Journal of Structural Engineering Vol.54A (March 2008) JSCE

Fatigue assessment of out-of-plane attachments with various angles by using local stress approaches

Park Wooryong*, Miki Chitoshi**

* PhD Candidate, Dept. of Civil Eng., Tokyo Institute of Technology, 2-12-1 Oookayama, Meguro-ku, Tokyo 152-8552
** Dr. of Eng., Professor, Dept. of Civil Eng., Tokyo Institute of Technology, 2-12-1 Oookayama, Meguro-ku, Tokyo 152-8552

In order to investigate the effect of the angle between principal stress direction and weld attachment on the fatigue behavior, crack initiation points and fatigue strengths have been examined by using the fatigue test results of out-of-plane attachments with various angles under uniaxial loading. As fatigue assessment methods, the nominal stress approach, the structural hot spot stress approach and the effective notch stress approach are used. It is possible to find fatigue crack initiation points by using the effective notch stress approach, regardless of the angle between principal stress direction and weld attachment. The effect of the angle between principal stress direction and weld attachment on the fatigue crack initiation life cannot be considered when the nominal stress approach and the structural hot spot stress approach are used. However, by using the effective notch stress approach, it is possible to consider the effect of the angle on the crack initiation life.

Key Words: crack initiation point, fatigue strength, structural hot spot stress approach, effective notch stress approach

1. Introduction

Fatigue design codes[1)2)] can be broadly applied to the fatigue assessment of welded structures. However, their application can be limited when weld attachments are under biaxial stress state because the fatigue design codes are mainly based on the fatigue test results where weld lines are parallel or perpendicular to uniaxial loading. For the fatigue assessment of weld attachments under biaxial stress state, the JSSC fatigue design recommendations[1)] recommend that fatigue assessment is basically conducted by using normal stress and shear stress separately. However, the JSSC fatigue design recommendations recommend that designers and organizations judge whether evaluation using combined stress (principal stress) is suitable or not, in case of need. In the IIW fatigue design recommendations[2)], it is recommended to use the principal stress which is approximately in line with the perpendicular to the weld toe, i.e., within a deviation of ±60°, for fatigue assessment of weld attachments under biaxial stress state. However, the methods recommended in above fatigue design recommendations are still controversial issues because it is not clear whether the recommended methods are appropriate. Hence, it is necessary to find out a method which can handle the fatigue assessment of weld attachments under biaxial stress state.

In order to examine the characteristics of fatigue cracks which initiate under biaxial stress state, Sonsino and Lagoda[3)4)] studied the fatigue behavior of welded tube-tube and flange-tube joints under pure and combined bending and torsion. Takahashi et al.[5)], Hirayama et al.[6)] studied the fatigue behavior of out-of-plane boxing welded joints under biaxial cyclic loading. Kim and Yamada[7)] studied fatigue life evaluation method for welded joints under combined normal and shear stress.

When weld attachments are under biaxial stress state, it is necessary to make sure the issues such as the effects of the shear stress and the angle between principal stress direction and weld attachment on the fatigue behavior. Of the above issues, this study focuses on the latter. In order to investigate the effect of the angle between principal stress direction and weld attachment on the fatigue behavior, crack initiation points and fatigue strengths have been examined by using the fatigue test results of out-of-plane attachments with various angles under uniaxial loading. As fatigue assessment methods, the nominal stress approach, the structural hot spot stress approach[1)2)] and the effective notch stress approach[8)-13)] are used. The effective notch stress approach is a fatigue assessment method where a fictitious radius of 1 mm is assumed at weld toes and weld roots, as shown in Fig. 1, and this method can distinguish the difference of weld profiles between full penetration welding and fillet (or partial penetration) welding.

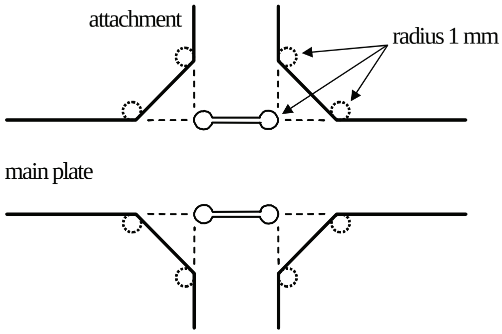


Fig.1 Fictitious effective notches at weld toes and weld roots

2. Experiments

2.1 Specimens

Fig. 2 shows the dimensions of specimens. The specimens of which the angle of attachment is 0°, 30°, 45°, 60° and 90° are named Types AW0, AW30, AW45, AW60 and AW90, respectively. For Type AW0, the length of attachment is 100 mm. For Types AW30, AW45, AW60 and AW90, the length of attachment decreases as the angle of attachment increases, keeping the length between the side of main plate and the corner of attachment end in the same size as main plate thickness (20 mm). All the specimens are as-welded fillet-welded joints. CO_2 semiautomatic welding was carried out and the start and end points were located at the center of attachments, not at the end of attachments. Design weld size is 6 mm. Measured values of weld sizes, flank angle and toe radius around the initiation point of main crack at the end of attachment are given in Table 1. Table 2 shows the mechanical properties and plate thickness of specimens.

2.2 Fatigue tests

The fatigue tests were carried out under uniaxial loading by using dynamic actuators with capacity of 300 kN, 500 kN and 2,000 kN. The stress ratio (R) of specimens was 0.02 ~ 0.15. The loading rate was 2 ~ 15 Hz. In order to make beach marks on fracture surfaces, beach mark tests were also conducted for all types of specimens.

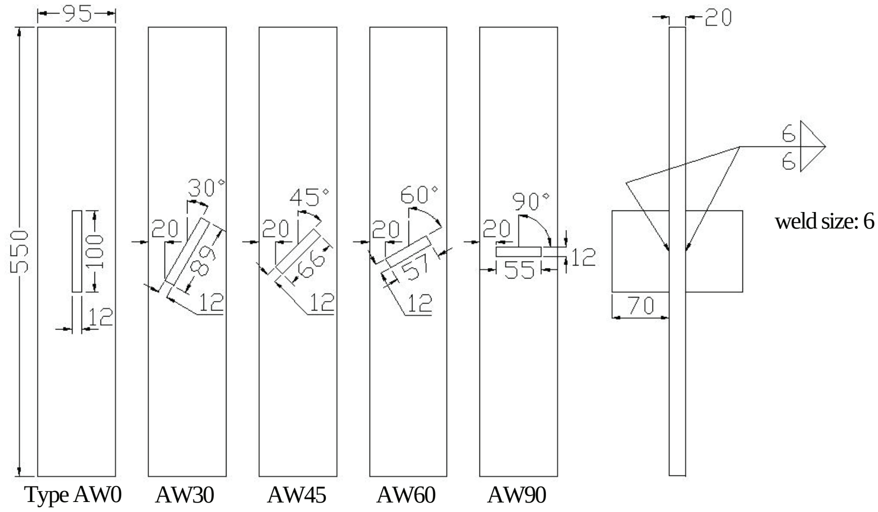


Fig.2 Dimensions of specimens (unit: mm)

Table 1 Weld sizes, flank angle and toe radius of specimens

		Weld size on main plate (mm)	Weld size on attachment (mm)	Flank angle (°)	Toe radius (mm)
AW0	Average	11.15	8.01	60.58	0.95 [a]
	Standard deviation	0.62	0.53	9.81	0.42 [b]
AW30	Average	10.71	6.33	47.72	
	Standard deviation	0.69	1.00	11.76	
AW45	Average	10.02	6.29	60.62	0.82
	Standard deviation	1.06	0.37	9.69	0.21
AW60	Average	10.72	6.51	55.20	
	Standard deviation	0.51	0.40	8.61	
AW90	Average	10.23	7.49	56.15	0.72
	Standard deviation	0.75	1.04	7.89	0.47

a average of two specimens among total four specimens

b standard deviation of two specimens among total four specimens

Table 2 Mechanical properties and plate thickness of specimens

	Thickness (mm)	Yield point (MPa)	Tensile strength (MPa)	Elongation (%)
Main plate (BHS500)	20	611	691	36
Attachment (SM490Y)	12	over 365 [a]	490 ~ 610 [a]	over 15 [a]
Welding wire (MX-60)		560 [b]	640 [b]	28 [b]

a mechanical properties of JIS G3106 SM490Y steel

b mechanical properties of JIS Z3313 YFW-C60FM welding wire

3. Finite element analyses

3.1 The effective notch stress approach

For out-of-plane gusset joints, cruciform joints and diaphragm joints where weld lines are parallel or perpendicular to uniaxial loading, it is possible to distinguish whether fatigue cracks will initiate at the weld toe or the weld root by using the effective notch stress approach[13]. However, for the specimens of this study, it is not clear where fatigue cracks will initiate because the stress distributions at weld toes and weld roots may be affected according to the angle between principal stress direction and weld attachment. Hence, finite element models are prepared for both weld toes and weld roots. Fig. 3 shows an example of a finite element model to calculate effective notch stresses. For each type of specimens, global and sub-model are prepared by using the sub-modeling technique of ABAQUS[14]. Both global models for the whole specimens and sub-models for the local parts around weld toe and weld root are made of three-dimensional (quadratic tetrahedral) solid elements. In case of global models, 1/2 models are made considering the symmetry plane of specimens. Weld beads of design weld size (6 mm, 45° flank angle), root gaps of 0.5 mm and effective notches of radius 1 mm are introduced in the global and sub-models. As shown in Figs. 1 and 3, the locations of effective notch radius tips for weld toes and weld roots are positioned to touch the roots of real notches[2]. In the IIW fatigue design recommendations, it is recommended that the element size of effective notch is not more than 1/4 of radius in case of high order elements[2]. Originally, this rule for element size means to arrange at least three elements along an arc of 45°[12]. When three elements are arranged along an arc of 45°, the exact element size is 0.262 mm in case that the radius of effective notch is 1 mm. Hence, the element size of effective notch in this study is about 0.262 mm in the circumferential direction. The element size in the weld line direction is also about 0.262 mm. The element size in the direction normal to the surface of effective notch increases from about 0.262 mm to larger length.

3.2 The structural hot spot stress approach

Fig. 4 shows an example of a finite element model to calculate

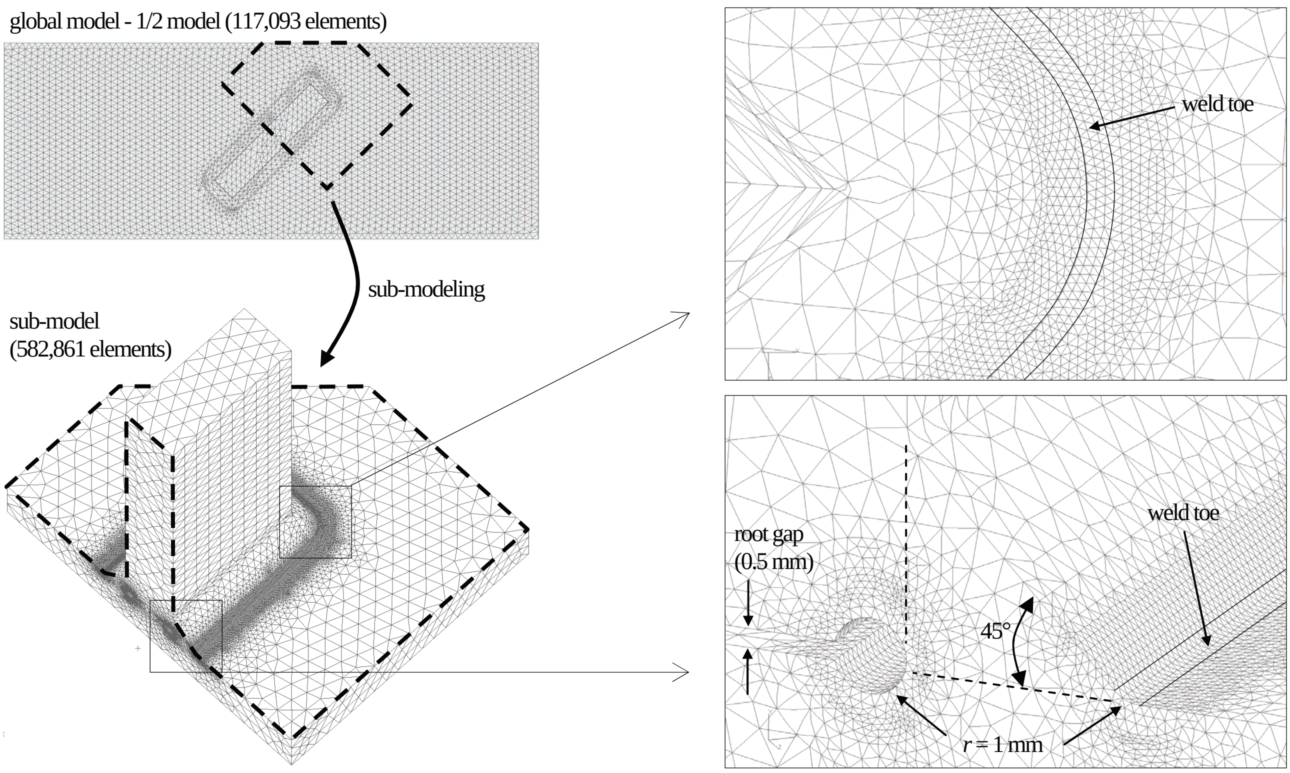


Fig.3 Global and sub-model for Type AW45 when using the effective notch stress approach

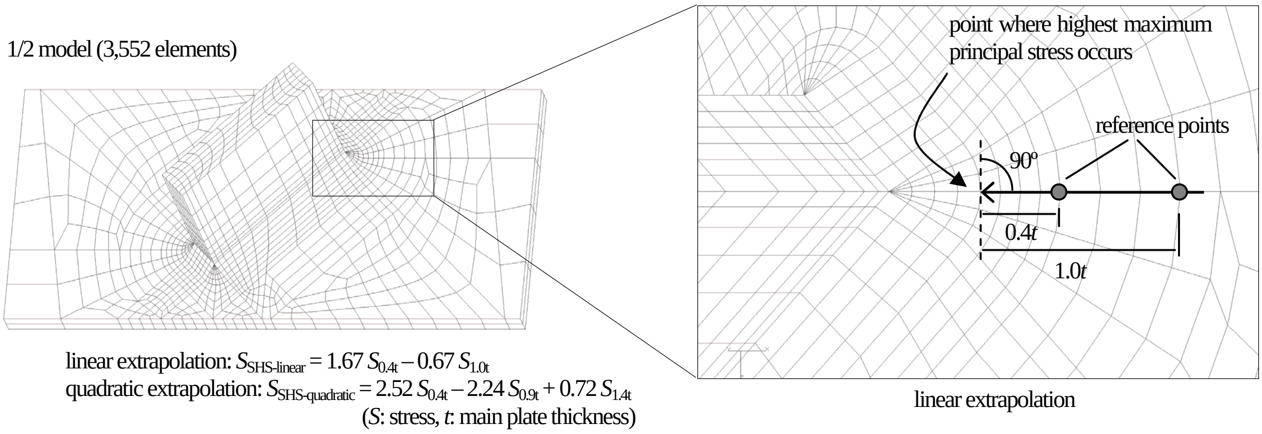


Fig.4 Finite element model for Type AW45 when using the structural hot spot stress approach

structural hot spot stresses. The finite element models using relatively fine mesh are made of three-dimensional 8 node solid elements[15] and are analyzed with ABAQUS. Structural hot spot stresses at weld toes where the highest maximum principal stress occurs are calculated by extrapolating surface stresses at reference points in the direction normal to weld toes. Two reference points at 0.4t and 1.0t from weld toe are used for linear extrapolation[2)15)]. In addition, quadratic extrapolation using three reference points at 0.4t, 0.9t and 1.4t from weld toes is used to compare with the results of linear extrapolation[2)15)].

4. Discussion

4.1 Fatigue crack initiation points

(1) Fatigue test results

In all types of specimens, fatigue cracks initiated from the tip of weld toes at the end of weld attachments. Fig. 5 shows the fatigue cracks and fracture surfaces of Types AW0, AW45 and AW90. In early stage, small cracks were formed at the same time. The cracks made separate crack propagation planes perpendicular to the direction of loading and developed on each plane in semi-elliptical form. In the end, fracture occurred on a dominant crack propagation plane. Main crack initiation points are indicated by the arrows in Fig. 5. Any difference of crack initiation points depending on the angle between principal stress direction and weld attachment was not observed. For Type AW90, cracks which developed from craters around the center of attachment were also found.

(2) Choosing the type of the stress on effective notch surfaces

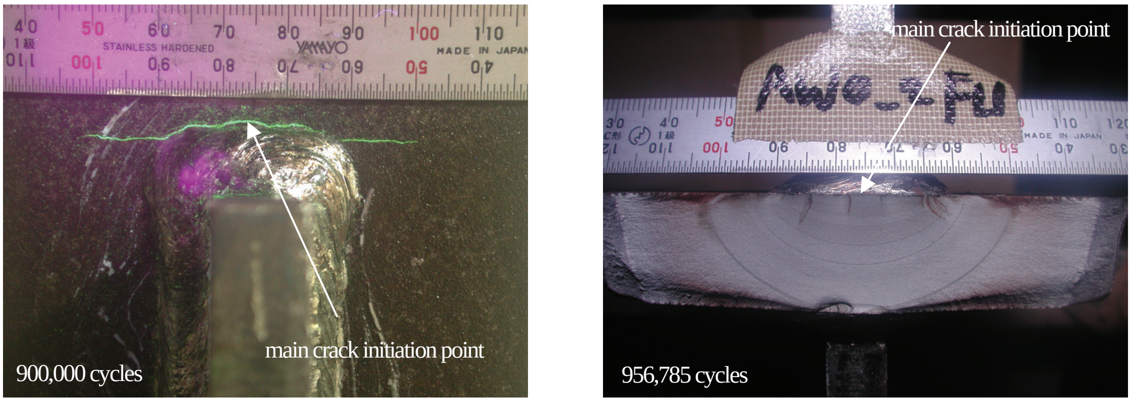
In Fig. 6, coordinates RC, TC and T are defined to show specific locations on the effective notch surfaces. The cross sections at specific positions along the target weld root line and target weld toe line are named sections (a) ~ (i) and sections (a`) ~ (i`), respectively. Using the coordinates RC and TC in Fig. 6, Fig. 7 shows the stress distributions on effective notch surfaces for Type AW45. Each graph shows maximum principal stress, minimum principal stress and Von Mises stress which are normalized by the nominal stress, at different cross sections along the weld root line and weld toe line.

Along the weld root line of Type AW45 (Fig. 7a), the highest absolute value of minimum principal stress is less than the highest maximum principal stress along the weld root line. Along the weld toe line of Type AW45 (Fig. 7b), the minimum principal stresses are almost zero. Along the weld root line or weld toe line of Type AW45 (Fig. 7), the highest Von Mises stress is less than the highest maximum principal stress. In addition, for weld root lines or weld toe lines of other types of specimens, the highest maximum principal stress is more than the absolute value of minimum principal stress and the Von Mises stress. Hence, in the following Section 4.1(3), the stresses on effective notch surfaces are expressed in terms of normalized maximum principal stresses.

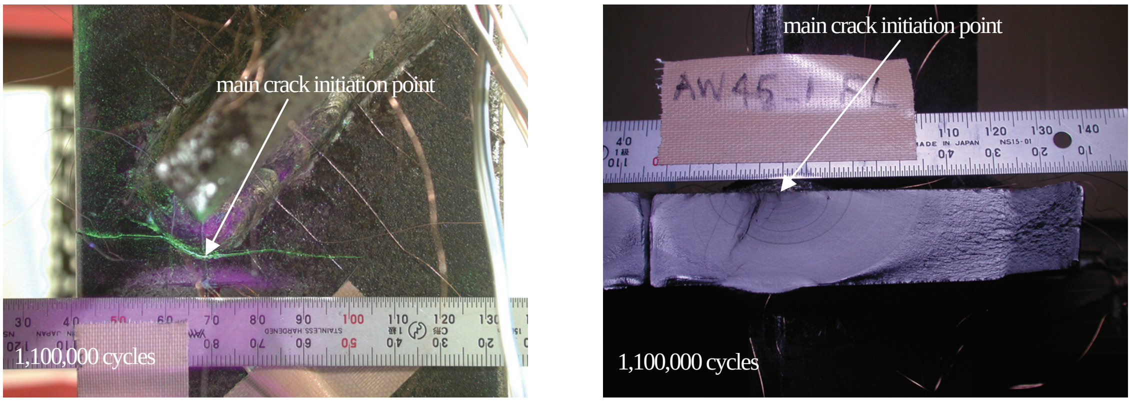
(3) Relationships between crack initiation points and effective notch stress peak points

In Fig. 7, when the maximum principal stresses in weld toe line are compared with the maximum principal stresses in weld root line, the highest maximum principal stress of Type AW45 is observed at the cross section (c`) of weld toe. In addition, for other types of specimens, the highest maximum principal stresses occur at weld toes, not at weld roots. Hence, in Fig. 8, the stress distributions on effective notch surfaces of Types AW0, AW30, AW45, AW60 and AW90 are plotted only in case of weld toe lines. In Fig. 8b (bottom graph), vertical axis means the effective notch stress which is expressed in terms of normalized maximum principal stress and horizontal axis represents coordinate T which is defined for weld toe line in Fig. 6. As shown in Fig. 7, for each type of specimens the location of coordinate T is decided so that the coordinate T passes through the point of the highest maximum principal stress. In Fig. 8, six points along coordinate T are named points t1, t2, t3, t4, t5 and t6.

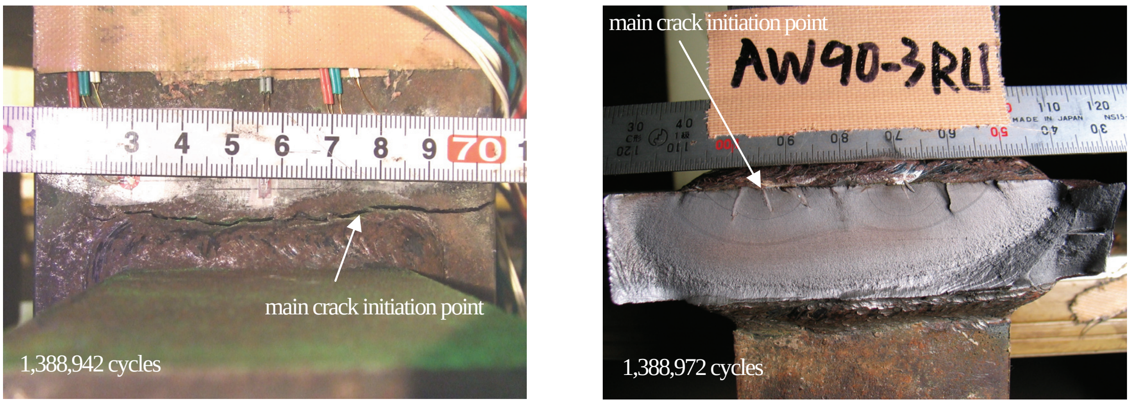
In Fig. 8, the peak points of effective notch stresses of specimens are located between point t2 and point t4. In all types of specimens, the



(a) Type AW0 (AW0-2)



(b) Type AW45 (AW45-1)



(c) Type AW90 (AW90-3)

Fig.5 Fatigue cracks and fracture surfaces of Types AW0, AW45 and AW90

peak points of effective notch stresses are almost the same as the main crack initiation points. Hence, it is possible to find crack initiation points by using the effective notch stress approach, regardless of the angle between principal stress direction and weld attachment.

4.2 Fatigue strengths

In order to examine the effect of the angle between principal stress direction and weld attachment on the fatigue crack initiation and propagation separately, fatigue test results are arranged with fatigue life (N_f), initiation life (N_c) and propagation life (N_p) in Figs. 9-11. N_f is the total number of cycles when specimens failed. N_c is defined as the number of cycles when the surface length of fatigue crack is 10 mm which is calculated by reading the crack lengths on the photographs of magnetic particle tests and beach marks, with the corresponding numbers of cycles. N_p is calculated by subtracting N_c from N_f.

Fig. 9 shows the fatigue test results obtained using the nominal stress approach. Fatigue strength difference depending on the angle between principal stress direction and weld attachment is observed in Fig. 9a. From Fig. 9b and c, it can be seen that the fatigue strength difference shown in Fig. 9a occurs mainly in crack initiation, not in crack propagation.

Fig. 10 shows the fatigue test results obtained using the structural hot spot stress approach. Structural hot spot stresses are calculated by using linear and quadratic extrapolation (see Fig. 4) and the stresses are expressed in terms of the maximum principal stresses. Structural hot spot stresses normalized by the nominal stresses are given in Table 3. In Fig. 10, structural hot spot stress ranges are calculated by multiplying nominal stress ranges by the normalized structural hot spot stresses. Here only the stress ranges obtained using linear extrapolation are used because the difference between the values using linear extrapolation and the values using quadratic extrapolation is only 2 ~ 4%. The fatigue strength difference observed in the nominal stress approach results (Fig. 9a and b) decreases but it does not disappear in Fig. 10a and b.

Fig. 11 shows the fatigue test results obtained using the effective notch stress approach. The effective notch stress ranges are calculated by multiplying nominal stress ranges by the highest normalized maximum principal stresses on the effective notch surface of weld toe line. The fatigue strength difference observed in the results of the nominal stress approach (Fig. 9a and b) and the structural hot spot stress approach (Fig. 10a and b) is not observed in Fig. 11a and b. These results mean that the effect of the angle between principal stress direction and weld attachment on the fatigue crack initiation life disappears when the effective notch stress approach is used. For out-of-plane gusset joints, the fatigue strength decreases as the length of gusset increases when the nominal stress approach is used. In the JSSC fatigue design recommendations, fatigue strength category F (FAT65) is used for out-of-plane gusset joints when the length of gusset is less than 100 mm, but G (FAT50) when the length of gusset is more than 100 mm[1]. Here as shown in Fig. 2, each type of specimens has a different length of attachment. Hence, the results in Fig. 11a and b mean that the effect of attachment length on the fatigue crack initiation life also disappears when the effective notch stress approach is used.

In order to compare with the results in Fig. 11a, the available fatigue test results of plates with inclined out-of-plane gussets[16] are rearranged by using the effective notch stress approach, as shown in Fig. 12. By using the same way explained in Section 3.1, finite element models for the specimens in Ref. 16 are prepared and the effective notch stress ranges are calculated. Types As90, As60, As45, As30 and As0 which are the specimens in Ref. 16 correspond to Types AW0, AW30, AW45, AW60 and AW90 in this study, respectively. Fatigue strength difference between specimens in Ref. 16 and specimens in this study is small and the fatigue strengths satisfy the fatigue design curve of FAT225[17] for welded steel joints in the IIW fatigue design recommendations. In addition, when the effective notch stress approach is used, the fatigue strengths of specimens of this study are almost the same as the fatigue strengths of available test results of large-size specimens for out-of-plane gusset joints, cruciform joints and diaphragm joints[13], where the definition of fatigue life (N_f) is the same as the definition in Fig. 11a. These results mean that the effects of joint type, size, weld attachment length and the angle between principal stress direction and weld attachment on fatigue strength, which are observed in the nominal stress approach results, disappear when the effective notch stress approach is used.

Table 3 Structural hot spot stresses normalized by the nominal stresses (maximum principal stress is used as structural hot spot stress)

	AW0	AW30	AW45	AW60	AW90
(1) linear extrapolation	1.21	1.15	1.12	1.08	1.04
(2) quadratic extrapolation	1.26	1.18	1.15	1.10	1.07
(2) / (1)	1.04	1.03	1.03	1.02	1.02

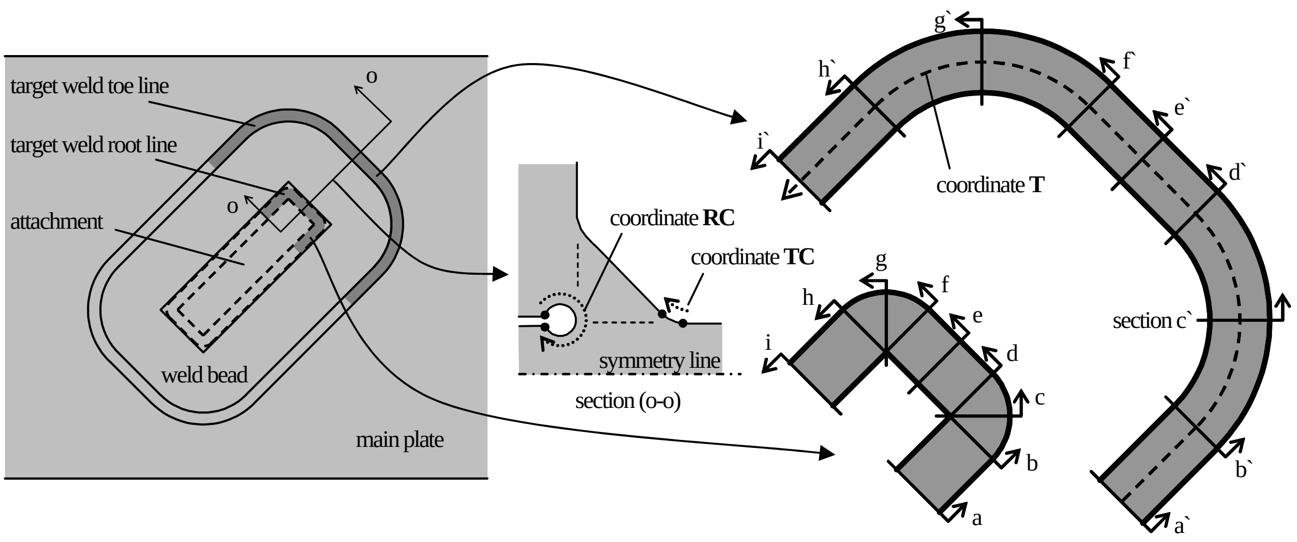


Fig.6 Effective notches along the weld root line and weld toe line showing coordinates RC, TC and T

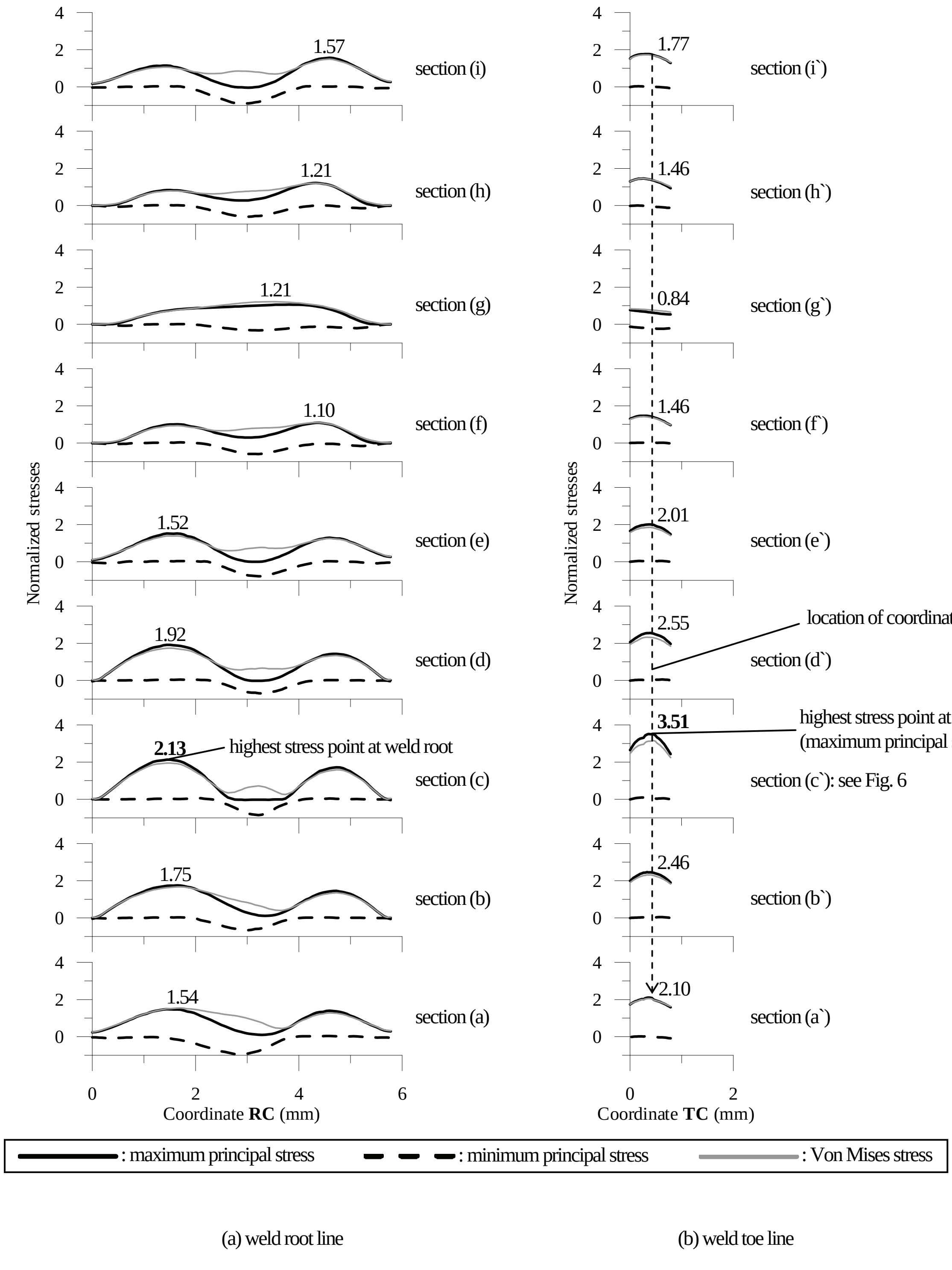
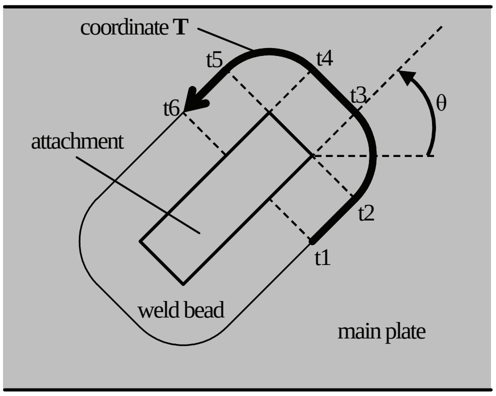
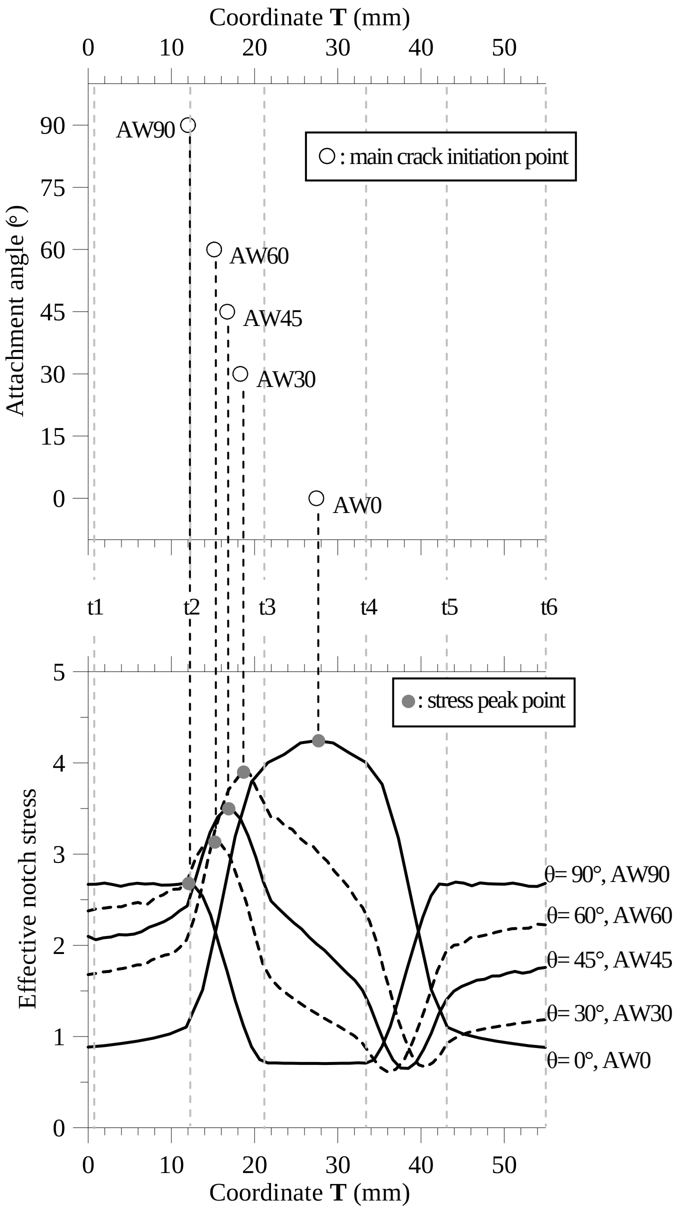


Fig.7 Maximum principal stress, minimum principal stress and Von Mises stress which are normalized by nominal stress, at different cross sections along the weld root line and weld toe line for Type AW45 (see Fig. 6 for coordinates RC, TC and T, sections (a) ~ (i) and sections (a`) ~ (i`))

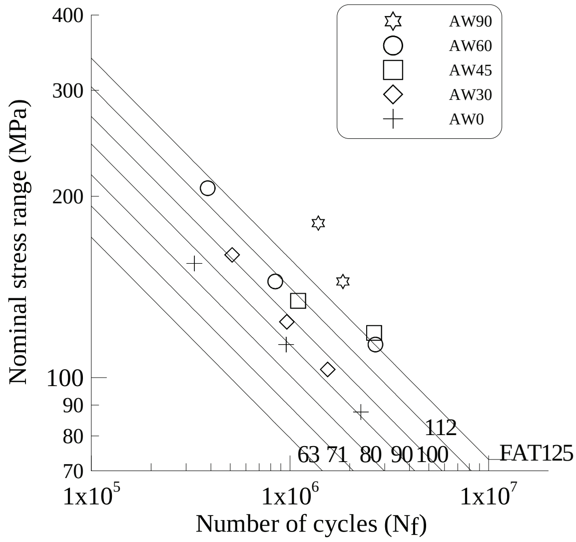


(a)

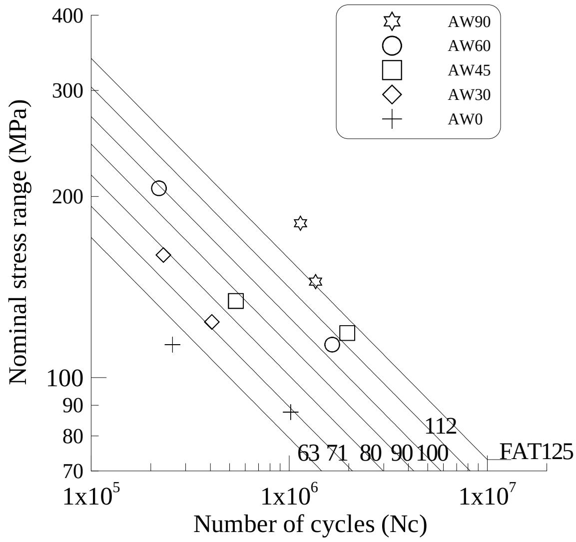


(b)

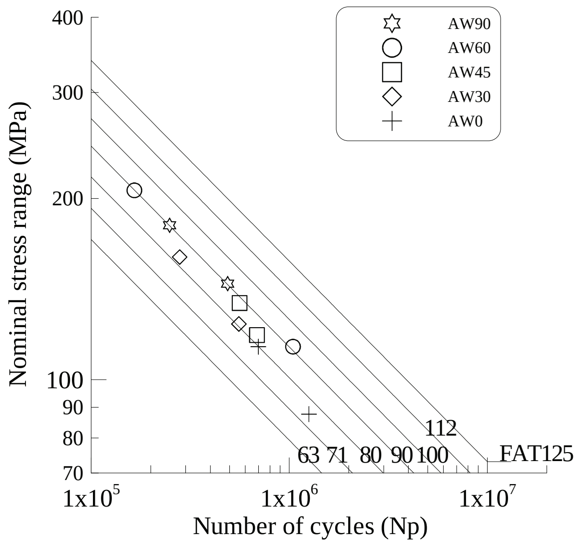
Fig.8 Main crack initiation points and effective notch stresses along the weld toe line (effective notch stresses are expressed in terms of normalized maximum principal stresses)



(a)



(b)



(c)

Fig.9 Fatigue test results using the nominal stress approach

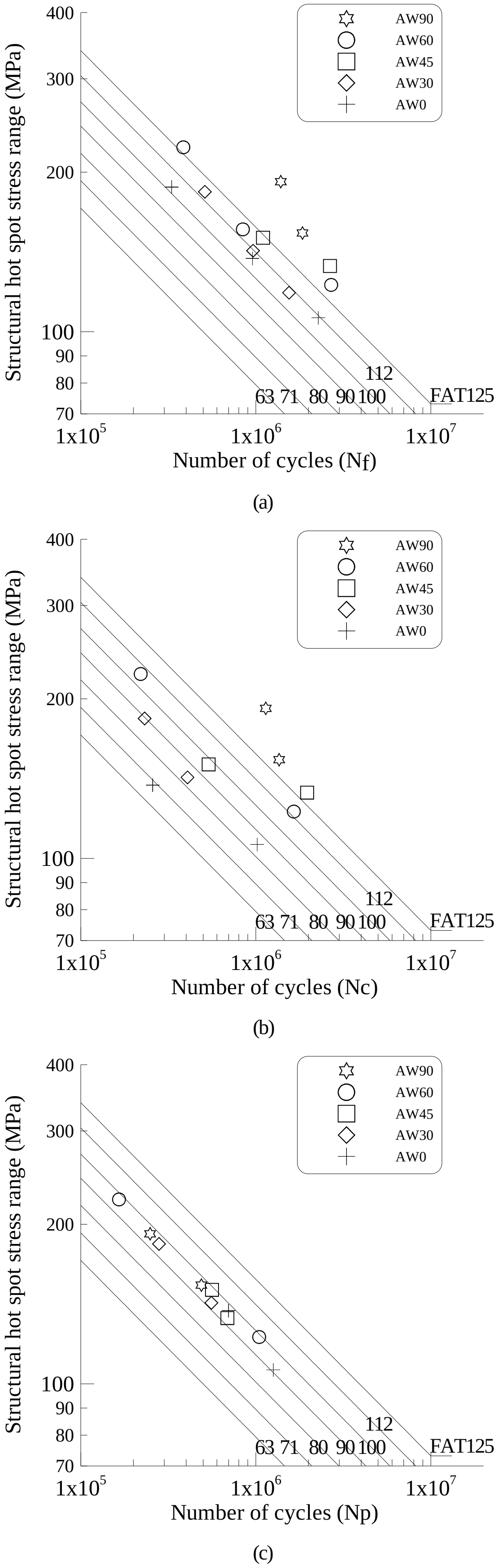


Fig.10 Fatigue test results using the structural hot spot stress approach

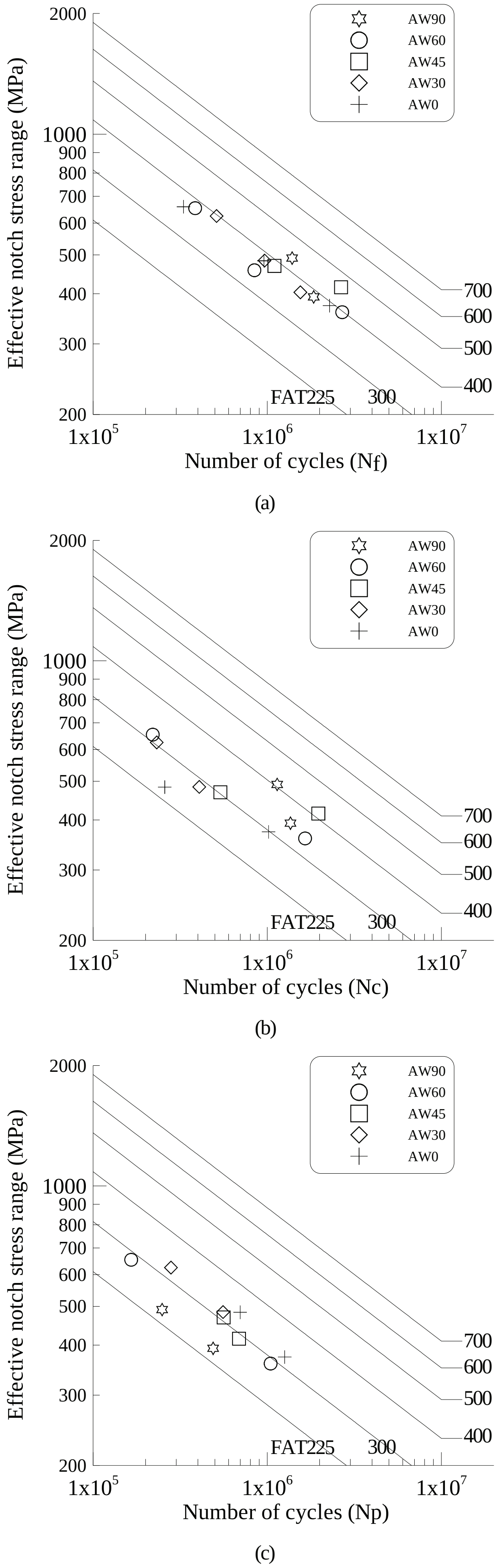


Fig.11 Fatigue test results using the effective notch stress approach

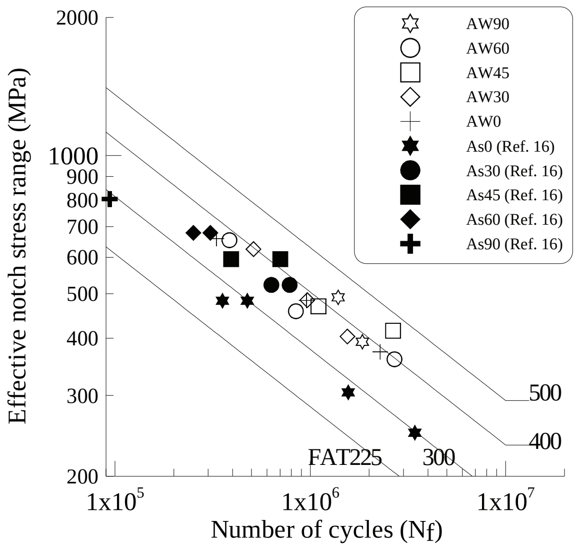


Fig.12 Comparison between fatigue test results of this study and available fatigue test results of plates with inclined out-of-plane gussets using the effective notch stress approach (Types As90, As60, As45, As30 and As0 in Ref. 16 correspond to Types AW0, AW30, AW45, AW60 and AW90 in this study, respectively)

5. Conclusions

Through the fatigue assessment of out-of-plane attachments with various angles based on the results of the fatigue tests and finite element analyses, the following conclusions have been obtained.

- It is possible to find fatigue crack initiation points by using the effective notch stress approach because the peak points of effective notch stress coincide with main crack initiation points at weld toes, regardless of the angle between principal stress direction and weld attachment.

- The effect of the angle between principal stress direction and weld attachment on the fatigue crack initiation life cannot be considered when the nominal stress approach and the structural hot spot stress approach are used. However, by using the effective notch stress approach, it is possible to consider the effect of the angle between principal stress direction and weld attachment on the fatigue crack initiation life.

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(Received September 18, 2007)