Assessment of Brittle Fracture of Welded Structures under Seismic Wave

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Summary

It is necessary to develop the estimation method of fracture toughness at arbitrary strain rates because fracture toughness for most metals under high strain rates such as impact loading is lower than static fracture toughness. As a result of two dimensional FE analyses, it turned out that the strain rate-temperature parameter (R) keeps a certain constant value in fracture process zone at an arbitrary moment of loading process. Based on this result, we postulated that fracture toughness is a function of R value in a fracture process zone. Using this hypothesis, we developed the estimation method of fracture toughness under arbitrary strain rates. Failure analysis for brittle fracture of two kinds of structures were carried out. As a result of these analysis, we found evidence of the validity of this brittle fracture evaluation method. In addition, the up-to-date Japanese activities of the assessment of brittle fracture of structures under seismic wave were mentioned briefly.

Introduction

It is well known that fracture toughness decreases with increase of strain rate. Strain rate acting on various structures is three or four order faster than one under static fracture toughness test. On the contrary, it was a very severe evaluation of brittle fracture strength by K_{Id} test for practical welded build-up structures. The authors had proposed the quantitative estimation method of fracture toughness at arbitrary strain rates taking the effect of strain rate on fracture toughness into consideration [1] and the practical evaluation method of fracture toughness at arbitrary strain rates [2].

The purpose of this study is for the practical assessment of brittle fracture of structures which had occurred during the Great Hanshin Earthquake (17th Jan. 1995). Two kinds of structures were analyzed in this paper. One is a building of which a beam scallop bottom of box column-to-H beam connection was broken down. The other is a cast steel vertical column of a railway bridge. The up-to-date Japanese activities concerning the assessment of brittle fracture for structures under seismic wave are mentioned briefly in this paper.

Basic Concept for The Quantitative Effect of Strain Rate on Fracture Toughness

It is well known that yield strength of welded structural steels increases as the temperature decreases and as the strain rate increases. Adopting a strain rate-temperature parameter (R) [3], yield strength of steels could be represented only by R value as shown in Fig.1 for example. The authors had made clear that the strain rate at static loading condition corresponds to 5.0×10^{-5} [1/s] and we had given the correlation between static yield strength at room temperature and one at low temperature [4].

By using these results, it could obtain the yield strength at various R values only using static yield strength at room temperature. The solid curve in Fig.1 shows this estimation result.

Postulating the constitutive equation of materials followed by the n-th power work hardening ($\sigma = F\varepsilon^n$), it was also confirmed that strain hardening exponent (n) depends only on yield strength in case of static condition [1]. Therefore stress-strain diagram of steels under arbitrary strain rates can be assessed only by static yield strength although it usually changes by R value throughout the loading. Figure 2 shows examples of stress-strain diagram estimated by the procedure mentioned above in case of changing R value throughout the loading [2]. As understood from Fig.2, R value under dynamic condition plays the same role as temperature under static loading condition for the constitutive equation of steels. On the other hand, the fracture toughness is a function of temperature under static loading. For these reasons, the authors presumed that fracture toughness is a function of R value under dynamic loading. However, R value may change as a function of distance from a crack tip, because strain rate increases when approaching a crack tip. Therefore we might investigate the fracture initiation point in advance for discussing the strain rate effect on fracture toughness.

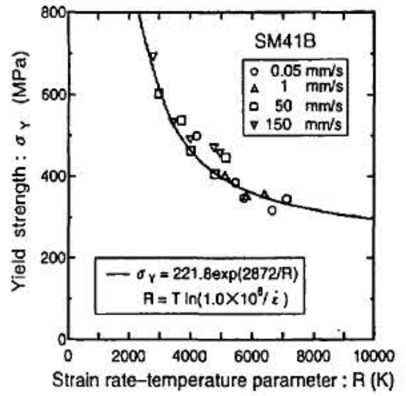

Fig. 1 Result of round bar tensile tests with various crosshead speeds and temperatures

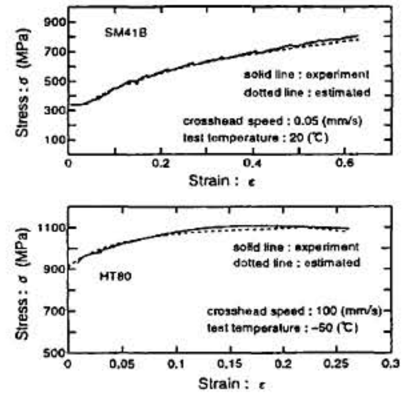

Fig. 2 Estimated and experimented stress-strain diagrams at different crosshead speeds and temperatures

The two dimensional dynamic thermo elastic-plastic FEM code including above constitutive equation had been developed [5]. In this FEM, the effect of crack blunting is taken into consideration. It could give the temperature rise distribution in the vicinity of a crack tip due to plastic deformation, where the conversion ratio of plastic work to heat energy equals 0.9 [6]. Figure 3 shows the estimation result of temperature rise in the vicinity of a crack tip by using this FEM. Estimated distribution is in good agreement with measured one [6]. Moreover, we revealed an improtant phenomenon from these calculation results of this FEM. This phenomenon is that R parameter takes almost constant value in the fracture process zone at an arbitrary moment as shown in Fig.4 for example. In this figure, IDNZ means intensely deformed non-linear zone [7], which is considered to equal fracture process zone. This reason is the mutual effect of blunting of a crack, temperature rise due to plastic work and changing of strain rate in the vicinity of a crack tip. Because of this phenomenon in the fracture process zone and the hypothesis which fracture toughness is a function of R value, we need not discuss the precise

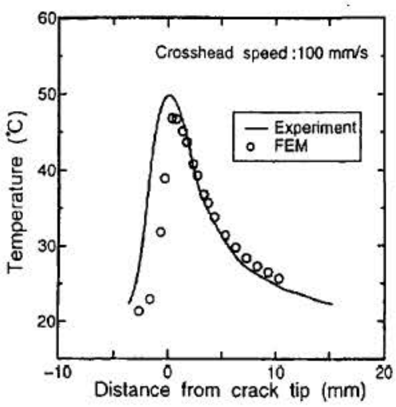

Fig. 3 Temperature distribution measured near a crack tip and one calculated by FEM

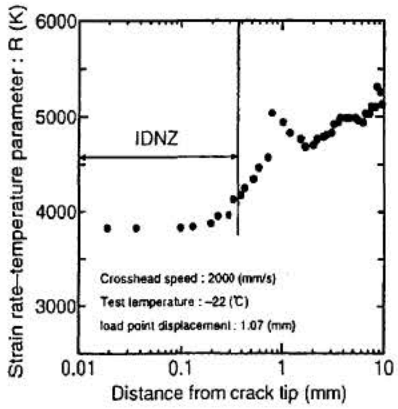

Fig. 4 An example of strain rate-temperature parameter distribution in the vicinity of crack tip

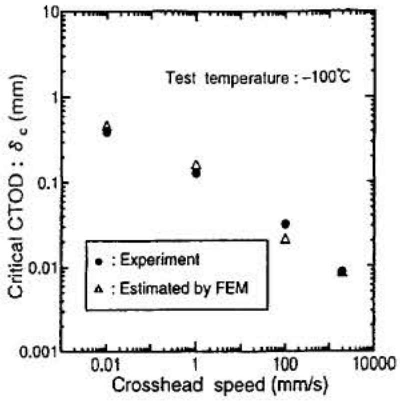

Fig. 5 Estimated critical CTOD at arbitrary crosshead speeds from the quasi-static fracture toughness test

fracture initiation point for evaluating strain rate effect on fracture toughness. Now let us express this constant R value as R_γ. It could be presumed that fracture toughness, for example critical CTOD (δ_c), is a function of R_γ value under dynamic condition. Postulating that the relation between R_γ and δ_c is the inherent characteristic of materials, it became clear that δ_c under arbitrary strain rates could be quantitatively estimated by using the above mentioned FEM as shown in Fig.5 for example [1].

The authors had proposed the practical estimation method of R_γ and CTOD throughout dynamic loading process. Details of these method are mentioned in the reference [2].

Failure Analyses of Brittle Fracture on A Lower Flange Near A Box-Column

We obtained data of a brittle fracture accident on a lower flange of a building at the end of a scallop in the Great Hanshin Earthquake. Charpy impact tests, Vickers hardness tests and round bar tension tests had been carried out by using this failed element. Since the above data for the Charpy impact value and yield strength are a part for sufficiently apart from the crack initiation point, these values are considered not to be affected by strain hardening of seismic cyclic loading. Temperature (T) $\sim \delta_c$ curve of a material under static loading condition was obtained from Charpy energy curve [2]. Similar curves of which Charpy transition temperature is 20[℃] and 40[℃] higher or lower than that of this failed element were also given for later discussion. Applying the authors' procedure [2], it could be converted the $T \sim \delta_c$ curve to $R_\gamma \sim \delta_c$ curve. It had been reported from visual inspection of the brittle crack surface that no flaw exists in the failed element. Then we used the inherent crack size of 0.2[mm] [9] for assessing the strain of brittle fracture initiation for this element.

Figures 6 and 7 show the estimated gross strain, when brittle fracture occurred, for this element with K_t=1.3 and K_t=2.2 respectively. K_t means the stress concentration factor on a lower flange of a building at the end of a scallop. Upper limit of the K_t value of practical scallop shape was 2.2 and lower limit of one was 1.3 [8]. A value in parenthesis in these figures shows the value of the estimated strain at fracture initiation point when the fracture occurred. Hatching zone in these figures corresponds to the

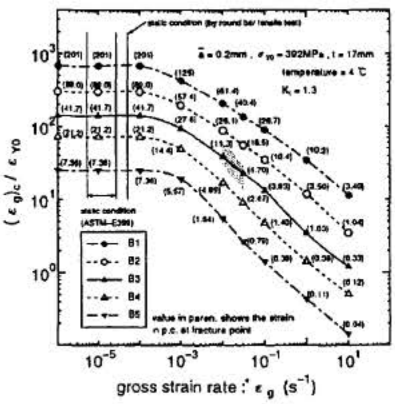

Fig. 6 Calculated results of gross strain on flange at fracture originated from boxing fillet weld toe at the end of scallop (K_t=1.3)

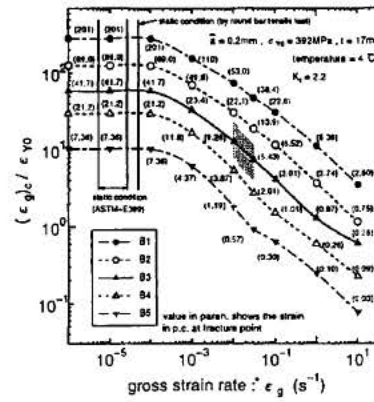

Fig. 7 Calculated results of gross strain on flange at fracture originated from boxing fillet weld toe at the end of scallop (K_t=2.2)

region of strain rate received on a failed element. It was assessed that the strain at fracture initiation point when fracture occurred was 6.7% $\sim$ 11.3% in case of K_t=1.3 and 5.43% $\sim$ 9.26% in case of K_t=2.2. These assessed strains seem to be in good agreement with the assessed skeleton strain of about 10% converted from measured hardness number of failed element. Skeleton strain is usually different from acted strain. However, before fatigue crack initiation, skeleton strain is considered to coincide with acted strain. Because the seismic cyclic loading which is smaller than the load when brittle fracture occurs and with small number of cycles forces only generate a ductile crack previous to brittle fracture generation.

The ordinate in these figures shows non-dimensional gross strain on the lower flange when brittle fracture occurred. ε_{Y0} means yield strain of static loading at room temperature. It is indicated from these figures that the brittle fracture of this element had occurred after full yielding which coincided with some surveyed reports at the Great Hanshin Earthquake. It could be also suggested from these figures that the use of material of which the Charpy transition temperature is 20[℃] lower than that of the failed material increases its brittle fracture resistance ability up to 2.32 $\sim$2.55 times. Two kinds of range for static loading condition are also shown in Figs.6 and 7. One is obtained by the authors [4]. The other is the strain rate region into which converted stress intensity factor rate which is standardized in ASTM-E399. Fracture resistance ability (gross strain) for horizontal member of structures at the Great Hanshin Earthquake decreases by about one-forth or below the gross strain under static condition. This result indicates that it is too dangerous to evaluate brittle fractrue strength under intermediate or high strain rate on the basis of static fracture toughness test.

Failure Analyses of Brittle Fracture on A Cast Steel Column

A cast steel column of railway bridge had been broken at the Great Hanshin Earthquake. A Survey report mentioned that the fracture initiation region was the inner side of final solidification layer in this column and that there were many defects like shrinkage cavity and nonmetallic inclusion in this region. Then it was presumed that brittle fracture initiation point was from the largest one among these defects.

To investigate this failure accident, it is necessary to obtain $R_\gamma \sim \delta_c$ curve of failed material. Fracture toughness tests using CT specimens under some temperatures and crosshead speeds had been carried out, which test specimens had been extracted from the imitation of failed column which had made the same progress of work and material. We obtained the relation between R_γ and δ_c from these test results. Figure 8 shows these results. A value in parenthesis in this figure shows the assessed temperature rise due to plastic work at fracture occurrence using a simplified method. In these calculations, the effect of enlargement of plastic zone due to temperature rise caused by decrease of yield strength was ignored.

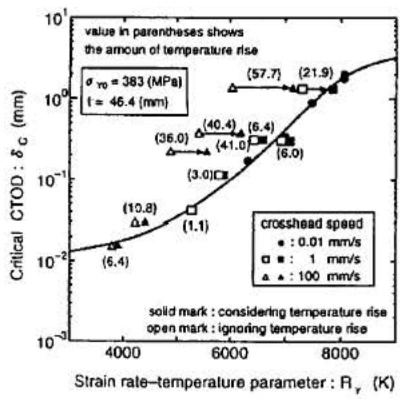

Fig. 8 Relation between R_γ and δ_c

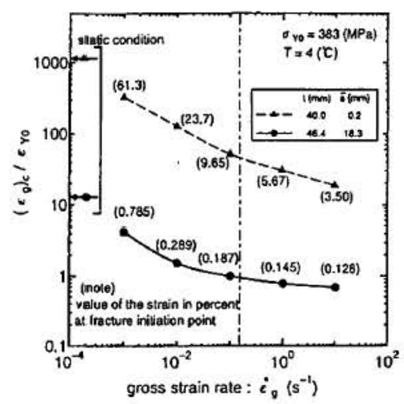

Fig. 9 Calculated results of gross strain at the fracture initiation point

On the condition that the crosshead speed is 100 [mm/s], the assessed maximum temperature rise at fracture occurrence reaches 57.7 [℃] which may be the lower limit of temperature rise. Although crosshead speed is 1 [mm/s], the assessed maximum temperature rise at fracture occurrence reaches 21.9 [℃]. These calculations results indicate that it can not ignore the temperature rise due to plastic work to evaluate brittle fractrue strength under intermediate or high strain rate. The solid curve in Fig.8 was $R_\gamma \sim \delta_c$ curve considering the temperature rise due to plastic work of this material.

Figure 9 shows the estimated gross strain at fracture initiation for this column with two cases of initial defect respectively. The solid curve shows the case of which there is the largest defect observed in this column. The dashed curve shows the case of no defect. The inherent crack size was adopted in the latter calculation. $\bar{a}$ in Fig.9 is defined as a half length of through thickness crack of which stress intensity factor equals to the maximum value along a front edge of the surface flaw. A value in parenthesis in Fig.9 shows the value of the estimated strain at fracture initiation point when fracture occurred. The alternate long and short dash line in Fig.9 corresponds to the maximum strain rate received on a failed column. It is indicated from Fig.9 that brittle fracture of a failed column had occurred just before yielding, which coincided with a survey report at the Great Hanshin Earthquake. It could be also suggested from Fig.9 that the fracture resistance ability in the case of no defect was about 40 times that of failed column. These results indicate that it is necessary to eliminate initial defects perfectly in a cast steel column in the case of receiving impact loading.

The Up-to-date Japanese Activities of The Assessment of Brittle Fracture of Structures Under Seismic Wave

A joint research project for advanced earthquake resistant design of structures is now under way. A large three dimeisional vibration table with vertical shock wave by collision of a flying solid with the weight of 4,500 [kg] having the maximum flying speed of 10 [m/s] has been constructed. We expect that advanced earthquake resistant design will be established through our proof tests by using this vibration table and analyses with considering the strain rate effect, which will be supported by FINAS (Ver.13) in which constitutive equation as the function of strain rate and temperature could be given in the near future.

Conclusion

Postulating that the relation between R_γ and δ_c is the inherent characteristic of materials, it was able to assess the brittle fracture resistance ability of structural elements under arbitrary strain rates.

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