EVALUATION OF A BRITTLE FRACTURE ACCIDENT THAT OCCURRED AT THE HYOGO-KEN NANBU EARTHQUAKE

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ABSTRACT

Many fracture accidents of steel structures, which did not enable to occur under static loading, were found at the Hyogo-ken Nanbu Earthquake (17 January, 1995). Considering the strain rate effect on fracture toughness was required to evaluate these fracture accidents quantitatively. The evaluation concept of fracture toughness at arbitrary strain rate is explained briefly. An analysis on the brittle fracture accident of centrifugal cast steel bridge pier for railway was performed by means of this method. The result makes clear that vertical impulsive seismic wave is considered to be the major cause of the brittle fracture accident generated on this bridge pier at the Hyogo-ken Nanbu Earthquake.

KEYWORDS

brittle fracture, strain rate, impulsive seismic wave, dynamic loading, R prameter, cast steel bridge pier, Hyogo-ken Nanbu Earthquake

INTRODUCTION

Many fracture accidents of steel structures were found at the Hyogo-ken Nanbu Earthquake (17 January, 1995). In a design of structures, it was certificated that most of these accidents could not occur even though the same amount of static load acted on the structures. On the other hand, it is well known that fracture toughness decreases with increasing strain rate. Strain rate effect on fracture toughness was ignored on the design stage of the structures. Considering the strain rate effect on fracture toughness is necessary to evaluate the resisting ability on brittle fracture of steel structures.

Authors [1] had shown that fracture toughness is the function of strain rate-temperature parameter (R) proposed by Bennet et al. [2] under arbitrary strain rate and temperature condition. The estimation method of fracture toughness under arbitrary strain rate and temperature by using the results of static fracture toughness test had also stated in ref.[1] in detail. R parameter, which is derived from thermaly activated process of dislocation behaviour, is defined in Eqn. 1.

$$R = T \ln(A/\dot{\varepsilon}) \tag{1}$$

where T: temperature [K], A: frequency factor ($= 10^8 [\mathrm{s}^{-1}]$), $\dot{\varepsilon}$: strain rate [s^{-1}]. In this study, an evaluation of brittle fracture accident occurred in the centrifugal cast steel bridge pier at the Hyogo-ken Nanbu Earthquake was performed by using the method in ref.[1]. An outline of the concept for

the quantitative evaluation method of strain rate effect on fracture toughness is explained to the next section. Refer to ref.[1] for more precise information concerning this procedure.

BASIC CONCEPT FOR THE QUANTITATIVE EVALUATION METHOD OF STRAIN RATE EFFECT ON FRACTURE TOUGHNESS

Yield stress of steel materials can be represented only by R parameter, because yield stress increases with the temperature drop and with the strain rate rise. R value under dynamic loading condition plays the same role as temperature under static loading condition for the constitutive equation of steels. 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 stress in case of static condition. Static loading in our researches was defined as the condition that no strain rate effect appeares in the constitutive equation and the value is equal to $5.0 \times 10^{-5}\text{s}^{-1}$ [1].

Constitutive relation of steels under arbitrary strain rates, therefore, can be estimated only by the yield stress obtained from R value although R value usually changes throughout a loading process.
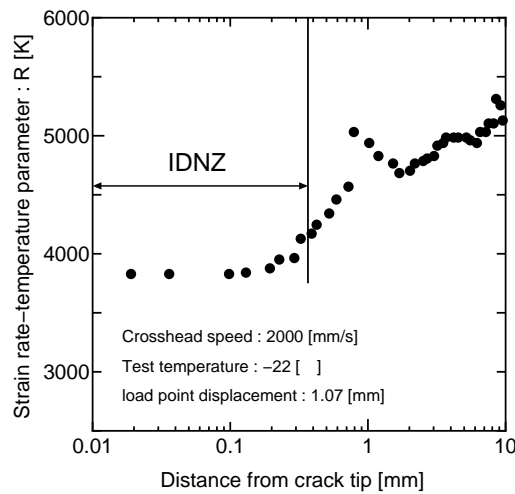

Figure 1 An example of R parameter distribution in the vicinity of a crack tip

Authors had presumed that fracture toughness is a function of R parameter under dynamic loading, because the fracture toughness is a function of temperature under static loading and R parameter performs a equivalent role of temperature under dynamic loading. Besides, R parameter considered the temperature rise generating by plastic work takes almost constant value in the fracture process zone at an arbitrary moment as shown in Fig. 1 [1] for example. This flat distribution could be appear as the additive effects obtained by combining temperature rise due to plastic work with strain rate distribution in the vicinity of a crack tip. In this figure, IDNZ defined by Rice and Johnson [4] corresponds to fracture process zone. This phenomenon and the hypothesis which fracture toughness is a function of R parameter enable to ignore identifying the precise fracture initiation point for evaluating strain rate effect on fracture toughness. R parameter which keeps almost constant value in fracture process zone denotes R_γ as follows. It can be recognized that fracture toughness is a function of R_γ under dynamic condition. Postulating that the relationship between R_γ and fracture toughness is the inherent characteristic of materials, fracture toughness under arbitrary strain rates can be quantitatively estimated from the results of static fracture toughness tests.

GENERAL ASPECT OF THE BROKEN CAST STEEL BRIDGE PIER

Some defects like shrinkage cavity existed in the inside layer of the broken cast steel bridge pier. These defects remained in service of this railway for the following reasons 1 and 2.

1. The inside layer was eliminated from load supporting member in structural design.
2. It was supposed that only compressive load acts on the section in service.

Figure 2 shows a fracture surface of the broken cast steel bridge pier. It is recognized that there were some large shrinkage cavities which played a role of the brittle fracture generating point in the bridge pier. Maximum depth and breadth of the shrinkage cavity were 18.8mm and 37.1mm respectively. To investigate the brittle fracture strength of this pier, this surface shaped defect was replaced by two dimensional infinite cracked body subjected to remote tensile stress, which the maximum value of stress intensity factor along the contour of the surface defect is equal [3]. The half crack length of one is equal to 18.3mm.
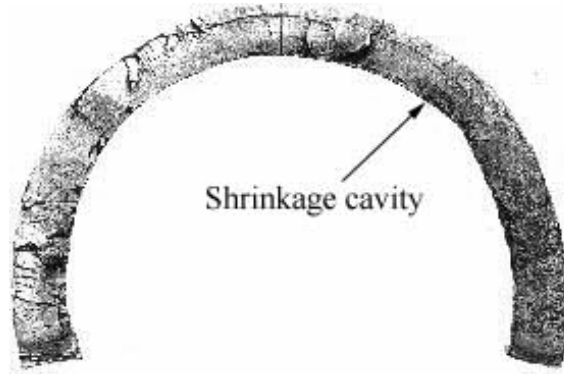

Figure 2 Fracture surface of the broken cast steel bridge pier

FRACTURE TOUGHNESS CHARACTERISTIC CURVE

Fracture toughness characteristic curve of the broken cast steel bridge pier must be prepared to evaluate the brittle fracture accident. This curve represents the relationship between R_γ and fracture toughness. Fracture toughness tests under three loading speed (0.01, 1, 100mm/s) and four ambient tempreature (0, -20, -40, -60 °C) had carried out to identfy the characteristic curve. Calculation procedure for R_γ is stated in ref.[1].
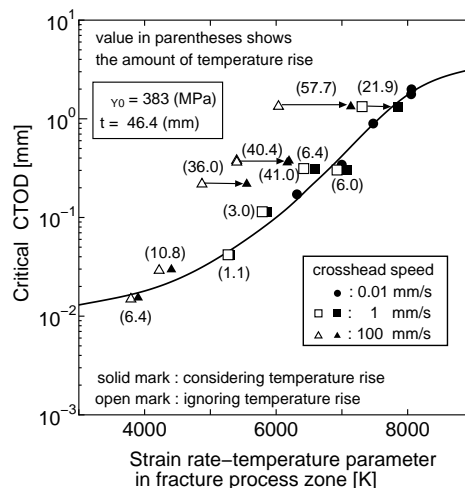

Figure 3 Relationship between R parameter in fracture process zone and critical CTOD

Figure 3 shows the characteristic curve of the broken steel material. Figures in parentheses in Fig. 3 indicate the estimated value of temperature rise (unit in degree) due to plastic work at the tip of IDNZ. R_γ in Fig. 3 were acquired by adding this temperature rise to the ambient temperature of fracture toughness test condition. It makes clear that fracture toughness can be recognized as the function of R_γ over the wide loading speed and temperature conditions by considering the temperature rise due to

plastic work. Bold curve in Fig. 3 could be recognized the fracture toughness characterisitic curve for the material of broken cast steel bridge pier.

THE BRIDGE PIER BEHAVIOUR UNDER SEISMIC LOADING

To estimate the applied load to the bridge pier, static elastic-plastic FE analyses were carried out at frist. Four nodal shell element was used to idealize this FE model. Shell thickness of FE model varied step by step to model the thickness variation of the pier. Total number of nodal point was 3017 and of element was 2912. Added vertical load derived from superstructure was inputted at bearing plate shoes of the pier. Yield stress of column material was 258MPa and of beam material was 235MPa. Stress-strain curve of both materials were approximated as a bi-linear (second modulus is equal to $E/100$, where E is Young's modulus).
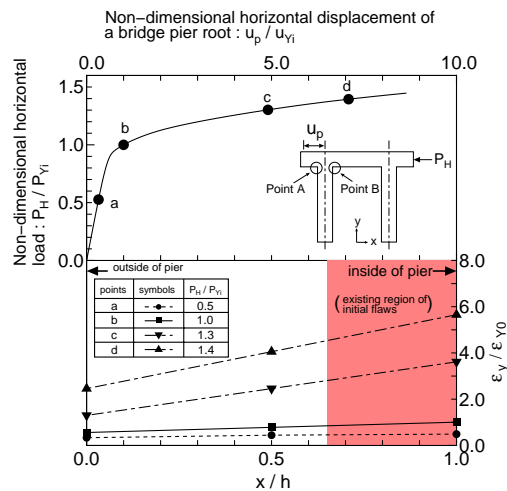

Figure 4 Displacement versus load curve at the pier top and strain distribution of vertical component through the reference cross section.

Figure 4 shows the calculation resutls. Upper side of Fig. 4 shows the horizontal displacement of the pier top undertaken the horizontal load illustrated in this figure. Both axes are normalized by the displacement and the load at the start of yielding on the reference cross section respectively, which is 400mm below the beam flange. Etou et al. [5] also estimated that the maximum horizontal displacement is equal to 21cm by means of elastic-plastic FE analyses. The displacement and load curve acquried by them was in good agreement with upper side of Fig. 4.

Lower side of Fig. 4 shows the vertical component of the strain distribution at the reference cross section in the column shell plate. a, b, c and d denote the appled load level respectively shown in upper part in Fig. 4. Shaded region of the graph means the initial flaw existing region. Ordinates is normalized by yield strain of column material and abscissa is done by shell thickness (h). This figure indicates that tensile strain generates at fracture generating region and that the value of strain exceeds yield strain by applying horizontal load at fracture generating.

Brittle fracture generating point was the area in which uniform strain distributed throughout shell thickness direction of the broken bridge pier. Besides, the reference strain to evaluate fracture parameter can be regarded as the average value of strain distribution on the defect position in no defect structures. Considering these condition, hilighted accident, namely brittle fracture generating from a large defect, can be evaluated by using average strain in the defect position from these FE analyses.

POSSIBILITY OF BRITTLE FRACTURE GENERATED BY HORIZONTAL SEISMIC WAVE

Brittle fracture genreating loads caused by horizontal seismic wave were estimated by inputting one pulse, which time duration equals 0.3s, to the FE model shown in Fig. 3. Supposed pulse time duration was almost equal to the average of observed time duration of horizontal seismic wave (north to south direction), which was equal to 034s, at the earthquake. Ambient temperature for the calculations was 4 °Cwhich was the same temperature at the day of earthquake.
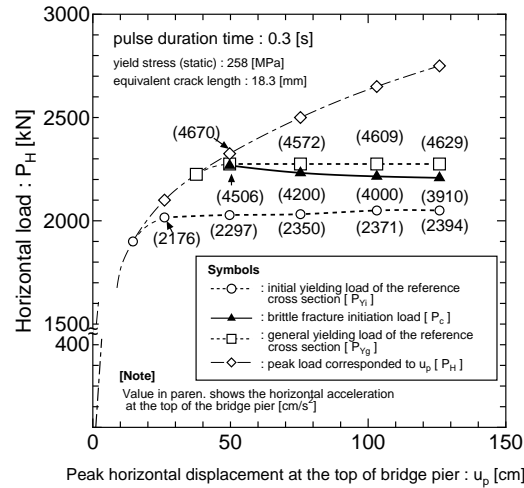

Figure 5 Estimation of brittle fracture generating load caused by horizontal seismic wave

Figure 5 shows the calculation results. Solid triangle marks represent the relationship between brittle fracture generating load and horizontal displacement at the pier top. Open circle marks represent the initial yielding load of the reference cross section and open square marks represent the genreal yielding load on the same section. Diamond shape marks mean the peak load in case of no defect. Figures in parentheses are equal to the horizontal acceleration of the pier top (unit in cm/s^2) at the each state. These result indicate that the brittle fracture accidents could be generated in case that the acceleration reached at least 4000cm/s^2 and horizontal displacement of the pier top must exceed more than 40cm. Considering the observed maximum seismic wave acceleration of horizontal component equals 812.8cm/s^2, it makes clear that the brittle fracture accident could not be generated by horizontal seismic wave.

POSSIBILITY OF BRITTLE FRACTURE GENERATED BY VERTICAL SEISMIC WAVE

To investigate the possibility of the brittle fracture accident generated by vertical component of the seismic wave, following analyses were carried out.
1. Time history response analyses of the bridge pier by applying the observed vertical seismic wave (maximum acceleration was equal to 333.3cm/s^2).
2. Estimating the maximum amplitude of strain on the average of the reference cross section.
3. Calculation of time history of the relationship between R parameter in fracture process zone (R_γ) and CTOD by applying the half vertical pulse wave stated above.
Solid circle marks in Fig. 6 show this time history. Bold curve in Fig. 6 represents the fracture toughness characteristic curve of the bridge pier material, which is shown in Fig. 3. Cross point of the bold curve and the time history indicates the unstable fracture generating. This result implys that it was impossible to generate the brittle fracture accident by acting the observed vertical seismic wave to the bridge pier directly.
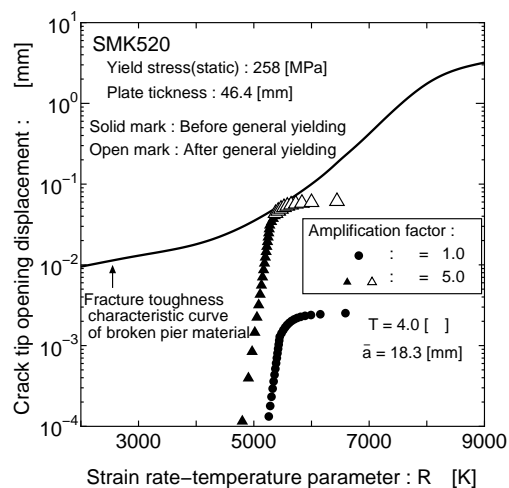
Figure 6 Estimation of brittle fracture caused by vertical seismic wave

Sonoda et al. [6] showed that the inputted vertical component of stress wave to the structures was amplified. The amplification factor (α) depends on the pulse period and velocity of the vertical seismic wave and the ratio of seismic wave acting area between ground and the bridge pier. Value of the amplification factor in case of our hilighted analysis condition (time duration equals 0.3s) was approximate to five [6].

Triangle marks in Fig. 6 show the R parameter in fracture process zone versus CTOD curve in case which the input vertical seismic wave was amplified to five times. Open marks of the triangle represent that the reference cross section reaches the general yielding condition.

By considering the following conditions (a) through (c), the brittle fracture accident caused by the vertical seismic wave could be understood as a natural phenomenon.

(a) Fracture toughness has a certain scattering.

(b) The fracture toughness characteristic curve of the bridge pier material corresponds to the average curve of one.

(c) Some specialists in seismology insisted that the stronger vertical short periodic pulse than the observed one could not be recorded because of the low ability of the recorders.

CONCLUDING REMARKS

Brittle fracture accident of centrifugal cast steel bridge pier at the Hyogo-ken Nanbu Earthquake was investigated by considering the strain rate effect on fracture toughness.

The result makes clear that vertical impulsive seismic wave is the major source to generate the brittle fracture accident on this bridge pier.

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