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Experimental Study on Effects of Root Gap and Fillet Size of Welds on Joint Strength*

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Welding processes often induce inaccuracies for ship-building fabrication such as an excessive root gap due to the level of cutting precision and welding deformation, etc. In the Japanese ship-building industry, the decision to allow a root gap, for example, depends on the accuracy states in the Japan Ship-building Quality Standard (JSQS). The JSQS is easy to use because it gives tolerance limits and countermeasures for various issues that occur in the ship construction, such as root gap, misalignment, and angular distortion. However, the tolerance limits and countermeasures of the JSQS might be insufficient, because they still focus on the shielded metal arc welding (SMAW), which was the primary welding process used when the first version of JSQS was established around 50 years ago. The validity of widely applying the JSQS to joint welds by currently used welding processes, such as gas metal arc welding (GMAW) and laser beam welding, has not been officially confirmed and not been included in the latest JSQS. It is necessary to learn the effects of many factors, such as the amount of root gap, countermeasures, and heat input, on the static strength, fatigue strength and corrosion of ship structures when recent weld processes such as GMAW are used in order to apply the current welding processes to a new JSQS or something like it. In this study, experiments on the static strength for fillet joints are carried out by changing the amount of root gap, plate thickness, and fillet weld leg length, and the relation between the static strength and the amount of root gap is established.

Key Words: weld joint, fillet joint, static strength, root gap, fillet size, JSQS

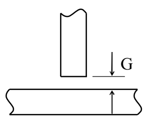
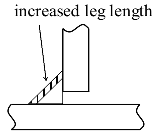
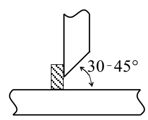
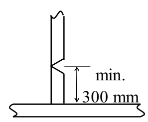
1. Introduction

Ships are huge welded structures, and the inaccuracy of fabrication processes used in ship construction often causes correction after each process[1]. Especially, excessive root gaps in fillet weld joints become an issue during weld process. In the Japanese ship-building industry, the ship-builder decides whether to allow an inaccurate joint according to the Japan Ship-building Quality Standard (JSQS)[2] and implements countermeasures according to the JSQS if the joint accuracy is not allowed within the provided tolerance limit. Table 1 shows the criteria for root gaps occurring in fillet welded joints and its countermeasure when the root gap exceeds tolerance limit. The “G” in Table 1 is the amount of root gap. If the amount of root gap is not more than 3 mm, that root gap is allowed, whereas root gaps of more than 3 mm are not allowed, and a countermeasure corresponding to the amount of root gap must be implemented.

It is important that the criteria and countermeasures described in the JSQS ensure the structural soundness of the constructed ships. Therefore, a lot of studies[3)-11)] have been carried out in order to confirm the validity of these criteria and countermeasures. These studies are of particular importance, but the JSQS generally focuses on the shielded metal arc welding (SMAW), which is no longer widely used in the Japanese ship-building industry. The first version of JSQS was established around 50 years ago, and this has not been revised even presently.

In this study, experiments were conducted to investigate the static strength of fillet joints for two different welding procedures, SMAW and gas metal arc welding (GMAW), in order to obtain a fundamental data and a new criteria of GMAW by the same analogy of that of SMAW in JSQS. Currently, GMAW is a widely used welding process in the Japanese ship-building industry. The first experiment was tested specimens with no root gap to confirm the relation among static strength, welding conditions such as welding current, speed, arc voltage, fillet weld leg length, penetration depth, and throat depth. The second experiment was also tested specimens with a root gap to confirm the relation between the static strength and the amount of root gap.

Table 1 Criteria and countermeasures for a root gap.

Item	Standard range	Tolerance limit	Countermeasure
Gap before welding (Fillet weld)  G Unit: mm	G≦2	G≦3	3<G≦5 Increased leg length Rule leg length + (G-2) increased leg length  5<G≦16 Welding with bevel preparation  30 - 45° 16<G Partial renewal  min. 300 mm

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2. Experiment without root gap

2.1 Experimental model and procedure

The material was rolled steel for ship structures, KA32, prescribed by Class-NK[12]. The plate thickness was 12.5 mm. The chemical composition and mechanical properties of the steel are shown in Tables 2. Welding consumables used in this experiment were LB-M52 and DW-Z100. The chemical composition and mechanical properties of the welding consumables are shown in Table 3. The configuration of the joint tensile specimen is shown in Fig. 1 and the welding conditions are shown in Table 4. Eight joint tensile specimens were prepared for each joint. Welding was carried out in two positions, flat and vertical-upward, and the welding current and the arc voltage were changed within the range of conditions used in an actual welding process in order to confirm the effect of heat input on the static strength of a joint.

The definition of throat depth, modified throat depth and penetration depth in this study are provided as shown in Fig. 2. Modified throat depth is defined with considering actual penetration depth which is measured from a picture of the cross-section after welding.

Table 2 Chemical composition and mechanical properties of steel plate.

Chemical composition (%)					Mechanical properties		
C	Si	Mn	P	S	Yield point (N/mm^2)	Tensile strength (N/mm^2)	Elongation (%)
0.15	0.19	0.98	0.017	0.007	372	489	25

Table 3 Chemical composition and mechanical properties of welding consumables.

Welding process	Trade name	Chemical composition (%)					Mechanical properties		
		C	Si	Mn	P	S	Yield point (N/mm^2)	Tensile strength (N/mm^2)	Elongation (%)
SMAW	LB-M52	0.08	0.57	0.97	0.012	0.006	490	570	31
GMAW	DW-Z100	0.05	0.45	1.35	0.013	0.009	510	570	30

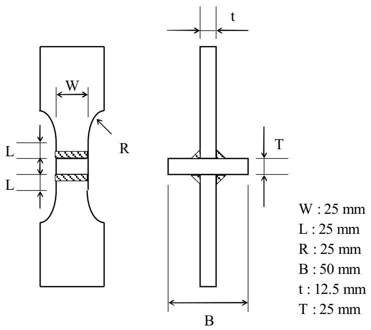


Fig. 1 Configuration of joint tensile test specimen with no root gap.

Table 4 Welding conditions.

Joint	A	B	C	D	E	F	G	H
Welding current (A)	180	135	120	135	260	200	170	150
Arc voltage (V)	27.2	25.4	24.8	25.4	34.0	28.0	24.0	22.0
Travel speed (cm/min)	11.7	8.5	8.0	9.1	60.4	69.3	25.6	15.4
Heat input (J/mm)	2500	2420	2250	2270	880	970	960	1280
Welding position	Flat		Vertical-upward		Flat		Vertical-upward	
Welding process	SMAW				GMAW			

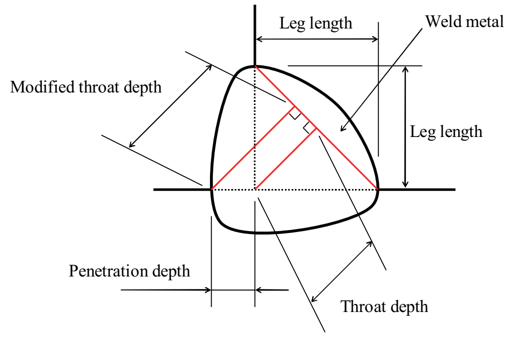


Fig. 2 Definition of throat depth, modified throat depth, and penetration depth.

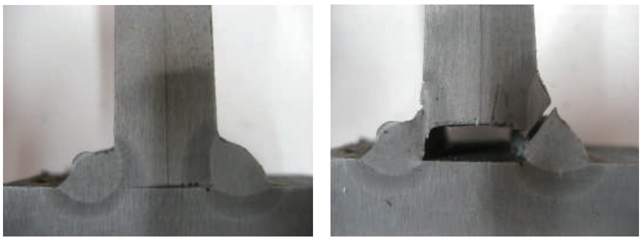
2.2 Experimental results

All experimental results are plotted in the following: Figure 3 shows the macro cross-section before and after the joint tensile test. Figure 4 shows the relation between leg length and joint strength. Figure 5 shows the relation between throat depth and joint strength. Figure 6 shows the relation between penetration depth and joint strength. Figure 7 shows the relation between the modified throat depth and joint strength. The average values of maximum strength, leg length, throat depth, penetration depth and modified throat depth in each joint are shown in Table 5.

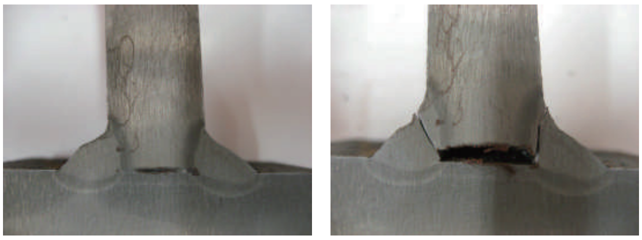
As shown in Fig. 4, the maximum strengths of joints G and H are distributed around 160 kN, so the base material of some of these joint tensile specimens broke. As shown in Figs. 4 and 5, and Table 5, it is clear from joints E and F that a long leg length and a big throat depth are not always necessary for higher joint strength. In contrast, the modified throat depth and the penetration depth have a high correlation with the static strength of the joint, as shown in Figs. 6 and 7, and Table 5. This shows that the penetration depth is a significant factor in determining the static strength of a joint because the modified throat depth, defined in this study, is directly affected by the penetration depth. Figures 3 and 6, and Table 5 show that the penetration depth on a joint welded by GMAW is deeper than that by SMAW, and the static strength of a joint welded by GMAW is stronger than that by SMAW. This shows that a shipbuilder can obtain deep penetration and higher strength joint by adjusting the welding conditions with GMAW relative to SMAW.

Table 5 The average values of maximum strength, leg length, throat depth, penetration depth and modified throat depth.

Joint	A	B	C	D	E	F	G	H
Average value of maximum strength (kN)	140.7	134.2	142.8	134.6	146.8	122.9	159.3	158.0
Average value of leg length (mm)	6.4	6.4	6.3	6.0	6.1	6.7	6.6	6.7
Average value of throat depth (mm)	4.5	4.5	4.4	4.2	4.3	4.7	4.7	4.7
Average value of penetration depth (mm)	0.6	0.2	0.7	0.2	1.0	0.3	1.3	0.8
Average value of modified throat depth (mm)	4.9	4.7	4.9	4.4	5.0	4.9	5.6	5.3
Welding process	SMAW				GMAW			



(a) Joint A welded by SMAW



(b) Joint E welded by GMAW

Fig. 3 Macro cross-section before and after joint tensile test.

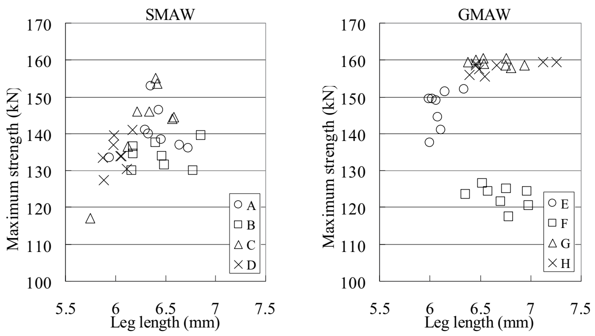


Fig. 4 The relation between leg length and maximum strength.

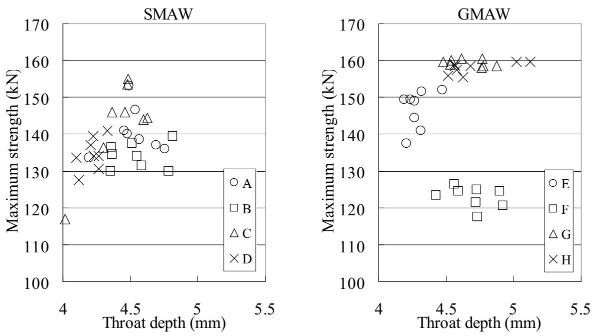


Fig. 5 The relation between throat depth and maximum strength.

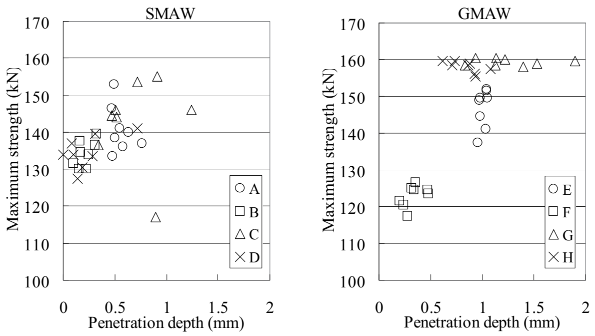


Fig. 6 The relation between penetration depth and maximum strength.

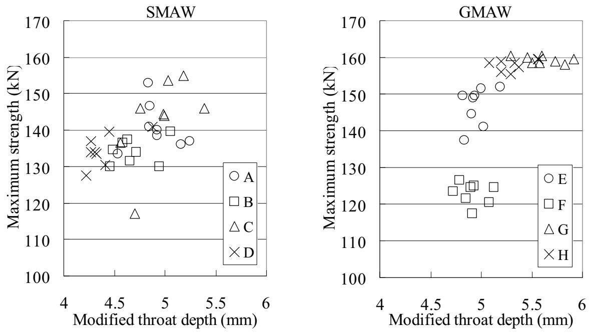


Fig. 7 The relation between modified throat depth and maximum strength.

3. Experiment with a root gap

3.1 Experimental model and procedure

In this experiment, the same material and welding consumables used in the first experiment was used. However, this experiment used two plate models: one had a thickness of 12.5 mm and the other had a thickness of 25 mm. Three joint tensile specimens were prepared for each joint. The configuration of the joint tensile test specimen is shown in Fig. 8 and the relation between the plate thickness, the amount of root gap, and the leg length of each joint tensile test specimen is shown in Table 6. Joints I and M are joints without a root gap and so satisfy the standard for joint strength. Joints J and N are joints with the maximum root gap allowed by the JSQS. Joints K and O are joints with an unallowable root gap and in which the JSQS countermeasure was not implemented. Joints L and P are joints with an unallowable root gap and in which the JSQS countermeasure was implemented.

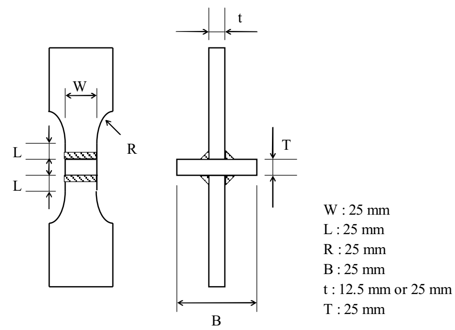
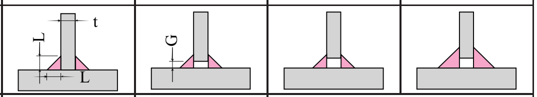


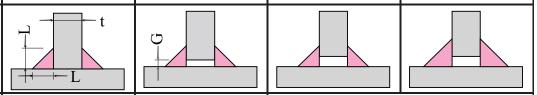
Fig. 8 Configuration of joint tensile test specimen with a root gap.

3.2 Experimental results

Figures 9 and 10 show the macro cross-sections before and after the joint tensile test. The effects of the root gap on the maximum strength are shown in Fig. 11. The average value of maximum strength, leg length and penetration depth in each joint are shown in Table 7 and 8.

Table 6　Relation between thickness, gap, and leg length.

Joint	I	J	K	L
Detail				
G	0 mm	3 mm	5 mm	
L	6 mm	6 mm	6 mm	9 mm
t	12.5 mm			

Joint	M	N	O	P
Detail				
G	0 mm	3 mm	5 mm	
L	9 mm	9 mm	9 mm	12 mm
t	25 mm			

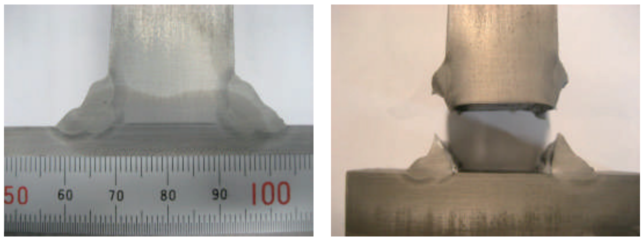
The maximum strengths of joints J, K, and L are distributed around 165 kN, so the base material of all joint tensile specimens of joints J, K, and L broke. Figure 11 shows that the strengths of joints J, K, and L are higher than that of joint I, and the strengths of joints N, O, and P are higher than that of joint M. This is because the penetration depth of the joint with the root gap is deeper than the joint without the root gap, so the static strength of the joint with the root gap is higher than that of the joint without the root gap as the same tendency, as shown in the previous experiment. This is clearly shown in Fig. 9 and Table 7 and 8, too. As shown in Table7, the average values of penetration depth of joint O with the 5 mm root gap is deeper than that of joint M without the root gap for both SMAW and GMAW. Also, the penetration depth of the joint welded by GMAW is deeper than that of the joint welded by SMAW, so the static strength of the joint welded by GMAW is higher than that of the joint welded by SMAW, as shown in the previous experiment. Additionally, it is clear from joints O and P welded by GMAW in Fig. 11 that a long leg length is not always necessary for higher joint strength. The static strength of joint P welded by GMAW is lower than that of joint O welded by GMAW in spite of the long leg length, because the penetration depth of joint O welded by GMAW was deeper than that of joint P welded by GMAW, as shown in Table 8. This shows that countermeasures and tolerance limits of the JSQS might remain a subject of re-examination, so that the ship-builder can obtain a higher strength joint by using GMAW, or the same strength shall be obtained with an adequate countermeasures and tolerance limits in GMAW.

Table 7　The average values of maximum strength, leg length and penetration depth in each joint welded by SMAW.

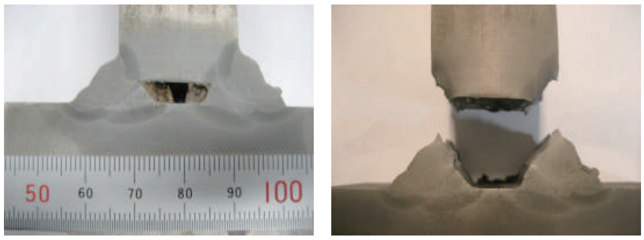
Joint	I	J	K	L	M	N	O	P
Average value of maximum strength (kN)	140.3	162.8	163.7	164.8	233.7	257.7	266.3	273.3
Average value of leg length (mm)	5.9	5.7	6.7	10.5	9.9	10.1	9.8	12.3
Average value of penetration depth (mm)	0.9	5.3	Full penetration	Full penetration	1.0	4.5	8.2	7.0
Breaking point	Weld metal	Parent metal	Parent metal	Parent metal	Weld metal	Weld metal	Weld metal	Weld metal

Table 8　The average values of maximum strength, leg length and penetration depth in each joint welded by GMAW.

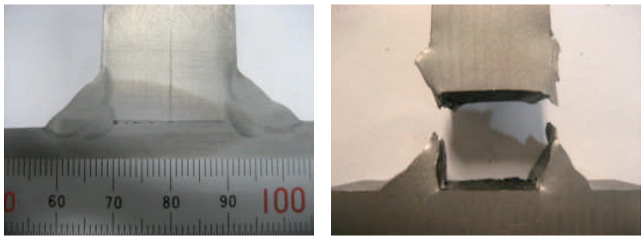
Joint	I	J	K	L	M	N	O	P
Average value of maximum strength (kN)	141.8	163.7	164.5	164.7	246.7	281.7	316.7	286.3
Average value of leg length (mm)	6.8	6.8	7.1	10.3	9.8	10.1	9.6	12.4
Average value of penetration depth (mm)	0.4	Full penetration	Full penetration	Full penetration	1.2	6.5	11.3	10.4
Breaking point	Weld metal	Weld metal	Weld metal	Weld metal	Weld metal	Weld metal	Weld metal	Weld metal



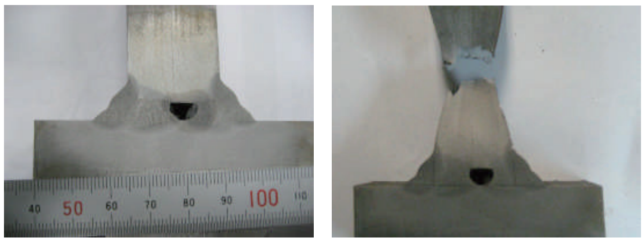
(a) Joint M welded by SMAW



(b) Joint O welded by SMAW



(c) Joint M welded by GMAW



(d) Joint O welded by GMAW

Fig. 9　Macro cross-sections before and after joint tensile test in specimens with a root gap.

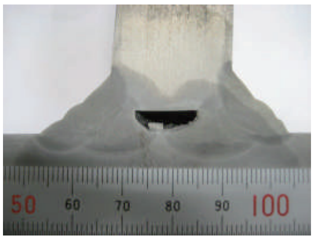


Fig. 10 Macro cross-section of joint P with a root gap and welded by GMAW before the joint tensile test.

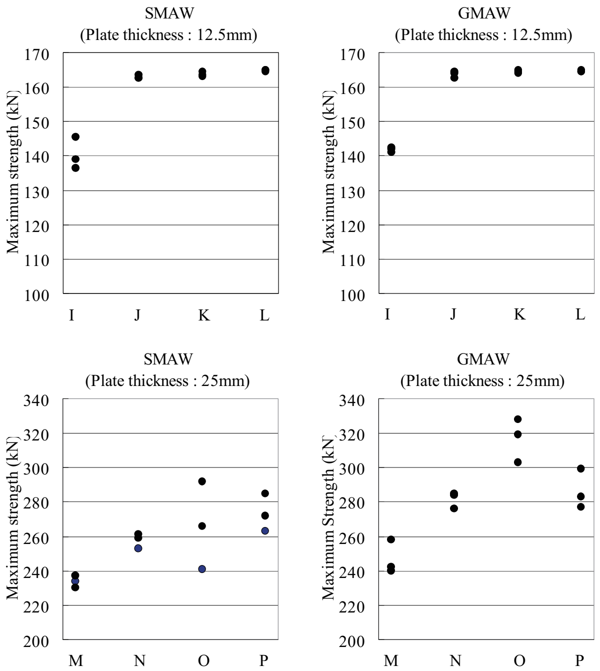


Fig. 11 Effects of root gap on maximum strength.

4. Conclusions

Experiments were carried out to confirm the relation between the static strength of a fillet weld joint and various factors, such as the amount of root gap, the leg length, and the welding conditions, in order to obtain a fundamental data and a new criteria of GMAW by the same analogy of that of SMAW in JSQS. In this study, it was clear that the leg length and the throat depth are not always necessary for high joint strength. A significant factor in determining the static strength of a fillet weld is the penetration depth, because the deeper the penetration depth is, the higher the joint strength is. The joint tensile strength with a root gap is higher than the joint tensile strength without a root gap. Moreover, the static strength of a fillet joint welded by GMAW is higher than that of a joint welded by SMAW because the penetration depth of the fillet joint welded by GMAW is deeper than that of the joint welded by SMAW by adjusting the welding conditions. Therefore, special countermeasures for the root gap in a fillet weld joint are not necessary from the standpoint of static strength of a root gap of at least 5 mm. Consequently, countermeasures and tolerance limits of the JSQS remain a subject of re-examination, so that the ship-builder can obtain a high-strength joint by using GMAW, and the same strength shall be obtained with an adequate countermeasures and tolerance limits in GMAW.

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