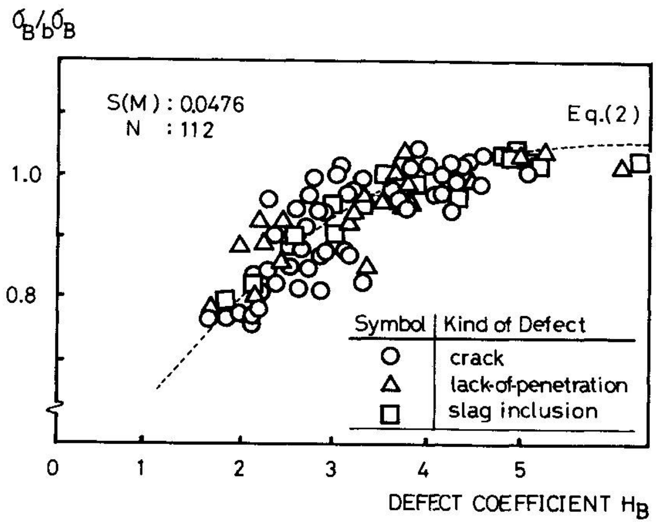


Fig.10 $\sigma_B/{}_b\sigma_B$ versus H_B Relationship for Butt Joints

$$M_B = \sigma_B / {}_b\sigma_B = (1.06\, e^{H_B} + 1.7)/(e^{H_B} + 4.6)\,. \quad \ldots (2)$$

Where, $H_B = 1.5 \ln((W/l_s)^{1.0} \times (T/h_s)^{0.8})$ is the defect coefficient for butt joints. The ranges of the experiments are $0.1 \leqq l_s/W \leqq 0.6$ and $0.07 \leqq h_s/T \leqq 0.86$.

The relationship between the test results and the regression equation is shown in Fig. 10. As seen in this figure, the difference of the influence among the defect kinds can not be observed. This can be attributed to the method of making artificial defect (5). The method of making crack defect in these experiments differs from the method adopted in the specimens of cross joints. No difference can be seen between artificial crack and lack-of-penetration in the mechanical viewpoint.

3.2 Acceptable Size of Weld Defect

3.2.1 Acceptance Criteria of Weld Defect

The following criteria, i.e., Level A and Level B are considered in this paper.

Level A: $\sigma_B \geqq {}_b\sigma_y \quad \ldots (3)$

Where, ${}_b\sigma_y$ is the actual yield stress of base metal. This step assures the condition that the welded joint is not to be fractured before the member connected yields in tension, and can be applicable to the joints of tension member such as the bracing members from the view point of seismic design.

Level B: $\sigma_B \geqq {}_b\sigma_{ST} \ldots (4)$

This step can be applicable to the joints with moment gradient such as the beam-to-column joints.

The acceptable size of the lack-of-penetration and slag inclusion defects is discussed in the followings when the welding procedure is limited to CO_2 arc semi-automatic welding or manual arc welding, and the steel grade is limited to SM50 whose ${}_b\sigma_{ST}$ is 490 N/mm².

3.2.2 Acceptable Size of Weld Defect for Level A Joints

Eq.(3) can be rewritten as $M = \sigma_B / {}_b\sigma_B \geqq {}_b\sigma_y / {}_b\sigma_B = Y$, where Y is the yield ratio of base metal. The mean value and standard deviation of Y for SM50 are $Y_m = 0.686$ and S(Y)=0.0455 from the statistical surveys (6). Based on the assumption that the values M and Y are the normal independent random variables, the next condition must be satisfied in order to satisfy Eq.(3) by 95% confidence limits.

$$M_m \geqq Y_m + 1.645\sqrt{(S(M))^2 + (S(Y))^2} \quad \ldots (5)$$

	Level A	Level B
Cross Joint	$H_C \geqq 1.0$	$H_C \geqq 4.3$
Butt Joint	$H_B \geqq 2.0$	$H_B \geqq 4.4$

Table 4 Result of Analysis

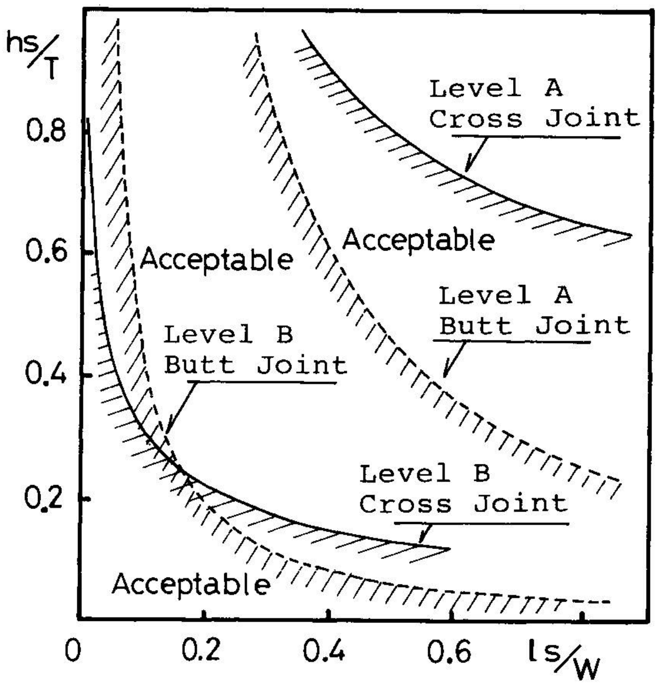


Fig.11 Acceptable Size of Weld Defect

Where, Mm=Mc of Eq.(1) for cross joints and $Mm=M_B$ of Eq.(2) for butt joints, and S(M) is the standard deviation of M(see, Fig. 7, 10).

The results of the analysis are shown in Table 4. The acceptable limits thus obtained are shown in Fig. 11 in terms of l_s/W and h_s/T.

3.2.3 Acceptable Size of Weld Defect for Level B Joints

The next condition must be satisfied in order to satisfy Eq.(4) by 95% confidence limits.

$$M_m \geqq ({}_b\sigma_{ST}/{}_b\sigma_B)_m + 1.645\sqrt{(S(M))^2 + (S({}_b\sigma_{ST}/{}_b\sigma_B))^2} \quad \ldots (6)$$

Where, $({}_b\sigma_{ST}/{}_b\sigma_B)_m$ and $S({}_b\sigma_{ST}/{}_b\sigma_B)$ are the mean value and the standard deviation of the values $({}_b\sigma_{ST}/{}_b\sigma_B)$. $({}_b\sigma_{ST}/{}_b\sigma_B)_m=0.9317$ and $S({}_b\sigma_{ST}/{}_b\sigma_B)=0.02957$ are obtained from the statistical surveys on SM50 (16mm $\leqq$ T $\leqq$ 50mm, N=74).
The results of the analysis and the acceptable size of weld defect are also shown in Table 4 and Fig. 11.

4. CONCLUSIONS

The conclusions obtained in this paper are as following;
- Through the factorial experiments, it was found that the important factors which give influence to the strength of welded joints are the geometric shapes of the joints and the size of weld defect, and also it was found the effects of such factors as the welding procedure, the steel grade, the loading condition, and the test temperature are insignificant.
- As the regression equations estimating the maximum strength of the joints involving weld defect, Eq.(1) for cross joints and Eq.(2) for butt joints are obtained respectively on the basis of the test results hitherto reported.
- A method to evaluate the acceptable sizes of lack-of-penetration and slag inclusion defects are presented for the joints subject to tension (Level A) and for the beam-to-column joints (Level B), and it is illustrated in Fig. 11 for cross and butt joints with SM50 grade steel.

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