PREDICTION OF TENSILE-SHEAR STRENGTH OF SPOT WELDS BASED ON FRACTURE MODES

S. Satonaka[1], K. Kaieda[2], S. Okamoto [2]

[1] Department of Mechanical Engineering and Materials Science, Kumamoto University
[2] Graduate School, Kumamoto University (Japan)

ABSTRACT

Assessment of the strength of spot welds is a key process in the design of spot welded structures. Moreover, the prediction method to be used to evaluate the strength of specimens is not always clear, even for static loading. This is because the strength of spot welds depends upon various factors such as nugget diameter, plate width and thickness, material strength, number and location of spot welds and different fracture patterns. In this study, three formulae were proposed for the prediction of the tensile-shear strength of spot welds, which are based upon the relationship between the maximum stress and material strength in three fracture modes; plug type fracture, shear type fracture and fracture across the base metal. In these formulae, two parameters were used for the assessment of maximum stress in the uneven stress distribution around a spot weld. Assuming that fracture takes place at the weakest portion of the structure, the tensile-shear strength is given by the minimum value of the fracture load evaluated for the three fracture modes. It was shown by comparing the predictions and experiments that the predicted fracture load and real fracture mode are in close agreement for both single- and multi-spot welds.

IIW-Thesaurus keywords: *Resistance spot welding; Resistance welding; Spot welds; Ultimate tensile strength; Shear strength; Mechanical properties; Strength; Shear tests, Mechanical tests; Fractures; Prediction; Stress distribution; Critical values; Low carbon steels; Unalloyed steels; Stainless steels; Steels; Parent materials; Weld metal; Nugget; Fusion zone; Weld zone; Size; Diameter; Dimensions; Distance; Loading; Influencing factors; Bending moment; Computation; Evaluation; Practical investigations.*

1 INTRODUCTION

Resistance spot welding is the predominant joining process for the assembly of thin sheet structures. Although this process has been widely used for many years, there are still a few subjects to be resolved. One of them is the assessment of strength of spot welded structures, which plays a key role in the design of thin sheet structures. A large number of publications [1-7] clarified the mechanical behaviour of single- and multi-spot welded structures under various operating conditions such as static, dynamic and impact loading. It was also clarified that the strength of spot welds depends upon various factors, such as nugget diameter, number and location of spot welds, plate thickness, width and material strength. Although some methods [1, 2, 4, 6] were proposed for the assessment of the strength of structures, their application is limited to simple cases, for example, single spot welded specimens with plug type fracture. However, various fracture patterns appear in the tensile-shear test of spot welded specimens, which are largely related to their strength. Nevertheless, the relationship between the fracture modes and the strength is not always clarified. As a result, empirical equations are often used in the actual design of spot welded structures and overestimated numbers of spot welds are used in the manufacture of spot welded structures. Therefore, high reliable and applicable methods are demanded in the assessment of strength. One promising method for high reliable assessment of strength is numerical calculation. Another one is the prediction of strength based upon formulae. Since the former method is time consuming, this study focused on the latter method, especially for the tensile-shear strength of spot welds. In the formulation of the strength of spot welds, however, the effects of factors, fracture modes, uneven and complex stress distribution on the fracture load should be taken into account.

In this study, first, we analysed three fracture modes; plug type fracture, shear type fracture and fracture across the base metal, which occurred in the tensile-shear tests. Based on the characteristics of fracture modes, a prediction method is proposed for the assessment of strength of spot welds, which consists of three equations derived from the relationship between the maximum stress and material strength for the three fracture modes. In these formulations, two appropriate parameters were proposed for the evaluation of maximum stress in the uneven stress distribution near the spot weld including the effect of the bending moment. These

---

Doc. IIW-1599-03 (ex-doc. III-1244-03) recommended for publication by Commission III “Resistance and solid state welding and allied joining processes”.

parameters also include the effects of plate geometry; weld size and material strength on the fracture load and become master curves for the evaluation of the fracture load for plug type fracture. Assuming that fracture takes place at the weakest position, the minimum value in the corresponding loads to three fracture modes gives the strength of spot welds. This prediction method based on fracture mode was applied to single- and multi-spot welded specimens and the accuracy of proposed method was confirmed by the comparison with the experimental results.

2 CHARACTERISTICS OF FRACTURE MODES IN TENSILE-SHEAR TEST OF SPOT WELDS

Resistance spot welding has been used for the construction of various sizes and shapes of thin sheet structures. Because of the complicated shape of structures, however, the empirical equation is often used in the design of structures and overestimated numbers of spot welds are made when manufacturing structures. This is caused by the insufficient assessment of strength in multi-spot welded structures. Therefore, this study investigates the prediction of strength for single- and multi-spot welded plates. Fig. 1 shows the single- and multi-spot welded specimens used in this experiments. As shown in Table 1, mild steel and stainless steel plates of different thickness and width were used to prepare these specimens. In the multi-spot welded specimens, the prediction of strength was performed on the double spot welded specimens, which are a constitutive element of the multi-spot welded specimens. These results also extend to the specimens with three or four spot welds distributed in the transverse direction. Otherwise, it is well known that various fracture patterns are observed in the tensile-shear test of spot-welded structures, which depend upon the weld size, plate geometry, number and location of spot welds. Fig. 2 schematically shows the typical patterns of fracture observed in the tensile-shear test of spot welds. These fracture modes can be classified as follows:

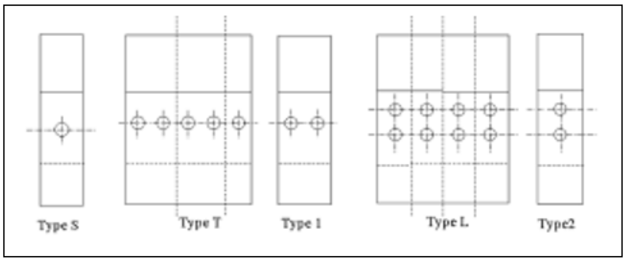

Fig. 1. Specimens.

Table 1. Specification of specimens.

	Type S	Type 1	Type 2
Plate thickness	0.8–1.2	0.8–1.2	0.8–1.2
Plate width	10–100	30–75	30–75
Distance between spot welds		10–50	10–50
Materials	Mild steel, Stainless steel	Mild steel, Stainless steel	Mild steel, Stainless steel

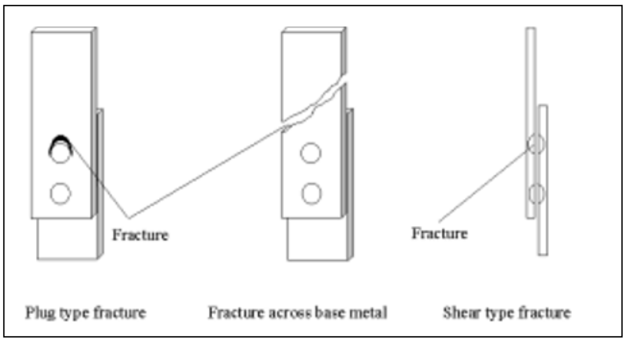

Fig. 2. Typical fracture patterns.

– Fracture across the base metal:
Similar to fracture observed in the tensile test of material, the fracture occurs across the base metal, far away from the spot welded area. This fracture pattern appears in the narrow mild steel specimens with large weld size. When the plate width increases or when the plate thickness decreases, this fracture mode tends to disappear.

– Plug type fracture:
This fracture mode occurs around the spot weld and a button shaped pattern remains on the surface of the other side of the plate. This is the typical fracture type observed in the tensile-shear test of spot welded specimens.

– Shear type fracture:
Fracture occurs through the nugget. This fracture modes typically occurs in the specimens with small weld size. This fracture pattern is also observed in the thick stainless steel plate, in which two spot welds of large size are distributed in the loading direction. Generally, this fracture takes place at a lower load.

From the mechanical point of view, it was clarified that these fracture modes were related to the interaction between the axial force and bending moment induced in the tensile-shear test of the specimens, as well as the material strength, especially weld metal and base metal. Fig. 3 shows a schematic illustration of the axial force and the bending moment, and the stress distribution at each fracture location. It is seen that the additional stress due to the bending moment increases the stress near the welded area, which results in the occurrence of plug type fracture. However, the bending moment has minor effects on the shear stress in the welded region and the stress in regions far from the spot weld. Assuming that fracture takes place when the maximum stress reaches the material strength, each fracture mode has the following relation.

Fracture across base metal:

$$\sigma_b = P_b/(t \cdot w) \text{ or } P_b = \sigma_b \cdot t \cdot w \quad (1)$$

Plug type fracture (single spot weld):

$$\sigma_w = \beta \cdot P_p/(t \cdot w) \text{ or } P_p = \sigma_w \cdot t \cdot w/\beta \quad (2)$$

Plug type fracture (double spot welds):

$$\sigma_w = \alpha \cdot P_p/(t \cdot w) \text{ or } P_p = \sigma_{wt} .w/\alpha \quad (2')$$

Shear type fracture:

$$\tau_s = P_s/A_w \text{ or } P_s = \tau_s \cdot A_w \quad (3)$$

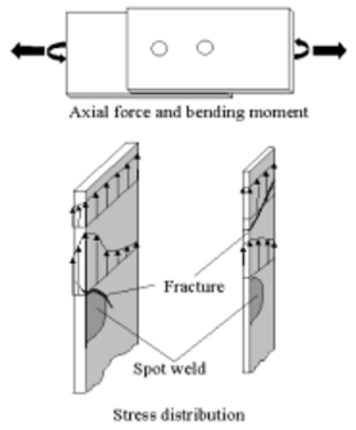

Fig. 3. Schematic illustration of axial force, bending moment and stress distribution.

Where

P_b, P_p and P_s are the fracture loads for fracture across the base metal, plug type and shear type fractures;

σ_b, σ_w and τ_s are the tensile strength of weld metal, base metal and shear strength of the weld metal;

t and w are the plate thickness and width; and

A_w is the welded area of the spot weld.

In these relations, the material strength is an important factor. Fig. 4 shows the shear strength of the weld metal and the base metal obtained from the shear test of specially designed slit type specimens. It is seen that the weld metal in the mild steel specimen has one and half times the strength of base metal, while the stainless steel has same strength in both weld metal and base metal. These tendencies are good agreement with the empirical equation $\sigma = 9.81\text{Hv}/3$ (Hv: Vicker's hardness) with respect to the deformation resistance to the load. Therefore, each fracture load is determined by different material strength criteria, i.e., shear strength of weld metal for shear type fracture, tensile strength of base metal for fracture across the base metal, and tensile strength of weld metal for plug type fracture. These different criteria result in different fracture loads ever for the same specimen. Since the fracture in the tensile-shear tests takes place at the weakest position, the minimum load in the ones evaluated by three above equations determines the strength and fracture mode of the specimen. However, some parameters are required for the evaluation of the effects of the bending moment and uneven stress distribution on the fracture strength in plug type fracture. These are shown below.

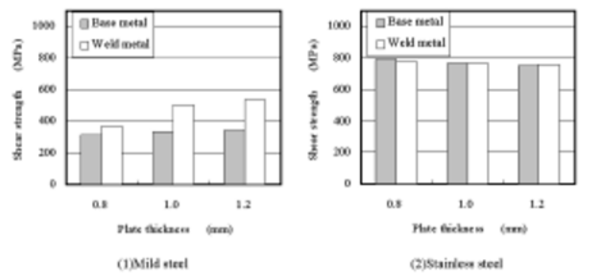

Fig. 4. Comparison of shear strength between base metal and weld metal.

3 EFFECT OF BENDING MOMENT ON FRACTURE LOAD

As above mentioned, there are three fracture patterns in the tensile-shear test of spot welds. Each pattern has a unique load depending on the fracture position. Since the actual fracture occurs at the weakest region, the strength and fracture mode of a specimen is determined by the fracture pattern of lowest load. Therefore, the assessment of the fracture load for the three fracture patterns is required to determine the minimum load. As shown in equations (1), (2) and (3), it is easy to assess the loads for shear type fracture and fracture across the base metal, but the appropriate parameter is required for the assessment of effect of the bending moment and the uneven stress distribution in plug type fracture. In this study, two parameters are proposed to have an influence on the fracture load.

3.1 Parameter β for single spot welds

The bending moment and uneven stress distribution induced by the tensile-shear test of single spot weld are complex, and depend upon the plate geometry, weld size and material. In this study, as shown in Fig. 5, their effect on the fracture load is evaluated by the ratio β of average stress to the material strength. The ratio of weld diameter to plate width c/w is also an important parameter in the application of parameter β to specimens of different weld size and plate width. Fig. 6 shows the relationship between parameters β and c/w (c: weld diameter, w: plate width). It is noted that the relation indicates the same trend in spite of the data being obtained from specimens of different weld size, plate width and material. It is also seen that the parameter β decreases with increasing c/w and becomes almost constant for $c/w > 0.4$. This means that the parameter β is useful in the evaluation of the effects of the bending moment and uneven stress distribution on the fracture load and becomes a master curve for the prediction of fracture load in plug type fracture of single spot weld. The fracture load is given by the equation $P_p = t.w.\sigma_w/\beta$.

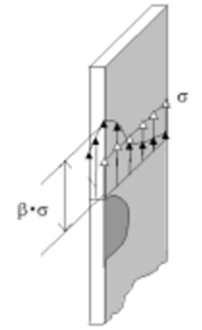

Fig. 5. Parameter β.

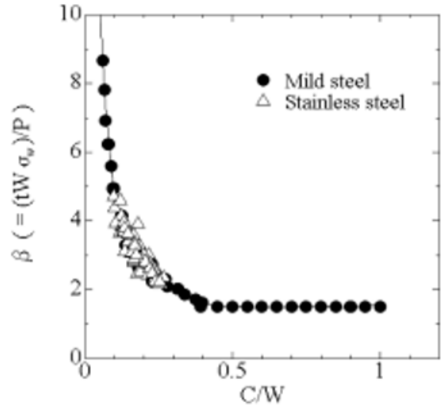

Fig. 6. Relation parameter β and c/w.

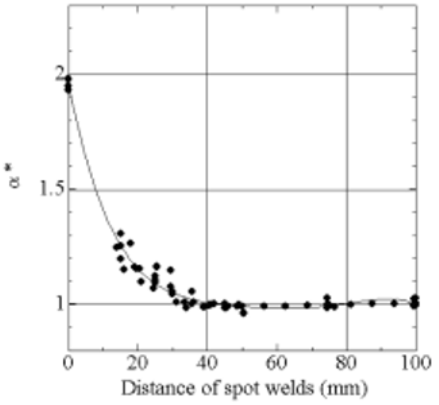

Fig. 8. Relation between parameter α* and distance between spot welds.

3.2 Parameter α for double spot welds

The bending moment in tensile-shear tests of spot welds is due to the eccentric structure of welded plates and largely depends upon the deformation near the spot welded area. When two spot welds are distributed separately in the direction of applied force, the distance between these two spot welds also affects the bending moment induced in the spot welded area, which is one of the dominant factors for the prediction of the fracture load. In a previous documents [6], we also considered the same parameter α, which is the ratio of the average stress to the material strength for multi-spot welds. As shown in Fig. 7, this parameter α decreases with the distance between spot welds and becomes almost constant for distances over 40 mm. However, the values of this parameter change with the plate geometry, e.g. plate thickness and width. Therefore, we proposed another parameter α^*, which is generalised by dividing each value by a constant value α_0 obtained for widely spaced spot welds. Fig. 8 shows the relationship between the generalized parameter α^* and the distance between spot welds. It is noted that the generalized parameter α^* indicates the same relationship regardless of plate thickness and width. Therefore, this curve is also a master curve for the prediction of fracture load in the plug type fracture of double spot welds. The fracture load can be calculated by the following procedure.

1. Plate thickness, width, weld size and distance of spot welds are given.

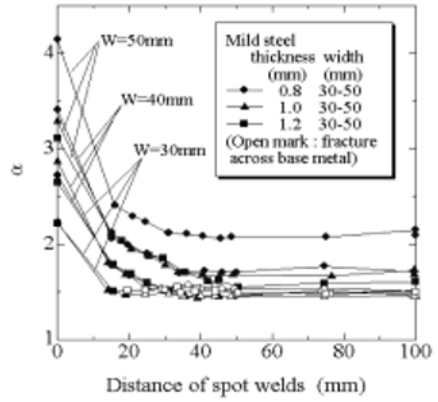

Fig. 7. Parameter α.

2. Fracture load and parameter β are obtained from the master curve of single spot weld, using given values of weld size, plate thickness, width and material strength.

3. Since value α at distance of 0 is equal to parameter β for a single spot weld and α^* is 1.96, the constant value α_0 in the spot welds located with a spacing greater than 40 mm is given by the product of 1.96 and β.

4. Multiplying α^* by the constant value α_0, the relations between the parameter α and the distance of spot welds is obtained for the given plate thickness, width and weld size of specimen.

5. Since the parameter α of given specimen is obtained from the relation between the parameter α and the distance between spot welds, the fracture load is given by $P_p = \sigma_w \cdot t \cdot w/\alpha$.

4 PREDICTION OF FRACTURE LOAD IN VARIOUS SPECIMENS

As mentioned above, three fracture patterns appear in the tensile-shear test of spot welds and each pattern is dominated by a specific criterion to fracture position and material strength. Although it is possible that every specimen may fracture according to every one of the three fracture patterns, its occurrence depends upon the fracture load. It is reasonable to assume that the fracture takes place at the weakest position. Therefore, the strength and fracture pattern can be predicted by the minimum fracture load of all the loads in three regions: around the spot weld, across the welded region and far area from the spot weld, which are calculated by equations (1), (2) and (3). The following results show the comparison of predicted and experimental fracture loads and fracture modes.

4.1 Single spot welded specimens; Type 1

Fig. 9 shows the relationship between weld diameter and fracture load in the mild steel specimens with different plate thickness and width. The three lines in the figures indicate the fracture load predicted by equations (1), (2) and (3). It is seen that the relation between the

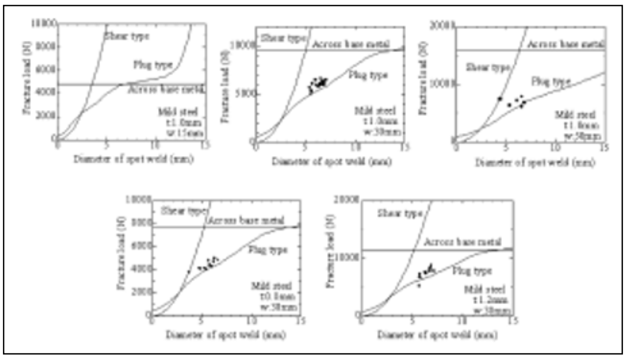

Fig. 9. Relations between fracture load and diameter of spot weld (mild steel).

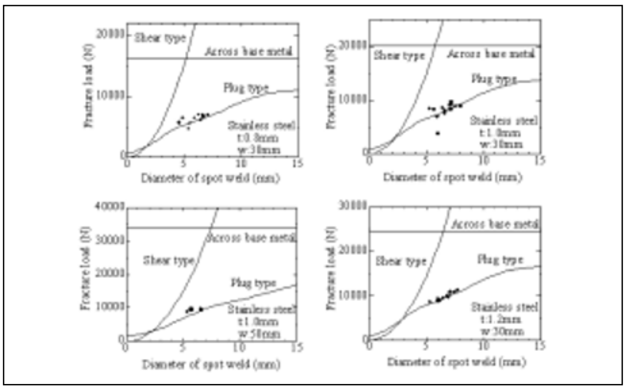

Fig. 10. Relations between fracture load and diameter of spot weld (stainless steel).

weld diameter and fracture load has a unique relation to the fracture pattern, as follows. Shear type fracture shows parabolic increases of fracture load with weld diameter, while the plug type gradually increases with increasing weld diameter. For fracture across the base metal, however, the fracture load remains constant regardless of the weld diameter. These relationships also show that the plate geometry affects the strength and fracture mode of a specimen. In the calculation of a 15 mm wide specimen, shear type fracture occurs for small weld diameters below 2.5 mm, while plug type fracture occurs for weld diameter from 2.5 mm to 6.5 mm. For large weld diameter over 6.5 mm, fracture occurs across the base metal. In wide specimens over 30 mm in width, on the other hand, most fractures are plug type fracture, except the shear type fracture for small weld diameter below 2 mm. If fracture takes place at the weakest position, a minimum load corresponding to the weld diameter gives the strength of spot-welded specimen. The minimum load is in close agreement with the data in the figures, which are obtained by ultrasonic measurement of spot weld size and the tensile-shear test of spot welded specimens. Therefore, the prediction method proposed is useful for the assessment of strength and design of spot welded structures.

Fig. 10 shows the relationship between fracture load and weld diameter of spot welded stainless steel specimens. Similar trend to the mild steel specimens can be observed. However, the calculated results suggest that there is no occurrence of the fracture across the base metal, since the maximum stress around the spot weld is always higher than that in regions far from the spot weld and the strength of the spot welded region is almost the same as for the base metal. It is also seen that the predicted strength of the spot weld is in close agreement with the experimental results.

4.2 Double spot welded specimens; Type 2

The basic procedure for the prediction of strength for the double spot welded specimens is almost the same as for single spot welded specimen. In this case, the parameter α is used for the evaluations of the effects of bending moment and uneven stress distribution instead of parameter β, which was used for the single spot welded specimens.

Fig. 11 shows the relationship between the distance of spot welds and the fracture load for the double spot welded specimens of different plate thickness and width. In these figures, the prediction line for shear type fracture is not shown because higher loads due to two spot weds are required in the specimen. It is seen that the relationship between the distance between spot welds and the fracture load show different trends, depending on the plate thickness and width and two fracture patterns occur in the double spot welded specimens. In this case, the assumption of minimum load for the prediction of strength was also confirmed by comparing predictions with the experimental results.

Fig. 12 shows the results for the stainless steel specimens. In the stainless steel specimens, two fracture patterns occur; plug type and shear type fractures. Although the predicted results of strength for plug type fracture coincide with the experimental results, the loads for the shear type fracture are higher than the actual fracture loads. The reason for the large differences between the prediction and the experiments is thought to be that the shear strength of the weld metal is overestimated. According to the experimental results, the shear strength across the welded region was estimated to be 530 MPa, which was 70% of shear strength shown in Fig. 4.

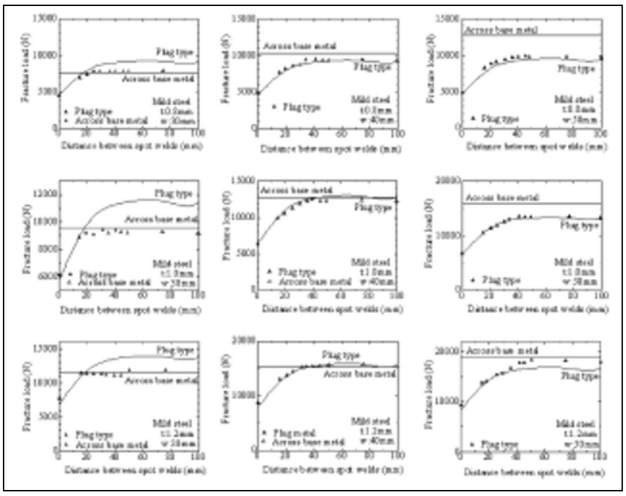

Fig. 11. Relations between fracture load and distance spot welds (mild steel).

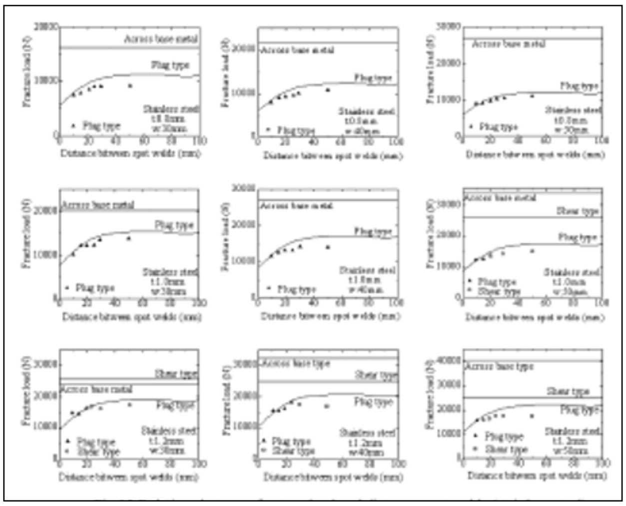

Fig. 12. Relations between fracture load and distance spot welds (stainless steel).

4.3 Multi-spot welded specimens; Type L

As shown in Fig. 1, multi-spot welded specimens are considered to be those in which a number of spot welds are linked transversely in a row. The constitutive spot welds in type T and type L specimens are single spot welds of type 1 and double spot welds of type 2, respectively. Since the strength of constitutive spot welds was estimated in the previous sections, the fracture loads for multi-spot welds are given by the summation of strength of the constitutive spot welds.

Fig. 13 shows the schematic illustration for the assessment of the fracture load for the multi-spot welded specimen, type L. Considering the effects of different weld size and weld spacing in the specimen, the multi-spot welded specimen is divided into a groups which are half the size of the single spot weld. Since each half size element supports half of the load of a single spot weld, the fracture load of type L is given by the summation of loads supported by each half size element.

Fig. 14 shows the comparison between the predicted and experimental fracture load. It is seen that the estimated loads are in close agreement with the experimental results for the multi-spot welded specimens with 2, 3 and 4 spot welds and various widths. This method can be applied to the type L specimens by replacing the single spot weld element with double spot welds. However, it was impossible to compare the estimated loads with actual loads for the type L specimen, since the estimated loads are higher than the capacity of the test machine used.

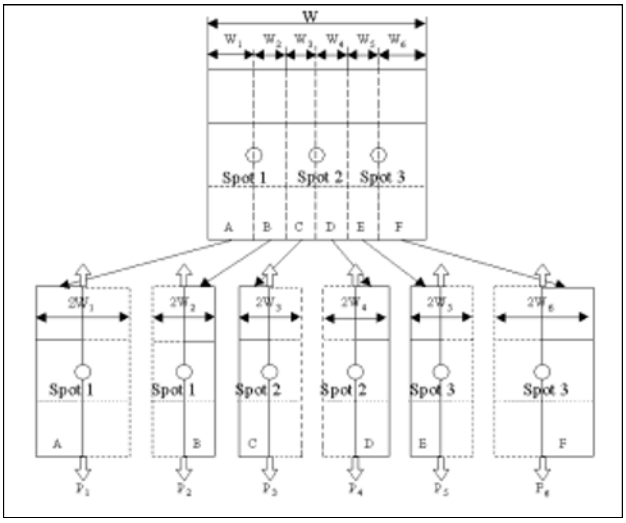

Fig. 13. Schematic illustration for assessment of fracture load for type L specimens.

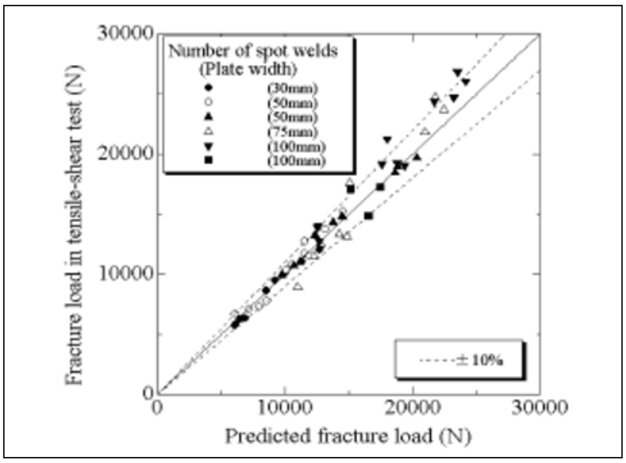

Fig. 14. Comparison between predicted and experimental fracture load.

5 CONCLUSIONS

In the tensile-shear test of spot welded structures, fracture takes place mainly around the spot weld, across the nugget and at the base metal. The fracture mode depends upon various factors, such as the uneven and complex stress distribution, as well as weld size, plate geometry, location and spacing of spot welds and material properties. These fracture modes are also related to the fracture load of spot welded specimen. In this study, a method of predicting the strength of spot welds is proposed, which is based on the fracture loads evaluated for three fracture modes; plug type fracture, shear type fracture and fracture across the base metal. The main results obtained are as follows.

1 Each mode has a different criterion for the assessment of fracture load, which depends upon the plate thickness, width, weld size and material strength. The typical fracture mode is the plug type fracture. Nevertheless, insufficient weld size and a weld metal strength higher than that of the base metal yield shear type fracture and fracture across the base metal, respectively.

2 Parameters α and β given by ratios of maximum stress to average stress are useful parameters for the quantitative evaluation of the bending moment in single and double spot welds, which become an important relationship in the prediction of fracture loads for plug type fracture.

3 The lowest fracture load of the three fracture modes determines the strength and fracture mode of spot welded specimens. This agrees well with the experimental results.

REFERENCES

1. Sawhill J.M., Bakers J.C.: Spot weldabilty of high-strength sheet steels, Welding Journal, 1980, vol. 59-1, pp. 19s-30s.

2. Funakawa Y., Kabasawa M.: Difference between carbon steel and stainless steel on tension shear strength, Preprints of the National Meeting of JWS, 1994, vol. 55, pp. 448-449, (in Japanese).

3. Hills D.R., Parker J.D., Williams N.T.: Effect of number of welds in spot welded and weldbonded arrays on static failure load of individual spot welds and adhesive bond, Ironmaking and Steelmaking, 1996, vol. 23-2, pp. 150-156.

4. Satonaka S., Arima S., Akamine M.: Prediction of strength of multi-spot welds by aid of ultrasonic evaluation, IIW doc. III-1082-97.

5. Satonaka S., Takashima T., Terada K., Nishiwaki T., Kohno Y.: Ultrasonic evaluation of fusion and solid-phase bonding in spot welds, IIW doc. III-1045-95.

6. Satonaka S., Hatta K., Kiyota H., Tsukamoto K., Shirakawa H.: Tensile-shear strength of spot welded structures – Prediction of strength and effect of weld position, IIW doc. III-1153-00.

7. Satonaka S., Kiyota H., Yamazaki S.: Relation between strength and fracture modes in tensile-shear test of spot welds, IIW doc. III-1213-02.