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; Janutienė 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 (Chaoaudi, Puzzolante 2008; Sreenivasan 2008). These correlations usually are valid only when linear elastic fracture mechanics lows are applicable, i.e. when stress intensity coefficient KI is used as fracture parameter. It was experimentally confirmed that absorbed energy during impact correlates with static stress intensity coefficient Kc and dynamic KId 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 Jd-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.
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):

\[ J = \frac{\eta U}{B(H-a)} \]  

(1)

where \( U \) – fracture energy, \( J \); \( \eta \) – 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 \( \eta \) factor. For deeply cracked specimens Rice suggested \( \eta \)-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 \( \eta \) affects the value of integral. Literature offers more detailed formulas of \( \eta \)-factor calculation at various crack length including deep and shallow cracks. For Three-Point Bend specimen (Fig. 1) these functions are (Sreenivasan, Mannan 2000):

\[ \eta = 13.818 \left( \frac{a}{H} \right) - 25.124 \left( \frac{a}{H} \right)^2 \text{ for } 0 < \frac{a}{H} \leq 0.275, \]  

(2)

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

(3)

\[ \eta = 0.9379 \left( \frac{a}{H} \right)^3 - 3.4509 \left( \frac{a}{H} \right)^2 + 3.81214 \left( \frac{a}{H} \right) + 0.70092 \text{ for } \frac{a}{H} > 0.05. \]  

(4)

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

\[ \eta = \left( \frac{a}{H} \right)^3 + 1. \]  

(5)

Keeping in mind that each series of tested specimens had a different \( \frac{a}{H} \) ratio parameter \( \eta \) was calculated applying valid Eqs (2–5) for particular \( \frac{a}{H} \) value. Comparison of \( \eta \)-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 \( \eta \) coefficient becomes 1. Coefficient \( \eta \) is approaching the value 2 when the crack’s length 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 \( \eta \) 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

| \( \frac{a}{H} \) | Numerical value of \( \eta \) 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. 1. Specimen’s types, where \( L \) – length; \( B \) – width; \( H \) – height, \( a \) – crack length

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 \( J_C \):

\[
J_S = \beta J_C + (1 - \beta) J_U, \quad \text{J (mm)}^{-2},
\]

(6)

where

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

(7)

\[
J_U = \frac{\eta E_U}{B(H - a_U)} J \text{ (mm)}^{-2}.
\]

(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 \( \beta \) is evaluated from ratio

\[
\beta = \frac{A_C}{A_U},
\]

(9)

where \( A_C \) is area of fracture zone at final failure state: \( A_C = B(H - a_C), \) mm²; \( A_U \) – area of fracture zone at max load: \( A_U = B(H - a_U), \) mm².

When \( \beta = 0 \) then there is no fracture zone at crack tip.

In this case

\[
J_S = J_U.
\]

(10)

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

\[
J_S = J_C.
\]

(11)

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

\[
J_S = \frac{\eta}{B(H - a_U)^2} \left( E_C (H - a_U) - E_U (H - a_U) \right), \quad \text{J (mm)}^{-2}.
\]

(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

\[
f \left( \frac{a}{H} \right) = 1 + 2.85 \left( \frac{H}{L} \right)^2 - 0.84 \left( \frac{H}{L} \right)^3 + 6 \left( \frac{H}{L} \right)^2 \sqrt{\left( \frac{a}{H} \right)^2}.
\]

(13)

where

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

(14)

Then, displacement of cracked specimen can be calculated:

\[
\begin{align*}
\sigma_d &= C \varepsilon_d^m, \\
\varepsilon_d &= \frac{1}{\rho} - \frac{y}{\rho},
\end{align*}
\]

(16)

where \( \sigma_d \) – dynamic normal stresses, MPa; \( C \) – constant; \( \varepsilon_d \) – dynamic relative deformation; \( m \) – material’s dynamic hardening coefficient.

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

\[
\frac{1}{\rho} = \frac{\varepsilon_d}{y}.
\]

(17)

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

Then

\[
\sigma_d = C \rho^m y^m.
\]

(18)

In terms of longitudinal force loading

\[
\int_A \sigma dA = 0
\]

where \( A \) – cross-section area, mm

\[
\int_A y^m dA = 0.
\]

(19)

Then in accordance with equilibrium condition

\[
\int_A \sigma y dA = M \quad \text{or} \quad M = \frac{C I_{n+1}}{p},
\]

(20)

where \( I_{n+1} = \int_A y^{n+1} dA = n + 1 \) row’s inertia moment of cross-section.

Differential Eq of displacement is expressed in form

\[
\frac{d^2 u}{dz^2} = m \sqrt{\frac{M}{C I_{n+1}}},
\]

(21)

where \( z \) – longitudinal axis of specimen, mm.
Conditional moment of inertia $I_{n+1}$ is obtained:

$$I_{n+1} = 2B \int_0^H y^{m+1} dy = \frac{BH^{m+2}}{2^{m+1}(2+m)}.$$  \hspace{1cm} (22)

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

$$\frac{d^2 u_0}{dz^2} = m \left( \frac{Fz}{2C I_{n+1}} \right) = \left( \frac{Fz 2^{m+1}(2+m)}{2CBH^{m+2}} \right)^{m-1}.$$ \hspace{1cm} (23)

Marking

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

Eq (23) becomes:

$$\frac{d^2 u_0}{dz^2} = Dz^{m-1}, \hspace{1cm} (25)$$

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

$$\frac{du_0}{dz} = D \int z^{m-1} dz = Dz^{m-1+1} + K.$$ \hspace{1cm} (26)

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

$$u_0 = \frac{D}{m^{m-1+1}} \int z^{m-1+1} dz + K \int dz = \frac{D}{m^{m-1+1}} \frac{z^{m-1+2}}{m-1+2} + Kz + N.$$ \hspace{1cm} (27)

Constant $N$ is obtained from boundary condition:

when $u_0 = 0$ then $N = 0$ and constant $K$, when $\frac{du_0}{dz} = 0$;

Thus:

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

and finally

$$u_0 = \frac{D}{m^{m-1+1}} \frac{z^{m-1+2}}{m-1+2} - \frac{D(0.5L)^{m-1+1}}{m^{m-1+1}} z.$$ \hspace{1cm} (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 specimen). 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 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 Deformation velocity 3.0–5.5 m/s | Dynamic Charpy impact test |
|-----------------------------------|--------|------|------------------------------------------|---------------------------|
| Ultimate stress $\sigma_u$        | $\sigma_u$ | MPa | 500                                      | 570                       |
| Yield stress $\sigma_y$           | $\sigma_y$ | MPa | 350                                      | 424                       |
| Elongation at break $\epsilon_u$  | $\epsilon_u$ | %  | 12                                       | 7.7                       |
| Elongation at yield $\epsilon_y$  | $\epsilon_y$ | %  | 1.0                                      | 0.64                      |
| Elasticity modulus $E$            | $E$ | GPa | 200                                      | 310                       |
| Shear modulus $G$                 | $G$ | GPa | 80                                       | 124                       |
| Poisson’s ratio $\nu$             | $\nu$ | 0.3 | 0.25                                     | 0.25                      |
| Constant $C$                      | $C$ | MPa | 694                                      | 746                       |
| Hardening coefficient $m$         | $m$ |     | 0.15                                     | 0.11                      |

Fig. 3. Relationship between $J_S$-integral and specimen’s height $H$.
integrals: integral corresponding max and load $J_{UC}$ 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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### Table 3. Results of experiment

| Specimen’s height $H$, mm | Energy at max load $E_{UP}$, J | Energy at failure $E_{C}$, J | Max load $F_{UP}$, kN | Load at failure $F_{C}$, kN | Deflection at max load $u_{UP}$, 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 $U_{C}$, mm | $J_{S}$-integral, MJ/m² |
|--------------------------|-----------------------------|------------------------------|------------------------|
| 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                  |