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DYNAMIC FRACTURE CRITERIA EVALUATION OF BRIDGE STRUCTURAL STEEL

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Abstract. *J*-integral is the main effective and commonly used tool for elastic-plastic cracked material resistance assessment. Considering ductile behavior of bridges steel integral approach is suitable for fracture toughness evaluation. The paper presents the method of dynamic fracture parameter *J*-integral evaluation in case of elastic-plastic deformation of bridge structural steel. This experimental technique is based on determination of impact fracture energies and displacements which correspond to these energies at the moment when loading rate reaches max and fracture loads. Theoretical solutions were confirmed by experimental data obtained from Three-Point Bend tests of rectangular cross section specimens with V form notch. Impact loading was generated by impact tester with drop weight. 5 series of specimens with different geometry were tested during experiment. The developed methodology enables to predict the impact fracture toughness of bridge structural elements.

Keywords: dynamic fracture toughness, impact loading, structural steel, Three-Point Bend, structural steel, load-displacement curve.

1. Introduction

Struts of the bridge construction during the operation period are deformed not only by the static, variable loads, but also by the dynamic forces (Reis, Pala 2009). Therefore it is important to develop the materials dynamic fracture criterion and the mechanical strength aspects of defected structure. It is known that mechanical properties of steel changes during service time (Nykyforchyn *et al.* 2010; Janutėnienė *et al.* 2009). The most significant sign of steel properties variation usually is brittleness appearance in behavior of material. Determination of impact resistance of new and used material is relevant procedure, which allows in the best way to asses brittle fracture possibility.

Most of the researches regarding high rate loading influence on fracture process are carried out applying correlation between values of absorbed energy during impact and the fracture parameters (Chaouadi, Puzzolante 2008; Sreenivasan 2008). These correlations usually are valid only when linear elastic fracture mechanics lows are applicable, i.e. when stress intensity coefficient K_I is used as fracture parameter. It was experimentally confirmed that absorbed energy during impact correlates with static stress intensity coefficient K_{Ic} and dynamic K_{Id} also. As basis of correlation establishment experimental results of standard Charpy specimen according *to LST EN ISO 148-1:2011 Metallic Materials – Charpy Pendulum Impact Test – Part 1: Test Method* usually are employed.

In elastic-plastic deformation case liner elastic fracture mechanics lows are not valid any more. For ductile material such as bridge construction steel S355 with high values of plasticity (Kala *et al.* 2009) dynamic fracture assessment *J*-integral are applicable.

Performing dynamic fracture tests and evaluating *J*-integral the Three-Point Bend specimens are often used, because geometry of such specimen is not complicated and low cost to manufacture. Sometimes it is not possible to follow standard specimen geometry requirements due to material lack especially in case when the specimen should be manufactured from operated constructions with various dimensions. Thus, procedure which enables to test specimens with various dimensions is a relevant topic.

The total absorbed energy amount is necessary for integral calculation (Eriksson 2010; Santana *et al.* 2010). In this work the total absorbed energy is divided into elastic and plastic energies and purposed experimental method to evaluate dynamic J_d -integral is more accurate and detailed. According to this method the specimens with nonstandard dimensions can be tested. It is different from other experimental techniques and has more advantages.

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2. Energetic fracture criteria

Energetic J-integral formulation and application for experimental proposes firstly was developed by Rice (Zhu 2009). For different cracked specimen configurations J-integral is calculated directly from the load-displacement curve using an approximate Eq (1):

$$J = \frac{\eta U}{B(H-a)}, \qquad (1)$$

where U – fracture energy, J; η – coefficient of geometry influence; B, H – specimen's dimensions, mm (Fig. 1).

As it can be seen from Eq (1) integral depends on the specimen size and absorbed fracture energy. Specimen's geometry (tension or bending specimen) influence on J-integral value is accounted via η factor. For deeply cracked specimens Rice suggested η-factor value $\eta = 2$ (Zhu 2009). But not in all cases the deformed specimen is deeply cracked and it is clear that the usage of value $\eta = 2$ is controversial. Obviously that different value of η affects the value of integral. Literature offers more detailed formulas of η-factor calculation at various crack length including deep and shallow cracks. For Three-Point Bend specimen (Fig. 1) these functions are (Sreenivasan, Mannan 2000):

$$\eta = 13.818\left(\frac{a}{H}\right) - 25.124\left(\frac{a}{H}\right)^2 \text{ for } 0 < \frac{a}{H} \le 0.275, \qquad (2)$$

$$\eta = 1.90 + 0.138\left(\frac{a}{H}\right) \text{ for } \frac{a}{H} > 0.275, \qquad (3)$$

$$\eta = 0.9379\left(\frac{a}{H}\right)^3 - 3.4509\left(\frac{a}{H}\right)^2 + 3.81214\left(\frac{a}{H}\right) + 0.70092$$

$$\text{for } \frac{a}{H} > 0.05. \qquad (4)$$

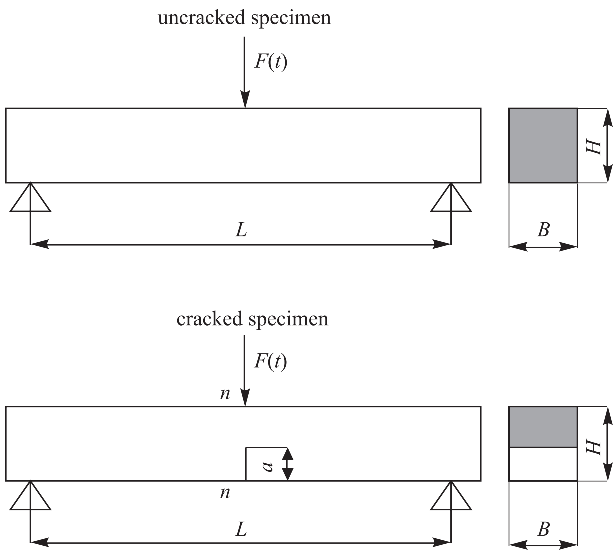

Fig. 1. Specimen's types, where L – length; B – width; H – hight, a – crack length

When the ratio of crack length and specimen height fits to interval $0 < \frac{a}{H} \le 1.0$ an approximate Eq for η factor determination can be used.

$$\eta = \left(\frac{a}{H}\right)^{\frac{1}{3}} + 1, \qquad (5)$$

Keeping in mind that each series of tested specimens had a different $\frac{a}{H}$ ratio parameter η was calculated applying valid Eqs (2–5) for particular $\frac{a}{H}$ value. Comparison of η-factor values evaluated by different methods is presented in Table 1. Each value of $\frac{a}{H}$ listed in Table 1 represents different specimen series.

As can be seen from Table 1 when value of ratio $\frac{a}{H}$ is near the 0 value of η coefficient becomes 1. Coefficient η is approaching the value 2 when the crack's length a reaches height H. Eqs (2–4) are valid only in specified interval of $\frac{a}{H}$ (Fig. 2). Thus authors of this paper propose Eq (5) as simplified and valid for whole $\frac{a}{H}$ interval numerical expression for η factor determination (curve $0 < \frac{a}{H} < 1$ in Fig. 2).

In order to ensure a more accurate assessment of fracture toughness a new approach of J-integral evaluation is presented. This model requires two amounts of energy

Table 1. Results of geometry factor calculation by different methods

$\frac{a}{H}$	Numerical value of η according to different Eq			
	(2)	(3)	(4)	(5)
0.40	–	1.96	1.73	1.74
0.29	–	1.94	1.53	1.66
0.22	1.83	–	1.39	1.60
0.18	1.68	–	1.29	1.56
0.15	1.53	–	1.21	1.53

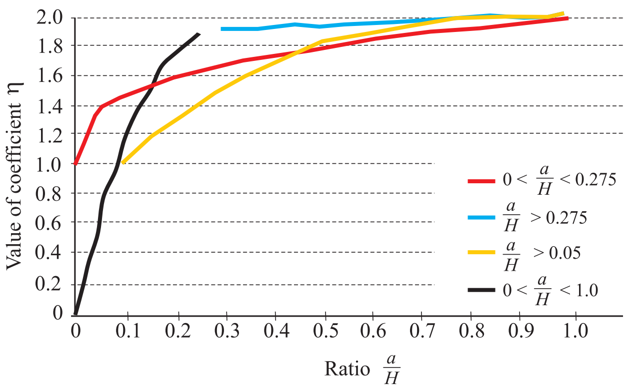

Fig. 2. Application boundaries of formulas listed in Table 1

defined experimentally as input data: E_U which corresponds to max impact load in load-displacement curve and E_C matching the final fracture state. These energies are necessary for calculation of relative fracture energy amount called as J_S-integral. This integral is expressed by ratio of J_U and J_C:

$$J_S = \beta J_C + (1-\beta) J_U, \text{ J (mm)}^{-2}, \tag{6}$$

where

$$J_C = \frac{\eta E_C}{B(H - a_C)}, \text{ J (mm)}^{-2}, \tag{7}$$

$$J_U = \frac{\eta E_U}{B(H - a_U)}, \text{ J (mm)}^{-2}. \tag{8}$$

Crack length a_C is defined at final fracture moment and length a_U at max load. These lengths match displacements u_C and u_U (Eq(15)).

Parameter β is evaluated from ratio

$$\beta = \frac{A_C}{A_U}, \tag{9}$$

where A_C is area of fracture zone at final failure state: $A_C = B(H - a_C)$, mm^2; A_U – area of fracture zone at max load: $A_U = B(H - a_U)$, mm^2.

When $\beta = 0$ then there is no fracture zone at crack tip. In this case

$$J_S = J_U. \tag{10}$$

When $\beta = 1$ then fracture zone overtakes all cross-section of specimen

$$J_S = J_C. \tag{11}$$

Result of substituting β values from Eq (9) into Eq (6) is expression (12)

$$J_S = \frac{\eta}{B(H - a_U)^2}[E_C(H - a_U) + E_U(H - a_U) - E_U(H - a_C)], \text{ J (mm)}^{-2}. \tag{12}$$

3. Displacement of cracked beam

During the impact a length of crack is increasing and it influences displacement of cross-section $n-n$ (Fig. 1). According to Fengchun *et al.* (2004) and Xu, Zhang (2008) the specimen's displacement due to the crack is corrected via function $f\left(\frac{a}{H}\right)$:

$$f\left(\frac{a}{H}\right) = 1 + 2.85\left(\frac{H}{L}\right)^2 - 0.84\left(\frac{H}{L}\right)^3 + \left(6\frac{H}{L}\right)V\left(\frac{a}{H}\right), \tag{13}$$

where

$$V\left(\frac{a}{H}\right) = \left[\left(\frac{a}{H}\right)^2\left(1 - \frac{a}{H}\right)^{-2}\right]\left(5.58 - 19.57\left(\frac{a}{H}\right)^2 + 36.82\left(\frac{a}{H}\right) - 34.94\left(\frac{a}{H}\right)^3 + 12.77\left(\frac{a}{H}\right)^4\right). \tag{14}$$

Then, displacement of cracked specimen can be calculated:

$$u(t) = u_0 f\left(\frac{a}{H}\right), \text{ mm} \tag{15}$$

where u_0 – displacement of uncracked specimen, mm.

Displacement u_0 is evaluated from the well-known approximated stress-deformation curve according to Eq (16):

$$\sigma_d = C\varepsilon_d^m, \tag{16}$$

where σ_d – dynamic normal stresses, MPa; C – constant; ε_d – dynamic relative deformation; m – material's dynamic hardening coefficient.

For bending specimen it's curving $\frac{1}{\rho}$ is expressed by Eq (17):

$$\frac{1}{\rho} = \frac{\varepsilon_d}{y}, \tag{17}$$

where y – distance from neutral line to selected point of specimen, mm.

Then

$$\sigma_d = \frac{C}{\rho^m} y^m. \tag{18}$$

In terms of longitudinal force loading $\int_A \sigma dA = 0$ (where A – cross-section area, mm) and

$$\int y^m dA = 0. \tag{19}$$

Then in accordance with equilibrium condition

$$\int_A \sigma y dA = M \text{ or } M = \frac{CI_{n+1}}{\rho}, \tag{20}$$

where $I_{n+1} = \int_A y^{m+1} dA$ – $n + 1$ row's inertia moment of cross-section.

Differential Eq of displacement is expressed in form

$$\frac{d^2u}{dz^2} = \sqrt[m]{\frac{M}{CI_{n+1}}}, \tag{21}$$

where z – longitudinal axis of specimen, mm.

Conditional moment of inertia I_{n+1} is obtained:

$$I_{n+1} = 2B\int_{0}^{\frac{H}{2}} y^{m+1}dy = \frac{BH^{m+2}}{2^{m+1}(2+m)}. \tag{22}$$

Then differential Eq of deflection for elastic – plastic deformation case can be written as:

$$\frac{d^2u_0}{dz^2} = \sqrt[m]{\frac{Fz}{2CI_{n+1}}} = \left(\frac{Fz2^{m+1}(2+m)}{2CBH^{m+2}}\right)^{m^{-1}}. \tag{23}$$

Marking

$$D = \left(\frac{F2^{m}(2+m)}{CBH^{m+2}}\right)^{m^{-1}}, \tag{24}$$

Eq (23) becomes:

$$\frac{d^2u_0}{dz^2} = Dz^{m^{-1}}, \tag{25}$$

Integration result of Eq (25) is the expression of beam's deviation:

$$\frac{du_0}{dz} = D\int z^{m^{-1}}dz = D\frac{z^{m^{-1}+1}}{m^{-1}+1} + K. \tag{26}$$

Seeking to evaluate deflection u_0 2nd integration of Eq(19) is necessary:

$$u_0 = \frac{D}{m^{-1}+1}\int z^{m^{-1}+1}dz + K\int dz = \frac{D}{m^{-1}+1} \times \frac{z^{m^{-1}+2}}{m^{-1}+2} + Kz + N \tag{27}$$

Constant N is obtained from boundary condition: when $u_0 = 0$ then $N = 0$ and constant K, when $\frac{du_0}{dz} = 0$; $z = 0.5L$.

Thus:

$$\frac{D(0.5L)^{m^{-1}+1}}{m^{-1}+1} + K = 0 \text{ or } K = -\frac{D(0.5L)^{m^{-1}+1}}{m^{-1}+1}, \tag{28}$$

and finally

$$u_0 = \frac{D}{m^{-1}+1} \times \frac{z^{m^{-1}+2}}{m^{-1}+2} - \frac{D(0.5L)^{m^{-1}+1}}{m^{-1}+1}z. \tag{29}$$

4. Experiment and results

Rectangular cross section specimens using Three-Point Bend test deformation scheme were tested under impact loading conditions (Fig. 1b cracked speciment). When performing experiment 5 series of specimens (dimensions: L = 50 mm; B = 10 mm; a = 2 mm) were manufactured. Each series differing from each other by parameter H (5; 7; 9; 11; 13 mm) consisted of 12 specimens.

Specimens were manufactured from steel S355. Mechanical properties of this steel grade are presented in Table 2. As impact the testing machine drop weight tower (Dynatup 9250HV Impact Tester from *Instron*) was used. Initial impact velocity was 3.60 m/s. Averages of registered parameters during the impact for each series are listed in Table 3.

Values of the length of cracks according to deflection Eqs (15) and (29) are presented in Table 4.

Calculating results of relative fracture energy J_S-integral according to Eq (6) are presented in Table 4. Specimen's height dependence on fracture energy expressed as an integral J_S is shown in Fig. 3.

5. Conclusions

For the assessment of dynamic elastic-plastic fracture the most appropriate characteristic is fracture energy expressed as J_S-integral and defined as the sum of two in-

Table 2. Static and dynamic mechanical properties of S355 steel

Mechanical properties	Symbol	Unit	Static	Dynamic
			Deformation velocity 3.0^{-5}, m/s	*Charpy* impact test
Ultimate stress	σ_u	MPa	500	570
Yield stress	σ_y,	MPa	350	424
Elongation at break	ε_u,	%	12	7.7
Elongation at yield	ε_y,	%	1.0	0.64
Elasticity modulus	E	GPa	200	310
Shear modulus	G	GPa	80	124
Poisson's ratio ν			0.3	0.25
Constant	C,	MPa	694	746
Hardening coefficient	m		0.15	0.11

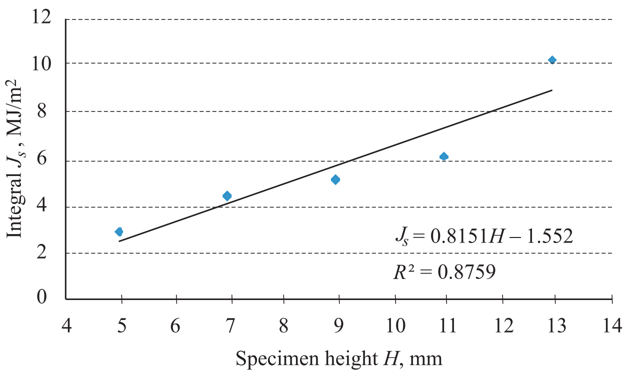

Fig. 3. Relationship between J_s-integral and specimen's heigth H

Table 3. Results of experiment

Specimen's height H, mm	Energy at max load E_U, J	Energy at failure E_C, J	Max load F_U, kN	Load at failure F_C, kN	Deflection at max load u_U, mm	Total deflection u_C, mm
5.0	6.39	39.42	1.99	0.37	4.33	28.66
7.0	19.33	101.83	4.95	0.97	4.85	28.45
9.0	32.02	170.54	9.18	1.82	5.46	25.41
11.0	61.15	242.90	14.64	2.91	7.21	22.32
13.0	117.56	322.60	19.77	3.93	7.71	21.08

Table 4. Values of the length of cracks and the calculated relative integral

Specimen's height H, mm	Length of crack a_C, mm	Length of crack $_U$, mm	J_S-integral, MJ/m^2
5.0	4.2	2.4	2.93
7.0	5.8	2.7	4.47
9.0	7.1	3.0	5.15
11.0	8.8	3.7	6.13
13.0	10.1	7.3	10.25

tegrals: integral corresponding max and load J_U and final failure J_C. This model has been applied to bridge steel S355 because of its elastic-plastic behavior under deformation.

When measurement data of bridge structural element deflection is available according to the presented model it is possible to predict whether construction with existing crack is safe to leave in-service or not.

Usually, dynamic fracture test are carried out on *Charpy* specimens which dimensions are strictly defined. The advantage of offered fracture criteria experimental determination is to test elements with various dimensions.

Value of fracture J_S-integral depends on the height of the specimen according to the linear dependence and is recommended for fracture prediction of different thicknesses structural elements made of S355 steel.

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