Application Research of Elastic-plastic Fracture Toughness Index CTOD in the Design of Railway Steel Bridge

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Abstract Railway steel bridge belongs to large scale weld structures suffered with cyclic dynamic stress generated by train. In recent years, the section of bridge member becomes bigger, plate becomes thicker, connection form becomes more complicated, and steel bridge is applied to more districts even lower temperature environment. Fatigue and fracture problems become more serious. On the basis of Crack Tip Open Displacement (CTOD) test data of 372 specimens tested in different temperature, this paper discusses research work about fracture proof design that involved how to determine the criterion of Charpy V Notch (CVN) impact toughness by building the relationship between CTOD and CVN, how to prevent brittle fracture by stress control in railway steel bridge design based on COD design curve from test data, and how to do the fatigue design for railway steel bridge at -50 ℃ of design temperature in an easy way, The method of fatigue design at -50 ℃ environment has been used for railway steel bridge structure of Qinghai-Tinet Railway in China.

Keywords Railway steel bridge, Fracture proof design, Fatigue at low temperature, CTOD test, Toughness criterion

1. Introduction

Fatigue fracture is one of the most important contents in design of railway steel bridge that belongs to large scale weld structure suffered with heavy cyclic dynamic stress generated by train. In recent years, the section of bridge member becomes bigger, plate becomes thicker, connection form becomes more complicated, and steel bridge is applied to wider districts even in lower temperature environment, so as to meet the needs of construction development in China. Fatigue and fracture problems become more serious. Traditional design concept and method is just focused on building steel bridge in the south part of China with warm weather, without enough experience for using steel bridge in cold weather, so it is necessary to supplement special regulation or renew some research method. It were given by an engineering test research[1] that, fatigue strength is higher when specimen is at lower temperature than it is at room temperature in comparison tests. The conclusion were doubted[2] and is not reasonable either. With the cognition developed the idea that, elastic-plastic fracture toughness has to be applied to fracture proof design in railway steel bridge, formed and expected to obtain reasonable interpretation and solve the fatigue problems as well when the steel bridge serving in lower temperature. A series of Crack Tip Open Displacement (CTOD) tests were carried out in different temperature to the common bridge steel with the thickness of 12, 16, 24, 32, 44, 50 mm both for base metal and butt weld seam. The total numbers of specimen was 372, and the effective test data was 364. CTOD test was done by straight three point bending specimen. The regression data point for weld seam and the relationship between CTOD and temperature after regression[3] are shown in Fig. 1 and Fig. 2.

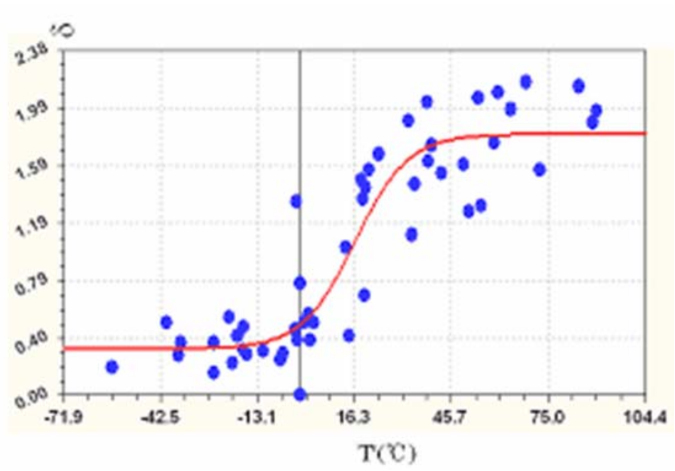

Figure 1. Statistics result of weld seam test data

Charpy V Notch (CVN) impact toughness is an important index proving toughness quality of steel material and weld joint. It is applied to engineering widely because of its simple and inexpensive test procedure compared with CTOD. In order to get the relationship between the two toughness indexes, 702 specimens of CVN impact test were also carried out in different temperature accordingly[4]. The regressed curve is shown in Fig. 3.

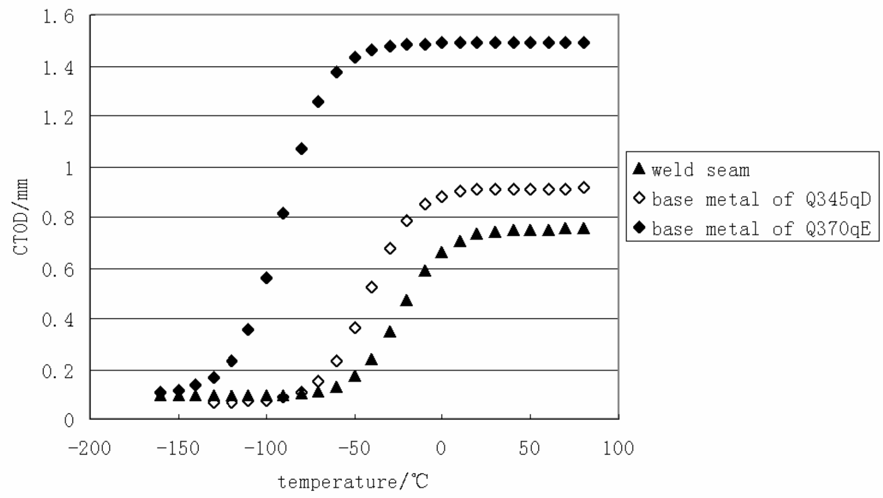

Figure 2. CTOD versus temperature of base metal and weld seam

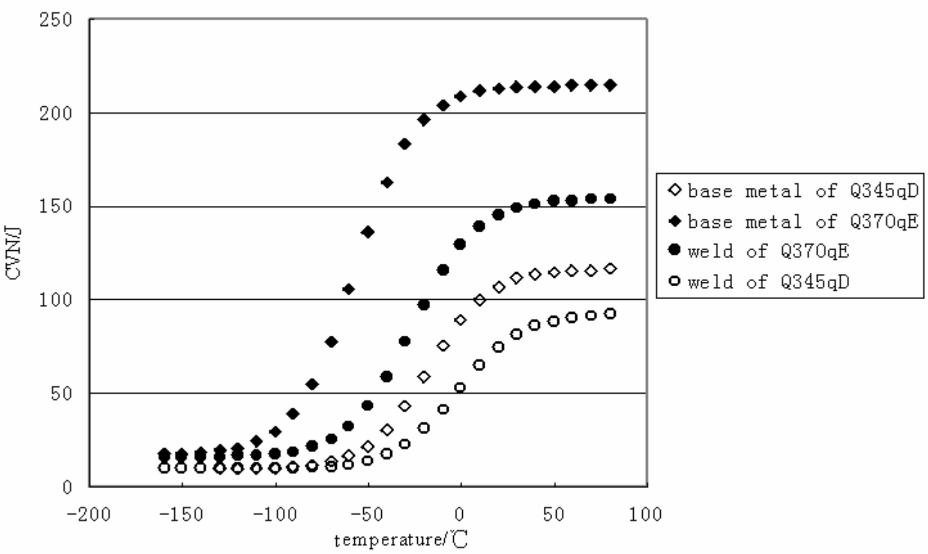

Figure 3. CVN versus temperature of base metal and weld

Three aspects of research are carried out around fatigue and fracture problem based on the test data of CTOD and CVN above: (1) to create the relationship between CTOD and CVN by absorption energy at the moment of specimen damaged in test, to find the basic CVN impact toughness of weld joint proof brittle fracture, and then to determine the toughness criterion that should be easy and practical. (2)find special stress calculation formula for railway steel bridge to check and control maximum stress level preventing from brittle fracture when the material and section of bridge member had be the fact. And (3) to determine the complementary requirement and provide method for fatigue design temperature at -50℃ to apply to Tsinghai-Tibet Railway line. The research result will be the reference of revising code later.

2. Weld toughness criterion

So far the major way to control toughness of steel material in engineering is to check the impact energy by CVN impact test. In bridge design, the first thing is to choose material and confirm the toughness criterion. Usually the lowest impact toughness criterion is determined by comparing with the similar bridge and accumulated experience. Which produce a lot of discussion and dispute. The better way to make sure the criterion is by means of CTOD test data, since it can be leant clearly that which situation would generate brittle fracture and which ductility damage. By this way it can guide to determine the toughness criterion. However, CTOD test is complicated comparatively and is unapt to inspect as normal way in engineering. Therefore, the absorption energy is taken as the instrumentality to establish the relationship between CTOD and CVN. The test record of vertical replacement at load point and loading value are utilized to get the basic absorption energy in CTOD test, and then it can be used to guide to work out basic CVN impact toughness criterion. The idea comes from the CTOD test data within temperature from room temperature to -70℃. It shows that the basic absorption energy provided by specimen is independent of test temperature when it gets to certain CTOD value. It also can leads to, on one side, the impact toughness for real bridge under the temperature from room to -70℃ should satisfy with basic absorption energy obtained from certain critical state in CTOD test. On the other side, the relationship also should be analyzed between loading velocity and character temperature for CTOD test, CVN impact test and service train passing bridge, by which the test temperature is confirmed for doing impact test. Consequently the reasonable impact toughness criterion with large amount of test basis can be prescribed.

Following regulation should be complied in analysis:：

(1) It is required for material to have the absorption energy ability that can suffer the destroy state with transition ability from brittle to ductility. In other words, when the structure gets to fracture, the maximum stress in member section would exceed yield strength, and the structure should have a certain deformation.

(2) Towards to safety direction, increasing 2 standard deviation to average value during statistics analysis.

2.1. Method to confirm basic toughness index

The step to determine the toughness criterion is followed by below items:

(1) Calculate integral to obtain the absorption energy by the test record of vertical replacement at load point and loading value;

(2) Analysis the loading model difference of CTOD test and CVN impact test, formulate the relation of energy between the absorption energy in CTOD test and impact energy in CVN test[5]. It is shown in formula (1).

$$A_{kv} = \frac{A_{CTOD}}{C_e} \tag{1}$$

where A_{CTOD} and A_{kv} = absorption energy in CTOD test and in CVN test, J; C_e = transition coefficient, $C_e = 0.32B$, B is the thickness of CTOD specimen.

(3) Sort the test data from CTOD test that were damaged at the transition situation from brittle and ductility, pick-up their absorption energy in list, and calculate the basic energy value that is corresponding to the specimen condition and is impossible to generate brittle fracture.

(4) Determine test temperature. It is shown from CTOD test that the basic absorption energy provided with a specimen when the crack tip in it open a certain displacement is independent of temperature when the thickness of specimen is certain. Meanwhile, in practical bridge the narrowest open displacement should be controlled mainly. Therefore it is no need to consider what temperature the CTOD test is done corresponding to absorption energy in step (3) above, just consider the difference of loading velocity in CTOD test and CVN impact test. It mainly affects the exact place at where the toughness-temperature character curve located on the temperature coordinate.

The analysis about temperature coordinate is shown below:

(1) As per the relation of character temperature point between fracture toughness stress intention factor K_{IC} that is tested by static or equivalently static loading and the loading velocity caused by service train, the character temperature of service train is equivalent to increase ΔT_1℃ by static K_{IC} test [6]. It can be shown by the following equation:

$$\Delta T_1 = (83 - 0.08\sigma_s)\varepsilon^{0.17} \tag{2}$$

Where: ε = loading strain velocity, s^{-1}.

(2) As per the relation of character temperature point between the loading velocity caused by service train and impact toughness test, the character temperature of service train is equivalent to decrease ΔT_2℃ from impact toughness test[7]. It can be shown by the following equation:

$$\Delta T2 = 70℉ = 39℃ \tag{3}$$

(3) The test character temperature replacement in impact test between loading slowly to and normal loading speed in engineering can be represented by ΔT_3 [8]:

$$\Delta T_3 = 120 - 0.121\sigma_s \ (℃) \tag{4}$$

(4) As per the relation of character temperature point between fracture toughness CTOD that is tested by static or equivalently static loading and impact toughness test, the character temperature of CTOD test is equivalent to decrease ΔT_4℃ from impact toughness test according to the test in comparison above:

$$\Delta T_4 = 15 \sim 35 \ (℃) \tag{5}$$

Taking bridge steel Q370qE as an example, the character temperature relationship above is summed up and drawn as Fig. 4.

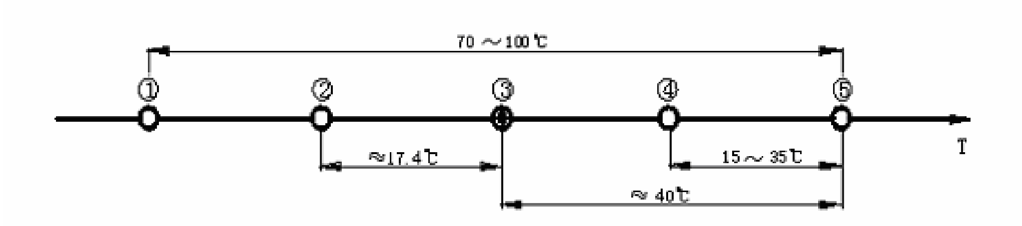

Figure 4. Comparative character temperature relation

Compared with the five situations in Fig. 4, the character temperature of CTOD test is higher than that under loading velocity caused by service train, even though it is static loading. It is understood that the loading way in CTOD test is three points bending, and the notch is sharp fatigue crack, which is very severe situation. As a result, the character temperature of service train is replaced by CTOD test temperature on the safe side, including the effect of temperature at bridge location and loading velocity. And then, the temperature replacement value from bridge site temperature to impact test is confirmed based on the character temperature relationship between CTOD and CVN test.

2.2. Analysis result and application

Followed by the steps above, the basic indexes of impact toughness proof brittle fracture are obtained in Table 1.

Table 1. Basic indexes of impact toughness

material		Thickness/mm	Environment temperature at bridge location /℃			
			-50	-40	-30	-20
Q370qE	Base metal	≤30	45J,-30℃	45J,-20℃	45J,-10℃	45J,0℃
		30-50	70J,-30℃	70J,-20℃	70J,-10℃	70J,0℃
	Weld		46J,-35℃	46J,-25℃	46J,-15℃	46J,-5℃
Q345qD	Base metal	≤32	43J,-30℃	43J,-20℃	43J,-10℃	43J,0℃
	Weld		34J,-35℃	34J,-25℃	34J,-15℃	34J,-5℃

The stipulation of steel material about the lowest impact toughness in national standard is classified by test temperature into 0℃, -20℃ and -40℃. The steel material used in railway steel bridge is the steel with -20℃ and -40℃ of requirement. Utilizing the curve equation of railway bridge steel regressed by CVN test (see Fig. 3), the equivalent index of the basic impact toughness in Table 1 are compared with the stipulation in national standard, and the commended toughness criterion for railway steel bridge is shown as Table 2-3.

Table 2. Commended lowest impact toughness criterion

material	Thickness/mm	Environment region and temperature at bridge location /℃	
		region E*	region D*

Q370qE	Base metal	≤30	41J,-40℃	41J,-20℃
		30-50	70J,-40℃	70J,-20℃
	Weld		41J,-40℃	41J,-20℃
Q345qD	Base metal	≤32	34J,-20℃	34J,-20℃
	Weld		30J,-20℃	30J,-20℃

*See Table 3.

Table 3. Region distribution for constructing bridge in China

Region mark	Name of territory	Extreme temperature in history/℃
E	Heilongjiang, Sinkiang, Inner Mongolia, Tibet, Jilin, Shanxi, Tsinghai	-40℃以下
	Liaoning, Gansu, Szechwan, Hebei, Shannxi, Ningxia	-30℃--40℃
D	Beijing, Tientsin, Shandong, Henan	-20℃--30℃
	Other	-20℃以上

3. Control stress prevent from brittle fracture

It is found by observing CTOD test process that, controlling action force on structure less than the force that would arouse brittle fracture can also prevent structure from brittle fracture. The purpose to research this subject is for exist bridges since their toughness situation had already been the fact. The controlling stress formula for railway steel bridge to prevent from brittle fracture can be deduced by means of the brittle fracture data in CTOD tests[3]. Formula (6) and (7) is for base metal, and (8) and (9) for weld seam:

$$\frac{\sigma}{\sigma_s} \le \frac{1}{1.12}\sqrt{\frac{E\delta}{2\pi a\sigma_s}} - 0.6 \tag{6}$$

$$\delta = \frac{a}{t}\left[0.1059 + \frac{1.383}{1+e^{-0.0778(T+90.666)}}\right] \tag{7}$$

$$\frac{\sigma}{\sigma_s} \le \frac{1}{1.12}\sqrt{\frac{E\delta}{2\pi a\sigma_s}} - 0.3 \tag{8}$$

$$\delta_W = \frac{a}{t}\left[0.0918 + \frac{0.6615}{1+e^{-0.0767(T+24.1927)}}\right] \tag{9}$$

Where: δ = base metal of Q370qE; δ_w = weld seam.

3.1. Analysis result

To base metal of Q370qE, elastic module $E = 2.1\times10^5 MPa$, average yield strength $\overline{\sigma}_s = 385MPa$, and put them into Formula (6) and (7), then:

$$\sigma \leq 3202.82\sqrt{\frac{1}{W}\left[0.2118+\frac{2.766}{1+e^{-0.0778(T+90.666)}}\right]}-206.25 \tag{10}$$

To weld joint, elastic module $E = 2.1\times10^5 MPa$, average yield strength $\overline{\sigma}_s = 377MPa$ (taking average value of base metal that is on safe side), and put them into Formula (8) and (9), then:

$$\sigma \leq 3169.37\sqrt{\frac{1}{W}\left[0.1836+\frac{1.3229}{1+e^{-0.0767(T+24.1927)}}\right]}-101 \tag{11}$$

Calculating by the formula (10) and (11), the available maximum stress σ without occurring brittle fracture to different thickness of bridge member can be obtained.

3.2. Application

Suppose α is available stress coefficient, $\alpha = \sigma / \sigma_s$, the calculation results to steel bridge steel are shown in Table 4.

Table 4. The maximum available stress coefficient α

Material	Tem. ℃	Thickness of steel plate/mm									
		12	16	20	24	30	32	38	40	44	50
Base metal of Q370qE	-50	1	1	1	1	1	1	1	1	1	1
	-40 to 0	1	1	1	1	1	1	1	1	1	1
Base metal of Q345qD	-50	1	1	1	0.95	0.79	0.75	-	-	-	-
	-40 to 0	1	1	1	1	1	1	-	-	-	-
weld	-50	1	0.97	0.83	0.74	0.63	0.60	0.53	0.51	0.48	0.43
	-40	1	1	1	0.93	0.80	0.77	0.68	0.66	0.62	0.56
	-30	1	1	1	1	1	0.98	0.87	0.84	0.79	0.73
	-20	1	1	1	1	1	1	1	1	0.97	0.89
	-10	1	1	1	1	1	1	1	1	1	1
	0	1	1	1	1	1	1	1	1	1	1

Usually, the ratio of design stress to yield strength is 0.58. Compared with the values in Table 4, it can be concluded that when the weld is used at the temperature of -40℃ to -50℃, some available stress is less than its design stress. It means that even though those members with the weld suffered the action stress that is below the allowable value in design code, brittle fracture may happen at some moment. In this way, reducing working stress calculated by the method above can stop some brittle fracture.

4. Fatigue design method of steel bridge at low temperature

Tsinghai-Tibet railway line is located at high altitude and cold region in China, where the extreme lowest temperature is -45 ℃, with undeveloped traffic and atrocious environment. The length of bridge within iced soil region exceeds 70 kilometers. In order to solve the problem of long time limit for constructing concrete bridge, the test investigation for steel-concrete composite bridge in Tsinghai-Tibet railway line were carried out. As per steel girder of composite bridge, the major effect under those bad conditions caused by the peculiar geography environment is the perennial cold weather. Low temperature would reduce toughness of steel and weld joint, make structure brittle, bring structure to a lower fatigue performance, and therefore reduce safety level of railway steel bridge suffered with very heavy live load. The current fatigue design parameter that is made and used to the structure at common temperature cannot meet the needs of Tsinghai-Tibet railway line.

4.1 Research Method

The test of fatigue crack propagation rate were carried out to 24mm thickness of Q370qD base steel and weld at -50℃ temperature. It indicated that, under -50℃ temperature the material coefficients of Paris equation in middle part of speed propagation region, $da/dN = C(\Delta K)^m$, have smaller 'C' and larger 'm', and have higher fatigue crack threshold ΔK_{th}, compared with room temperature. Furthermore, S-N curve at -50℃ is above the curve at room temperature, and its slope is even slightly from tests[1]. It leads the wrong direction that using common fatigue design method is good enough at low temperature.

However, CTOD tests indicate that, low temperature at -50℃ would reduce the critical crack open displacement, and increase the trend to brittle fracture. The average critical CTOD value at room temperature is 0.72mm, while it is only 0.14mm at -50℃.

Crack length can be expressed by Formula (12) at room temperature and Formula (13) at -50℃ according to the test result[3]:

$$a \le \frac{E\delta}{\pi(1.12\sigma + \sigma_s + 0.3\sigma_s)} \tag{12}$$

$$a \le \frac{E\delta\sigma_s}{2\pi(1.12\sigma + 0.3\sigma_s)^2} \tag{13}$$

Take $E = 2.1 \times 10^5 MPa$, $\delta = 0.72mm$ at room temperature and $\delta = 0.14mm$ at -50℃; $\sigma_s = 490MPa$ at room temperature[9] and $\sigma_s = 512MPa$ at -50℃[3]; $\sigma = 200MPa$ from allowable design stress in the code, the critical crack length are calculated by formula (12) and (13), that is, $a = 56mm$ at room temperature, and $a = 17mm$ at -50℃.

From Paris equation $\frac{da}{dN} = C(\Delta K)^m$, transform it into:

$$N = \int_{a_0}^{a_c} \frac{da}{C\Delta K^m} \tag{14}$$

where: $\Delta K = Y\Delta\sigma\sqrt{\pi a}$, Y= crack type coefficient. It can be taken as a destiny to bridge structure at both room and low temperature, then:

$$N = \frac{1}{CY^m \Delta\sigma^m \pi^{\frac{m}{2}} (\frac{m}{2} - 1)} \left(\frac{a_0}{\sqrt{a_0^m}} - \frac{a_c}{\sqrt{a_c^m}} \right) \tag{15}$$

4.2. Research Result

In formula (15), suppose original crack length $a_0 = 0.001m$, critical crack length $a_c = 0.056m$ at room temperature, and $a_c = 0.017m$ at -50℃. The coefficients of C and m are taken from the test data regressed with 97.7% probability, Y is taken for the most unfavourable situation in engineering when $a/W = 75\%$, and the life N is taken as the same cycles at both room and low temperature. The ratio of fatigue stress range between -50℃ and room temperature is 0.88.

This calculation result shows that, fatigue at low temperature should not be considered as a common fatigue problem. It is mainly because at low temperature, the critical fracture crack length shorten sharply. Consequently, the fatigue safety level drops, that can be noticed at the obvious intersection moving ahead between crack stable propagation region and sharp propagation region. The only way to solve the problem is to apply Fracture Mechanics theory and elastic-plastic CTOD test.

As a result, the allowable fatigue design stress range for steel bridge in Tsinghai-Tibet railway line is prescribed to 80% of the current fatigue design index. At the same time, the further requirement below should be followed:

(1) During design of bridge for Tsinghai-Tibet railway line, thinner steel plate should be preferred, so long as its local stabilization can be content.

(2) All of the steel material is required to fine microstructure by raising temperature during steel making to increase stopping-fracture ability.

(3) It should be taken into consideration to choose other kind of structure or connection style rather than to choose thicker plate when fatigue checking cannot pass the regulation at low temperature.

5. Conclusions

Fracture mechanics theory combined with the usual way for fatigue and toughness in railway steel bridge can solve the special problem when the environment is in low temperature. Three aspects of research can be concluded as below:

(1) It is important to select bridge steel that is both safe and economic. A reliable criterion can be made based on CTOD test. The recommended method this paper is easy to choose which steel category available.

(2) It is usually confused for engineer to check working stress for some bridge member with lower stress than allowable stress, impact toughness being above the normative value in the code, but the brittle fracture still happened. Additional method to check and control the stress level prevent from brittle fracture is suggested.

(3) The critical fracture crack length would be shorten sharply at low temperature. Fatigue at low temperature should not be considered as a common fatigue problem. As an example, the allowable fatigue design stress range for steel bridge in Tsinghai-Tibet railway line is prescribed to 80% of the current fatigue design value. The method is easy to be used for designer.

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