LOCAL STRESS APPROACH FOR FATIGUE ASSESSMENT OF WELDED JOINT

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***ABSTRACT*:** Local stress approach can be a strong tool for assessing the fatigue performance of welded joint in steel bridge structures, which is subjected to complicated stress field. This paper surveys the effectiveness and remaining problems of the local stress approaches. Then, this paper examines a method, which utilizes the measured stress, to evaluate fatigue strength of weld root of load carrying type cruciform welded joint.

KEYWORDS: fatigue, local stress approach load carrying cruciform welded joint

1. INTRODUCTION

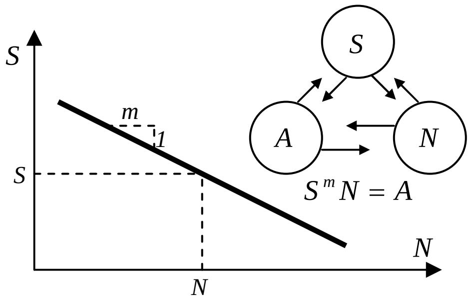


Fig.1 S-N diagram; *S*: stress range, *N*: fatigue life and *A*: representing fatigue strength

One of the most important deterioration mechanisms of steel bridge structures, which occurs in-service condition, is fatigue. In Japan, numerous number of fatigue cracks has been recently reported to initiate in steel bridge superstructures and even substructures. Since such fatigue cracks may lead a significant influence to the traffic and even collapse of the bridges if the cracks are left to propagate, repair and retrofitting works including investigation of fatigue mechanism for such fatigue damaged bridges are very urgent issues now.

As shown in Fig.1, relationship between the stress range applied, *S*, fatigue life (loading cycle to failure), *N* and fatigue strength *A* is simply expressed by following equation (1);

$$S^m N = A \qquad (1)$$

where

m: constant (=3 for weld subjected to cyclic normal stress)

This equation, for an example, means that fatigue life can be calculated when fatigue strength and applied stress range are known. Present fatigue design is conducted with this fatigue design S-N diagram, which is expressed with fatigue strength categories specified with nominal stress range. Therefore, if nominal stress range is unknown or hard to determine, it should say that fatigue strength category is also unknown. However, most of cracks in steel bridges have been found to initiate at the area where nominal stress range is hard to be determined because of the complexity of stress field (complexity of stress field itself and complexity of stress occurrence mechanism). For this reason, it is now very difficult to evaluate the fatigue life of such areas in the steel bridges at the design term and maintenance term. Therefore, it is very urgent issue to establish a method to evaluate the fatigue strength of welded joint subjected to such complicated stress field.

Recently, local stress approach for assessing the fatigue strength of welded joint is investigated. This approach utilizes the stress in the vicinity of the location of crack initiation, which can be obtained from stress measurement or numerical analysis like FE analysis. Philosophy of local stress approach and many research works are well surveyed by Radaj and Sonsino (1998). First part of this paper surveys the effectiveness and remaining problems (recent topics) of the local stress approaches.

As mentioned above, local stress approaches utilize the stress in the vicinity of the location of crack initiation. In order to obtain a precise stress by calculation, it is necessary to know the detail information of local structural geometry. While the stress at cracked location is sometimes very sensitive against the local geometry, but the structural modeling of local geometry itself sometimes include very uncertainty. In addition, local stress at cracked location cannot be sometimes evaluated without considering the entire bridge behavior. In such area, it needs numerous efforts to obtain the precise stress analytically. Thus, it is necessary to estimate the method to evaluate the fatigue strength using measured stress. For the welded root cracking, since the crack initiation location is embedded inside the weld, it is not usually possible to measure the stress in the vicinity of the initiation point. The only method presently proposed to evaluate the fatigue strength as a local stress approach is effective notch stress method (which is explained later). In this study, a local stress approach which utilizes stress range measured in front of weld toe for load carrying type cruciform welded joint is examined.

2. LOCAL STRESS APPROACH

One of the factors, which dominate the fatigue strength category of welded joint, is stress concentration (*other factors are weld defect, welding residual stress, etc*). Usually, the difference of fatigue strength category of weld-attachment joint results from the difference of stress concentration at crack initiation location, which depends on the size and configuration of the joint. Local stress approach focuses this difference of stress concentration and evaluates the difference of the fatigue strength. In this section, hot spot stress approach and effective notch stress approach, which are widely used recently, are briefly introduced.

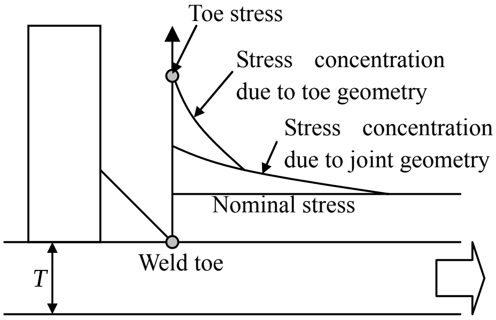


Fig.1 Schematic illustration of stress concentration at weld toe

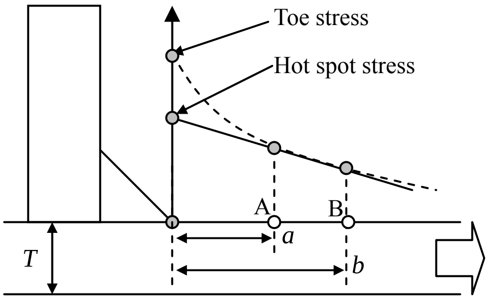


Fig.2 Extrapolation to calculate hot spot stress

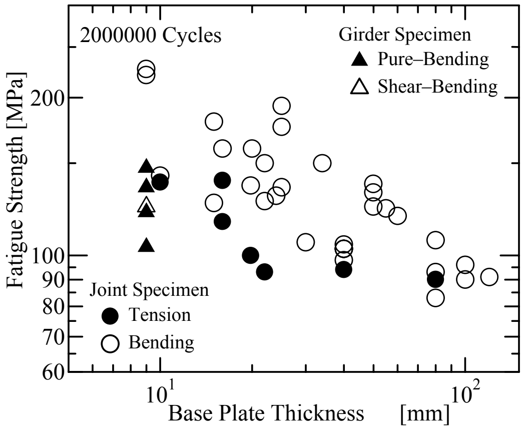
2-1 Hot spot stress approach

Stress concentration at weld toe can be divided into two parts as illustrated in Fig.1: stress concentration K_w depending on the size and type of welded joint, and stress concentration K_s depending on the local toe geometries, such as toe angle and toe radius (for example, Miki 1992). It is usually recognized that the influence of the difference of K_s results in the scatter in each fatigue strength category. Hot spot stress aims to grasp the structural stress K_w. Since fatigue strength categories of weld-attachment joints are usually classified with type and size of welded joint, it is said that fatigue strength of weld-attachment joint can expressed with only one fatigue strength category when using hot spot stress range.

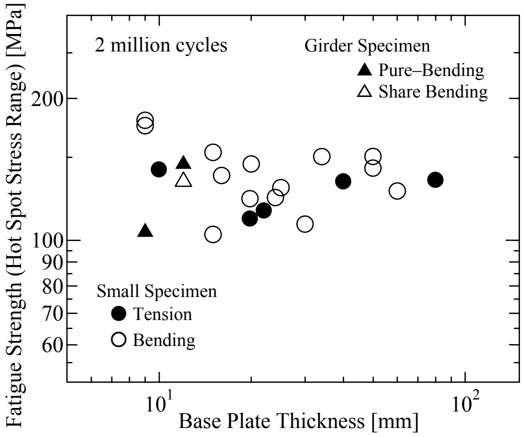
Several methods to calculate hot spot stress have been proposed. For an example, for pipe (with hollow section)-welded joints in marine/off-shore structures, several formulae for calculation of hot spot stress have been proposed and utilized in the fatigue design. Also for the flat-plate welded joints, which are usually used for bridge structures, several methods to calculate hot spot stress are proposed. Most of methods seem to obtain the stress at weld toe by extrapolation from stresses at two point in front of weld toe as illustrated in Fig.2. For an example, some extrapolation methods, which were proposed by Yagi (1991) and Huther (1990), are listed in Table 1. Miki (1992) also examined another extrapolation points, those are 4 mm and 6 mm from weld toe. Recently, International Institute of Welding (IIW) recommends the extrapolation points of 0.4*T* and 1.0*T* far from weld toe, where *T* is base plate thickness. (Other methods are also proposed, such as one-point stress method where stress at one location a certain distance (for example 0.3*T*: Nihei) far from weld toe is decided as hot spot stress.)

Table 1 Examples of calculation methods of HSS

	a	b
A	0.5T	1.0T
B	0.5T	1.5T
C	0.4T	2.0T
D	1.0T	3.0T
E	4.0mm	10.0mm
F	$1.57\sqrt[4]{T^3}$	$4.9\sqrt[4]{T^3}$



(a) with nominal stress range



(b) with hot spot stress range

Fig.3 Fatigue strength of cruciform weld joint

As mentioned above, when using hot spot stress range for the fatigue strength evaluation, the size effect and shape effect can be eliminated. Fig.3 shows an example, where the many results of the fatigue tests of cruciform welded joint specimens having widely-scattered base-plate thicknesses are arranged with (a) nominal stress range and (b) hot spot stress range calculated from the stresses at 4 and 6 mm away from weld toe (Anami, 2001). It is clearly observed if nominal stress range is used for vertical axis, fatigue strength decreases with an increase in the base plate thickness and fatigue strength of large-scale girder specimen is much smaller than that of small joint specimen. However, this tendency disappears when hot spot stress range is used instead of nominal stress range.

In order to use this hot spot stress range for fatigue evaluation, fatigue strength category specified with hot spot stress range is necessary as illustrated in Fig.1. Recently, Niemi and Marquis (2002) proposed the fatigue strength category of IIW-FAT100 or 90 (see the detail in the reference) specified with hot spot stress range for weld-attachment joints.

Advantages of the use of hot spot stress range might be summarized as follows;

- hot spot stress can be calculated from stresses in front of weld toe, which can be obtained from stress measurement in site (in real bridge structures) and also stress analysis,
- fatigue evaluation can be done for the weld joint whose (nominal stress base)fatigue strength category is unknown,
- since hot spot stress can be obtained in field, fatigue evaluation can be conducted even after change of structural detail by repair and retrofit,
- since hot spot stress can be obtained from structural analysis, this approach can contribute the FEA (or other structural analysis)-based bridge design.

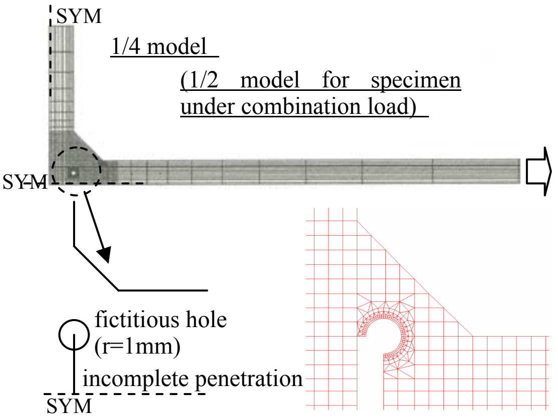


Fig.4 FE model for calculation of ENS

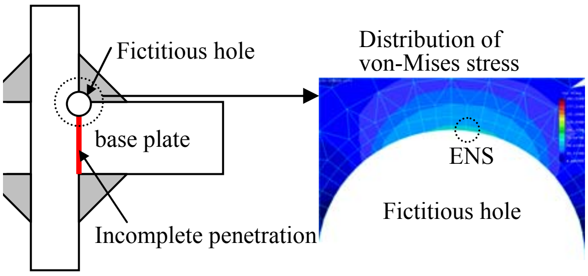


Fig.5 Distribution of von-Mises stress around fictitious hole

Other than establishing the method to calculate hot spot stress and establishing the fatigue strength category based on hot spot stress range, one of the research topics with respect to the hot spot stress is the applicability of hot spot stress approach for the complex stress field. Most of research works related to the fatigue strength focuses the fatigue behavior of welded joint subjected to in-plane stress normal to the weld line. However, as previously mentioned, many fatigue cracks are found in the area subjected to the complex stress field containing in-plane shear, out-of-plane bending/shear. In addition to this difficulty, in bridge structures, stress fluctuation, which causes fatigue cracks, mainly results from vehicle and train passing through the bridges. This means that the loading point on the bridges moves so that the stress field, such as principal stress direction, is possible to change even one load cycle. For an example, Anami (2001) investigate the stress condition around the boxer weld of out-of-plane gusset welded to the girder web by FEM analysis with entire girder model. This reference concluded that the maximum stress around the boxer weld of web gusset is not always at the intersection of gusset centerline and boxer weld line, and moves with the change in the ratio of shear stress and bending stress. The method for evaluating the fatigue behavior of welded joint in such a complicated stress field has not been established yet, and this topic is now very hot issue also from the view point of applicability of local stress approach for the fatigue evaluation.

2-2 Effective notch stress (ENS) approach

As mentioned above, while the hot spot stress approach is a strong tool to evaluate the fatigue strength, this approach is inapplicable for the root crack. For the evaluation of fatigue strength in the case of crack initiation from weld root, effective notch stress (ENS) approach may be a useful tool. (this method is applicable also for weld toe cracking). Effective notch stress is defined as the maximum von-Mises stress along the circumference of a fictitious hole which has a certain radius (IIW recommends the radius of 1mm, but there is also other radii proposed) installed at the crack initiation location. Fig.4 shows an example of FE model for calculating ENS (This model is also utilized in chapter.3), where a fictitious hole is installed at a tip of incomplete penetration. Fig.5 shows an example of distribution of von-Mises stress in the vicinity of the fictitious hole. IIW recommended that fatigue strength of welded joint is categorized into IIW-FAT 225 (fatigue strength at 2 million cycles is 225 MPa) when using ENS (fictitious hole radius of 1mm) (for example, Morgenstern, 2004).

Due to the recent development of computer technology, it is now possible to conduct structural stress analysis of complicated structural detail model with very fine mesh. Recently, many researchers focus this method and examine the reliability of this method by discussing the ENS and fatigue experimental data.

However, this method relies on structural analysis, which needs detail structural information in order to obtain precise stress value. Next chapter explains an examination of local stress approach with measured stress in front of weld toe for fatigue assessment of root cracking in load carrying cruciform weld joint.

3. LOCAL STRESS APPROACH OF LOAD CARRYING CRUCIFORM WELDED JOINT

Load carrying cruciform weld joint is illustrated in Fig.6. This type of joint has two possible locations of crack initiation, namely weld toe and weld root (tip of incomplete penetration). As mentioned above, while the fatigue strength of weld toe can be evaluated by hot spot stress approach, this approach cannot be applied for the root cracking. While it is proposed that effective notch stress (ENS) approach can evaluate the root cracking, this approach relies on numerical analysis and needs detailed information of welded joints. However, there are some parameters which strongly affect the fatigue behavior of the weld root, such as length of incomplete penetration (IP), root gap size (G), and weld leg length (L). These geometrical parameters are usually very hard to grasp properly in site even by using non-destructive testing. Therefore, it is

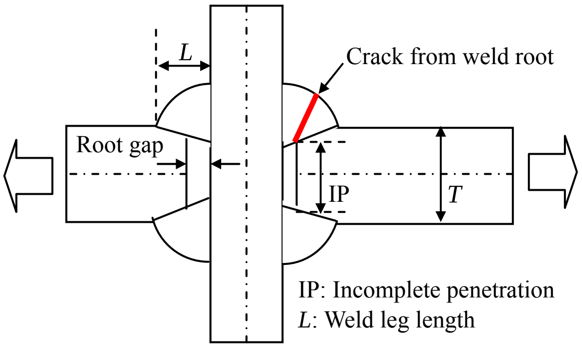


Fig.6 Crack from weld root of load carrying cruciform welded joint

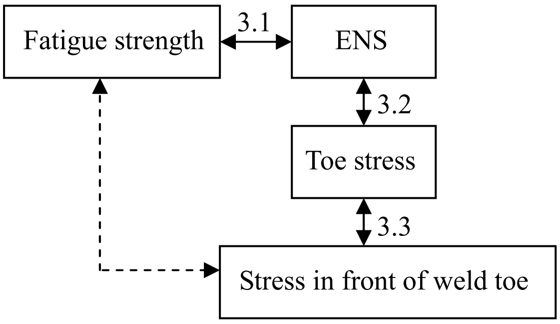


Fig.7 Illustration of purpose of this study

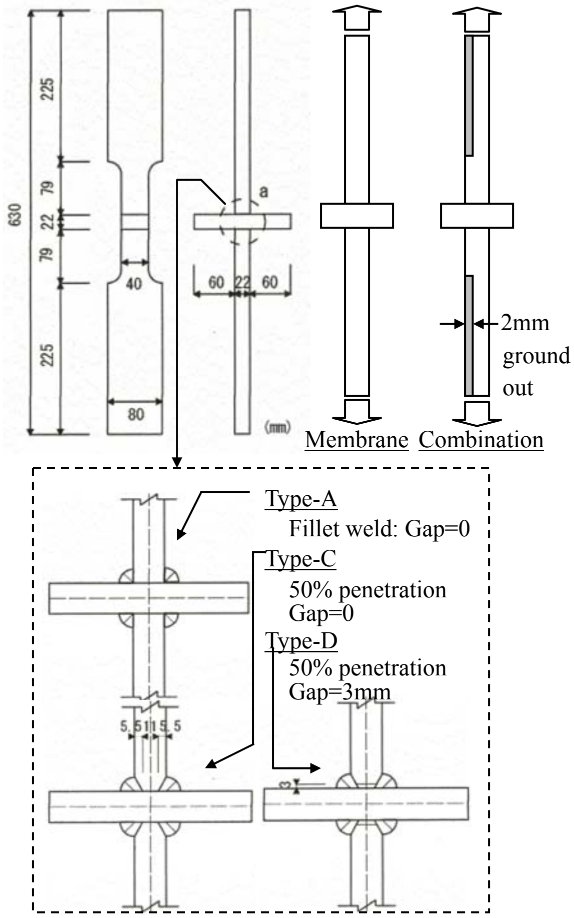


Fig.8 Specimens and Weld Details

necessary to investigate the method for evaluating the fatigue strength of the weld root of load carrying cruciform welded joint using the stress in front of the weld bead/toe. For this purpose, this study conducts following research works as illustrated in Fig.7; (1) applicability of effective notch stress for the crack from the weld root is examined experimentally, (2) relationship between the effective notch stress and toe stress is examined by parametric analytical work and (3) method to evaluate the toe stress by using the stress in front of weld toe is examined.

3-1 Applicability of ENS approach

Fatigue test specimens of load carrying type cruciform welded joint used in this study is shown in Fig.8. Fatigue tests of nine specimens are done under uni-axial membrane loading, and fatigue tests of other four specimens are carried out under combination of membrane loading and out-of-plane bending loading. One side of the surfaces of the specimens under combination loading is reduced at depth of 2 mm by grinding in order to apply an eccentric load. Calculated nominal out-of-plane bending stress is about 30 % of nominal membrane stress. Minimum loading of all of the fatigue tests are 10 kN. Figure 9 shows examples of fatigue cracks observed in this series of fatigue tests.

FE analyses are also conducted in order to obtain the effective notch stress (ENS). Examples of FE models are already shown in Fig.4. Minimum mesh size around the fictitious hole is about 0.08 mm that is less than 1/10 of the radius of the fictitious hole.

Fatigue test results are summarized in Fig. 10, where Kainuma's (2000) fatigue test results are also plotted with the results of FEM analysis carried out in this study. In the figure (a), nominal stress range (load range/cross section area of base plate) is for the vertical axis. For the specimen tested under

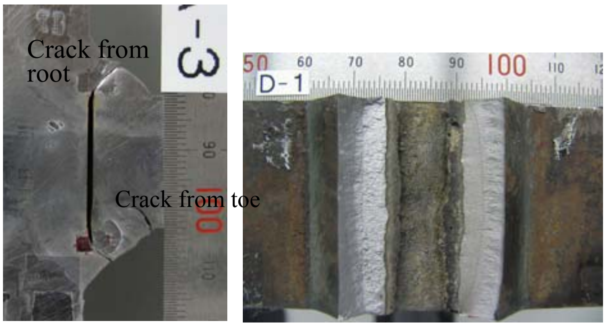
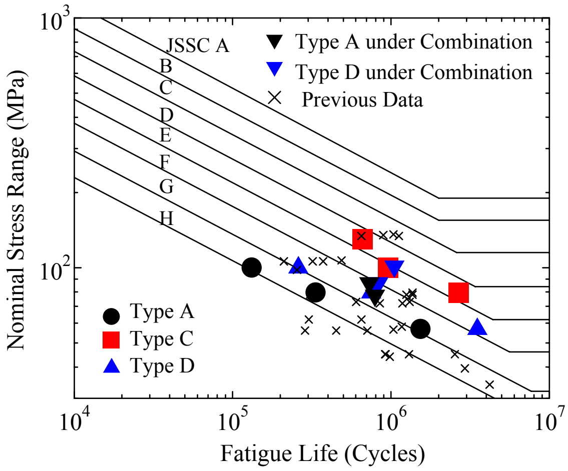
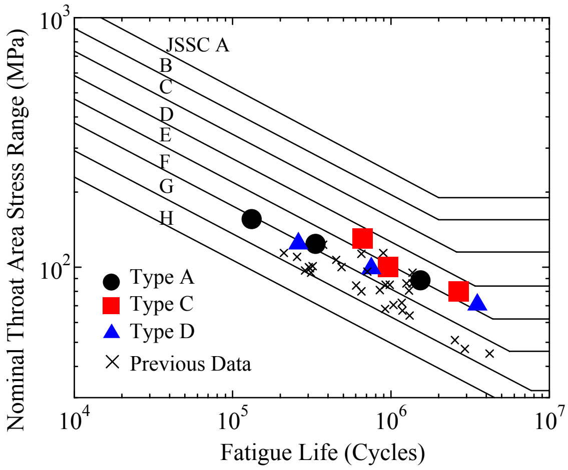


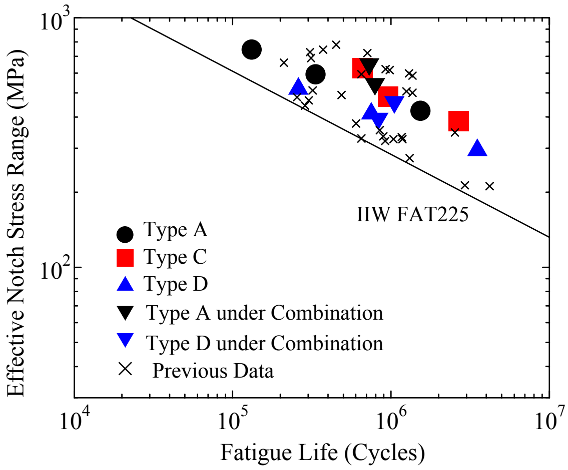
Fig.9 Fatigue cracks from root and toe



(a) S-N diagram with nominal stress range



(b) S-N diagram with nominal throat area stress range



(c) S-N diagram with ENS range

Fig.10 Fatigue test results

the combination load, sum of the nominal membrane stress range and out-of-plane bending stress range is used for the vertical axis. It is obviously observed that fatigue test results are much scattered. In the figure (b), nominal throat area stress range is used for the vertical axis. In Fatigue Design Recommendation from JSSC (Japanese Society of Steel Construction, 1995), it is specified that the fatigue strength category of load carrying cruciform welded joint is H class when evaluated with this nominal throat area stress range. All results are plotted over the JSSC-H class and the scatter band in (b) becomes much smaller than that in (a). In the figure (c), ENS range is used for the vertical axis. While slight difference between the specimens with and without the weld gap, the scatter band is smaller than that in (a). In addition, the influence of the out-of-plane bending is also evaluated well by using ENS range. In this figure (c), line of IIW (International Institute of Welding) FAT-225 class is also plotted. All fatigue test results including previous data are plotted over this IIW-FAT 225 line.

3-2 Relationship between the toe stress and ENS

In order to find out the stress at the area where strain gages can be installed for predicting the ENS, first the relationship between the toe stress and ENS is discussed. For calculating the longitudinal toe stress, the fictitious hole in each FE model used in previous section (Fig.4) is eliminated as shown in Fig.11. The weld detail parameters examined in this discussion is listed in Table 2. The minimum mesh size near weld toe is about 0.1 mm. Since the toe radius is 0 in this model, the toe stress is strongly influenced by the mesh size around the weld toe. However, since the mesh discretization near weld toe is the same in all models, it is possible to discuss the change of toe stress with the weld detail parameters.

Relationship between ENS and toe stress obtained from this series of FE analyses is shown in Fig.12. While the number of analysis cases (totally 54 cases) is not sufficient and all cases have equal weld leg-length, the relationship between the toe stress and ENS can be described with one curve, which is independent of the parameters, namely base plate thickness, weld gap size and incomplete penetration.

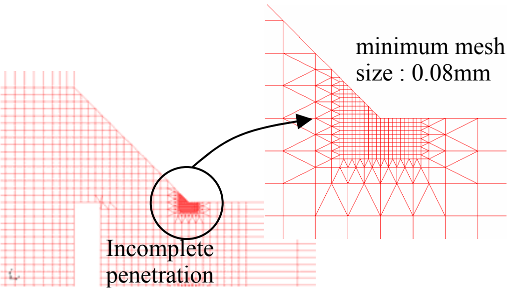


Fig.11 FE model for calculating toe stress

Table 2 Detail parameters for FEM

Base plate thickness *T*	11, 22, 33 mm
Weld leg length *L*	6.5, 13 mm
Weld Gap *G*	0, 1.5, 3, 4.5
Penetration ratio *IP*	0, 27, 50, 67 %
IP=0 means fillet welding	

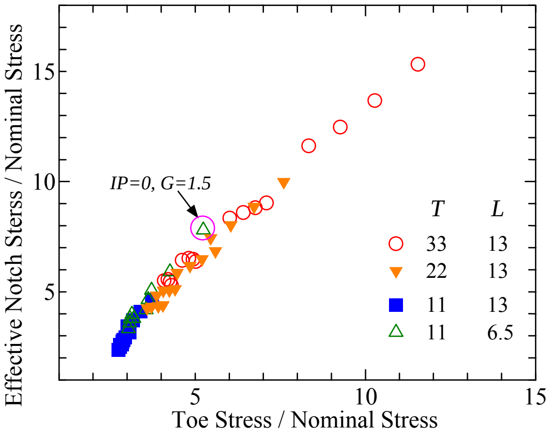


Fig.12 Relationship between ENS and Toe stress

3-3 Relationship between the toe stress and stress in front of weld toe

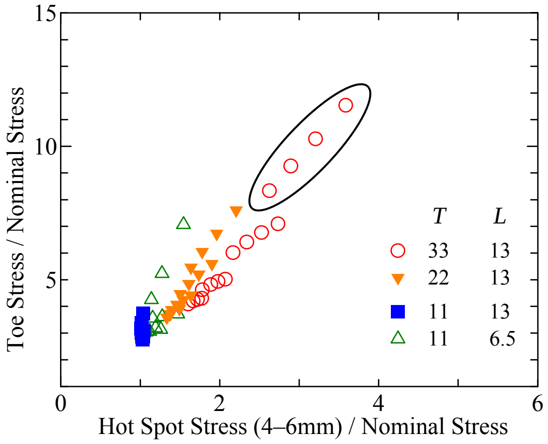
Previous section explains the possibility to evaluate ENS and even fatigue strength from toe stress, but it is impossible to measure directly toe stress itself. Thus, in this section, the possibility to predict the toe stress using stress in front of weld toe, which can be measured in field is examined.

As mentioned before, stress concentration at weld toe can be divided into two factors, K_w and K_s. Since the FE mesh near weld toe is the same in all models, K_s should be the same in all analytical cases. Thus, the difference of toe stress shown in Fig.12 results from the difference of K_w. On the other hand, hot spot stress (HSS) concentration factor is defined as the factor explaining structural stress concentration factor, K_w. Thus, the relationship between toe stress and HSS is examined here.

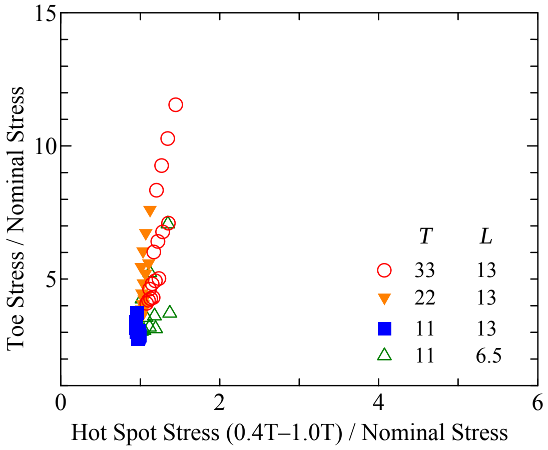
Fig. 13 shows the relationship between the toe stress and HSS, which calculated from the stresses at 4 and 6 mm from weld toe in Fig.(a) and from 0.4T and 1.0T from weld toe, where T is base plate thickness, in Fig.(b). While the results from the same models are plotted in the both figure, (a) and (b), significant difference in HSS is observed.

In the figure (a), there is a circle drawn over the 4 results (just as an example), which have the same length of incomplete penetration and different weld gap size. Relationship between HSS and toe stress when only weld gap size is changed seems linear, but that relationship strongly depends on the base plate thickness, weld leg length and incomplete penetration. The variation of HSS calculated from the stresses at 0.4T and 1.0T from weld toe between models is quite small compared to the variation of toe stress. In addition to that, in both figures (a) and (b), the change in HSS is quite small in the models having base plate thickness of 11 mm and weld leg length of 13 mm. This is because the changes in weld gap size and incomplete penetration size are occurred at the weld root and stress points for the extrapolation are far from that point (weld root).

Compared to Fig.12, the data plot is much scattered. As mentioned above in the definition of HSS, HSS evaluates the structural stress concentration. Since the toe configuration is the same in all models, it was expected that HSS and toe stress had a clear correlation. It is well known that fatigue strength of welded joint can not be directly evaluated using toe stress because fatigue life of welded joint is usually dominated by crack propagation life. Usually, the stress extrapolation points for calculating HSS are decided to evaluate well the fatigue strength of welded joint. Thus, it might be said that HSS currently proposed does not represent directly the toe stress. In order to achieve the goal of this study, it is necessary to find out the method to evaluate the toe stress by the stress measured in front of weld toe, but this topic is now on progress.



(a) HSS from stresses at 4 and 6mm from toe



(b) HSS from stresses at 0.4T and 0.6T from toe

Fig.13 Relationship between toe stress and HSS

4. SUMMARY

Presently, development of useful method to evaluate the fatigue strength of welded joint subjected to complicated stress field is strongly demanded for the purposes of design and also maintenance of steel bridges. In this paper, local stress approaches, advantages and remaining problems of use of hot spot stress approach and effective notch stress approach, are introduced.

Then, local stress approach for fatigue assessment of load carrying cruciform welded joint in the case of fatigue cracking from weld root is examined. From this discussion, the following remarks are obtained;

(1) Effective notch stress approach is useful for evaluating the fatigue strength of load carrying cruciform welded joint in case of root cracking even when the joint is subjected to the combination of membrane stress and out-of-plane stress fluctuation.

(2) Extent of effective notch stress can be evaluated by extent of longitudinal toe stress. This means, fatigue strength of weld root can be evaluated if toe stress can be predicted from measured stress.

(3) A good relationship between hot spot stresses and toe stress is not found in this study. This study is now investigating the stress in front of weld toe, which represent the toe stress and even can be measured.

REFERENCES

C. Miki, K. Tateishi, Y. Yamamoto and M. Miyauchi, 1992, *A Study on the Local Stress Approach to the Fatigue Assessment, Journal of Structural Engineering, JSCE (Japanese Society of Civil Engineering),* Vol. 38A: 989-997 (in Japanese).

D. Radaj and C. M. Sonsino, 1998, *Fatigue Assessment of Welded Joints by Local Approaches, Abington Publishing.*

S. Kainuma, et al., 2000, *Influence of Welding Position and Root Gap on Fatigue Strength of Load Carrying Fillet Welded Cruciform Weld Joint", Journal of JSCE,* No.647/I-51: 435-445 (in Japanese) .

Japan Society of Steel Construction (JSSC), 1993, *Fatigue Design Recommendation for Steel Structures,* Gihodo-Shuppan (in Japanese).

K. Anami, 2001, *Fatigue Strength Improvement of Welded Joints Made of High Strength Steel, Doctoral Thesis in Tokyo Institute of Technology.*

K. Anami and C. Miki, 2001, *Fatigue Strength of Welded Joint Made of High-Strength Steels, Structure Engineering Mater,* 86-94.

K. Nihei, 1996, *Study on Unified Fatigue Strength Assessment Method for Welded Structure – Hot Spot Stress Evaluating Method for Various Combinations of Plate Thickness and Weld Leg Length, Journal of SNAJ (The society of Naval Architects of Japan)*, 179 (in Japanese).

E. Niemi and G. Marquis, 2002, *Introduction to the Structural Stress Approach to Fatigue Analysis of Plate Structures, Proc. of The IIW Fatigue Seminar, IIW-Commission XIII*, 73-90.

C. Morgenstern et. al., 2004, *Fatigue design of aluminum welded joints by the local stress concept with the fictitious notch radius of rf=1mm, Doc. XIII-2009-04, International Institute of Welding.*

J. Yagi et. al, 1991, *Definition of Hot Spot Stress in Welded Plate Type Structure for Fatigue Assessment, IIW-XIII-1414-91*

F. Huther, 1990, *Recommendation for Hot Spot Stress Definition in Welded Joints, IIW WG XIII/XV*