DOI: 10.2478/adms-2013-0017

P. G. Kossakowski

Kielce University of Technology, Faculty of Civil Engineering and Architecture, Chair of Strength of Materials and Concrete Structures,
Tysiąclecia Państwa Polskiego 7, 25-314 Kielce, Poland; kossak@tu.kielce.pl

ASSESSMENT OF MATERIAL BEHAVIOUR AND STRUCTURAL INTEGRITY OF ENGINEERING STRUCTURES BASED ON R6 PROCEDURE

ABSTRACT

The R6 procedure is one of the most advanced, innovative and effective method developed and recommended for use in problems of material behaviour and structural integrity of engineering structures with defects. The idea and basic assumptions of R6 procedure are described in the paper as well as example of its practical application in analysis of damaged bridge structural element. As a result of the research, the highly conservative approach of R6 procedure was observed, which estimated the level of hazardous loads as the elastic limit load for analysed element.

Keywords: *R6 procedure, Failure Assessment Diagram (FAD), structural integrity, material behaviour*

INTRODUCTION

Properly designed and manufactured structural elements should meet a number of conditions and requirements, in particular in terms of their durability and reliability, with a direct impact on safety. The safety analysis is relatively simple in the case of the elements operating in the elastic range and without defects. The situation is much more complex when the elements are damaged and operate in the plastic range.

The assessment of the structure safety is extremely important in the event of the emergency state, when the components are deformed and contain cracks. Unfortunately, the design standards do not provide specific procedures or even the general rules in such cases. The analysis of structural elements operating in a plastic range and containing cracks is carried out based on assumptions of fracture mechanics. Unfortunately, a lot of procedures are developed only for small elements and sample design pieces. The research focused on the development of detailed procedures for the hazard assessment of the operation of structures containing damages has been conducted for many years. From developed methods the most useful are the R6 [1] SINTAP [2, 3] and FITNET [4, 5] procedures.

Due to the practical importance and the lack of design standard procedures, this paper attempts to present and discuss one of the mentioned method, i.e. R6 procedure, which allows to analyse the material behaviour and test and predict the structural integrity of the damaged components. The idea and assumptions of R6 method is described in detail as well as example of its practical application. Basing on the R6 procedure this analysis includes the assessment of material behaviour and the structural integrity of the support member containing a defect in the form of crack.

ASSUMPTIONS OF R6 PROCEDURE

The R6 procedure is one of the most powerful tools used in the strength analysis of structural elements containing defects. It enables analysis of the hazards of failure at one of three levels, from the first, the simplest and the most conservative, up to the most advanced, but giving the most accurate results.

The safety analysis of damaged component in the R6 method is generally based on the Failure Assessment Diagram, denoted as FAD. It is a basic graph that allows us to determine whether the flawed section works safely, the damage is possible or risk of damage is high. R6 procedure in Failure Assessment Diagram combines two main fracture criteria: limit load criterion and stress intensity factor criterion.

Consequently, in R6 procedure two main parameters are used, L_r and K_r. They are dependent on load, geometry and material properties. The parameter L_r connected to the limit load criterion is defined as:

$$L_r = \frac{P}{P_L(a, \sigma_y)} = \frac{\sigma_{ref}}{\sigma_y} \tag{1}$$

where: P is applied primary loading, $P_L(a, \sigma_y)$ is the corresponding limit load for the component with a crack size a and yield stress σ_y, σ_{ref} is primary reference stress, σ_y is yield stress equal 0.2% proof stress.

The second parameters K_r,which is linked to the stress intensity factor criterion, is defined as:

$$K_r = \frac{K}{K_{mat}} \tag{2}$$

where: K is stress intensity factor, K_{mat} is fracture toughness of the material.

The Failure Assessment Diagram in R6 method is constructed on the basis of above parameters, L_r and K_r, failure assessment curve $f(L_r)$ and the plastic collapse limit $L_r = L_r^{max}$. Assessment of the probability of the element failure is based on the comparison of the assessment point (L_r, K_r) with the failure assessment curve $K_r = f(L_r)$ and the plastic collapse limit $L_r = L_r^{max}$. If the point is located within the area bounded by failure assessment curve $f(L_r)$ and the plastic collapse limit $L_r = L_r^{max}$, which is shown schematically in Figure 1, the element will operate safely (point A). When the assessment point is out of this area (point C), the probability of the component failure is high.

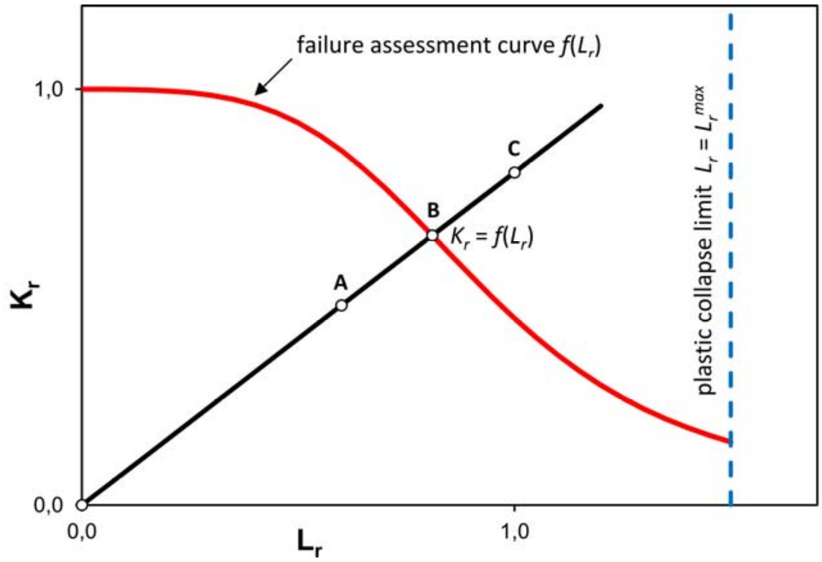

Fig. 1. Failure Assessment Diagram (FAD) according to R6 procedure

As mentioned before, the R6 procedure enables to assess the structure integrity on one of three levels of the analysis, depending on the available input data and expected conservatism and accuracy of the results. The first level is the easiest and indiscriminate in terms of the necessary information on the mechanical properties of the material. Hence, the results are the most conservative, but also the least accurate. Accuracy, complexity of analysis and requirements for the necessary material data increase on subsequent levels, so that failure criteria are less stringent in comparison to the first level. The levels of analysis used in the R6 method are described below, basing on the information given in [6].

The first level of R6 analysis is based on FAD. This level is used for materials which do not exhibit a strong strain initial hardening. This level is also used in situations where there is no specific data on the complete stress-strain curve, and only yield stress σ_y and ultimate tensile strength σ_m are known. When the material has a discontinuity at the level of yield stress analysis is carried out only in the range for $L_r < 1$. This is the simplest level, which requires only basic knowledge on mechanical properties of the material. As a result, the first level is conservative, that ensures the high degree of safety. It is suggested that the analysis should start from this level, because when it is determined that the component works safely, automatically there is no need to perform more sophisticated analysis at higher levels.

For the second level of analysis it is necessary to know more on the material strength parameters, in comparison to the first level. It concerns the full curve "real" stress – "real" strain, yield stress σ_y and ultimate tensile strength σ_m. This level is used for materials with strong hardening. The use of the second level of R6 procedure enables the analysis of material behaviour and structural integrity of elements operating in the range above the maximum load. It may be necessary in certain situations, when the first-level analysis shows that the assessment point is placed on the FAD in a hazardous area but close to the limit curve L_r^{max} for the low values of K_r.

The third level of analysis allows us to determine the most accurate results from these levels and is characterized by lower conservatism. Unfortunately, more strength parameters, including in particular the J integral and the full stress-strain curve is needed for the analyzed material. The third level is recommended when mixed loading modes are subjected to the considered element.

ASSESSMENT OF MATERIAL BEHAVIOUR AND STRUCTURAL INTEGRITY OF STRUCTURAL BRIDGE ELEMENT USING R6 PROCEDURE

The analysis presented below concerns the full R6-based assessment of material behaviour and structural integrity of damaged structural element, which models the bridge girder with defect, basing on the results presented in [7]. The analyzed element was made of S235JR steel, which is one of the most common steel grade used in engineering. The defect in the element was modelled as a crack. The research included determination of strength and fracture toughness parameters of S235JR steel, experimental test of considered element and essential R6 analysis, which is described in detail in subsequent sections.

Strength and fracture toughness parameters of S235JR steel

The strength parameters of S235JR steel were determined during standard tensile test according to [8]. The samples of rectangular cross-section $b \times h = 10 \times 12$ mm were used with initial length base $l_0 = 140$ mm and primary cross-sectional area $S_0 = 120$ mm^2. The mean strength parameters of tested material were: yield stress $\sigma_y = 290$ MPa, ultimate tensile strength $\sigma_m = 443$ MPa and percentage elongation $A_t = 22.7$ %.

The next part of the strength tests included determination of fracture toughness for S235JR steel, defined by critical values of $J_{\mathrm{I}c}$ integral, which is applied for ductile materials. The experiments were performed using SEN (B) type specimens. The critical values of $J_{\mathrm{I}c}$ integrals were estimated basing on the fracture toughness J_Q determined using specimens of dimensions corresponding to the geometry of cross-section of analyzed bridge element. The multiple specimen and electrical potential changes methods were applied in order to determine fracture toughness J_Q according to [9]. Basing on the results obtained, it was noticed, that fracture toughness determined using the electrical potential changes method was lower than those determined using multiple specimen method. Taking into consideration higher reliability of fracture toughness determined using the electrical potential changes method it was applied in order to assess fracture toughness J_Q and corresponding critical values of $J_{\mathrm{I}c}$ integral for S235JR steel. The lowest value of critical $J_{\mathrm{I}c}$ integral was assumed as fracture toughness parameter, $J_{\mathrm{I}c} = 135$ kN/m, to apply in fracture analysis of considered element. Then the critical value of stress intensity factor was estimated using the formula:

$$K_{\mathrm{I}c} = \sqrt{J_{\mathrm{I}c} \cdot E} \tag{3}$$

As a result, for S235JR steel, critical value of stress intensity factor was determined as $K_{\mathrm{I}c} = 166$ MPa m$^{0.5}$.

Experimental test

Experimental test was performed using a T-section beam element made of steel S235JR, modelling the lower bridge span. Damage was modelled in the lower part of the web in the form of a vertical crack (Fig. 2).

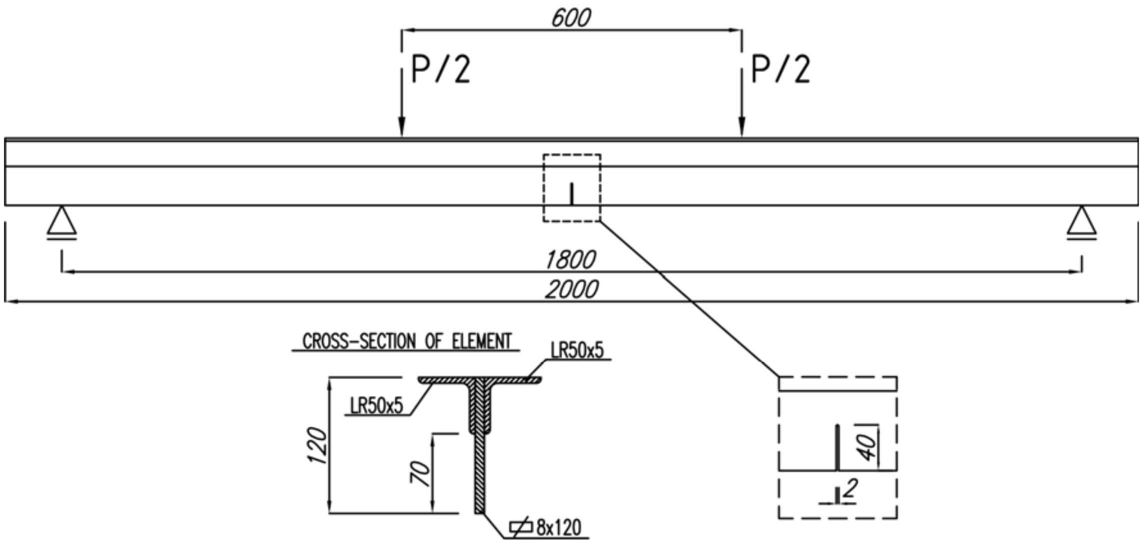

Fig. 2. Geometry of tested element [7]

The element had symmetrical and free supports. The test was performed under displacement control increase with a constant speed of traverse equal 2 mm/min. The loading P was applied at two points arranged symmetrically to obtain a constant bending moment and zero shear force zone. During the test the displacement of traverse l, i.e. deflection of loading points, the load P and surface crack opening displacement δ_M, determined with the use of an extensometer for measuring base of 5 mm, were measured. The test was conducted up to the total failure of the element.

R6 analysis of damaged structural bridge element

In the first range of this part of the analysis the critical value of crack opening displacement δ_{Tc} and limit load P_L corresponding to the material yielding were determined. These values were determined assuming the critical stress intensity factor K_{Ic} = 166 MPa $m^{0.5}$, i.e. fracture material toughness, using the formula [6]:

$$\delta_{Tc} = \frac{4}{\pi} \frac{K_{\mathrm{Ic}}^2}{\sigma_y E} \tag{4}$$

where: yield stress σ_y = 290 MPa, Young modulus E = 205GPa

Critical values of crack opening displacement was estimated as δ_{Tc} = 0.5927mm.

The value of limit load P_L was determined basing on the critical values of surface crack displacement opening δ_{Mc} according to the formula [6]:

$$\delta_{Mc} = \frac{\delta_{Tc} \lfloor r_y (W - a) + a \rfloor}{r_y (W - a)} \tag{5}$$

where: a = 40 mm, W = 120 mm, r_y = 0.44.

For determined values of δ_{Mc} = 1.266 mm and basing on the force–crack surface displacement curve P–δ_M, the limit load corresponding to the material yielding was estimated as P_L = 39.2 kN

In order to assess structure integrity of tested element, the function $K_r(S_r)$ was determined. The parameter K_r was defined as follows:

$$K_r = \frac{K_I}{K_{mat}} \tag{6}$$

where: K_I is stress intensity factor, K_{mat} is material fracture toughness.

Fracture toughness of tested material K_{mat} was identified on the basis of estimated values of K_{Ic}, i.e. $K_{mat} = K_{Ic}$ = 166 MPa $m^{0.5}$. Current value of stress intensity factor K_I was determined as a function of values of crack opening displacement δ_T according to the formula:

$$K_I = \frac{\sqrt{\delta_T \pi \sigma_y E}}{2} \tag{7}$$

According to [6] the parameter $L_r = P/P_L$ connected to the limit load criterion was expressed by parameter S_r, defined as:

$$S_r = L_r \frac{2\sigma_y}{\sigma_y + \sigma_m} = \frac{2P\sigma_y}{P_L(\sigma_y + \sigma_m)} \tag{8}$$

where: P is applied primary loading, P_L is the corresponding limit load for the component with a crack size a and yield stress σ_y, σ_y is material yield stress, σ_m is ultimate tensile strength.

The parameter S_r was established basing on the limit load P_L = 39.2 kN and material strength parameters σ_y = 290 MPa and σ_m = 443 MPa.

The failure assessment curve $f(L_r)$ was defined as $K_r(S_r)$ according to [6]:

$$\begin{aligned} K_r &= \frac{1 - 0.1S_r^2 + 0.1S_r^4}{1 + 3S_r^4} \qquad \text{for} \quad S_r < 1 \\ K_r &= 0 \qquad \text{for} \quad S_r \geq 1 \end{aligned} \tag{9}$$

As a result, the final Failure Assessment Diagram was determined for tested element according to R6 procedure, as shown in Figure 3.

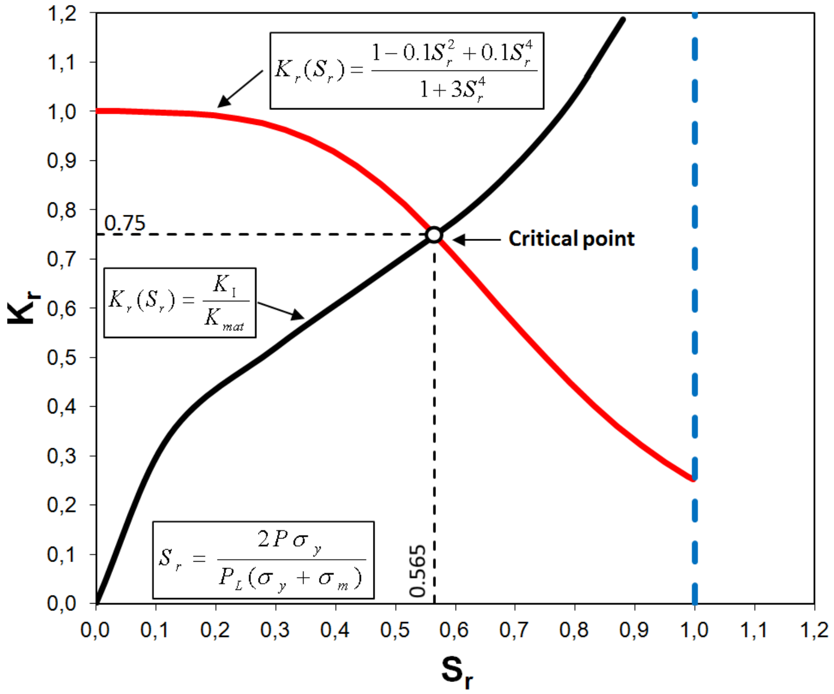

Fig. 3. FAD according to R6 procedure for tested element [7]

As can be seen, the failure assessment curve $f = K_r(S_r)$ defines the safe area for whole range of material deformation. The critical point is noticed when analysed curve meets the failure assessment curve. It correspond to the values of $S_r = 0.565$ and $K_r = 0.75$.

In the next diagram shown in Figure 4, the load–surface crack opening displacement curve P–δ_M is shown, where the point corresponding to the expected moment of element failure according to R6 procedure is denoted.

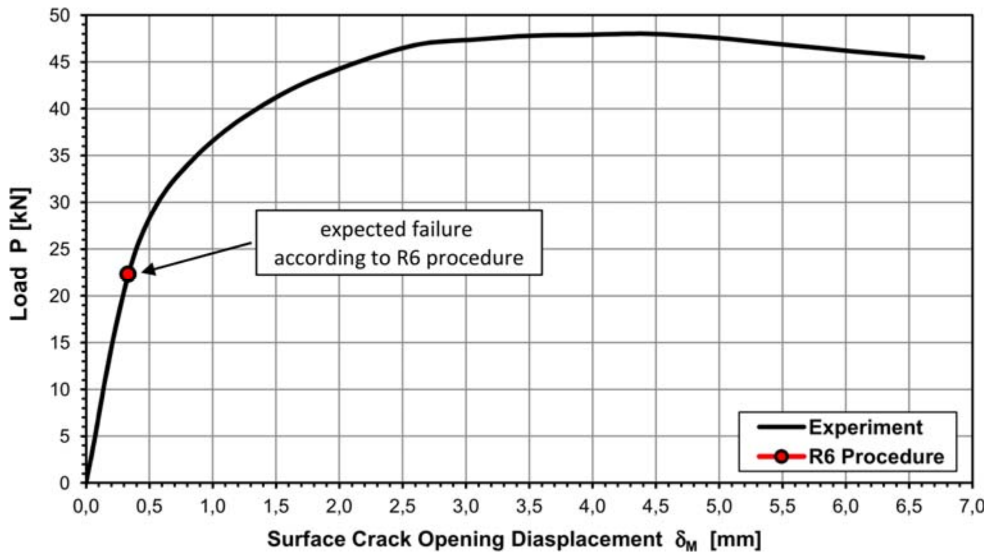

Fig. 4. Load–surface crack opening displacement curve P–δ_M [7]

It corresponds to the end of the material elastic range and the beginning of the material yielding in the case of tested element. In can be concluded that in such case the R6 procedure is quite conservative method which provide high level of safety.

CONCLUSIONS

In this paper, R6 procedure, which is applied in strength analysis of defected structural elements, is presented. It seems that in the case of lack of precise standard guidance, R6 procedure can be successfully used in problems of material behaviour and structural integrity of damaged elements used in engineering.

A good example of this are the results of the presented analysis, which concerns the structural integrity and material behaviour of beam element containing the damage in the form of crack. The results obtained showed that critical load according to the R6 procedure was equalled to 0.57 of S_r parameter, which correspond to the end of the elastic limit of the material. As a result, the R6 is conservative and restrictive method, which provides a high safety level for tested elements.

It seems that further research should be focused on adaptation and development of the methodology of structural analysis using R6 procedures so that the results obtained may be useful in the analysis and expertise in the field of load-bearing capacity of various damaged structural elements, especially operating in the emergency states.

REFERENCES

1. R6: Assessment of the integrity of structures containing defects. British Energy Generation Report R/H/R6, Revision 4, 2001.
2. SINTAP: Structural integrity assessment procedures for European industry. Brite-Euram Project No. BE95-1426, Contract No. BRPR-CT95-0024, Final Report, 1999.
3. Ranatowski E.: Relation Structure - Fracture Resistance in Process of Estimate the Weldability of Low Alloy Steels: Part II, Advances in Materials Science, 10, 2010, 41-47.
4. Koçak M., Hadley I., Szavai S., Tkach Y., Taylor N.: FITNET Fitness-for-Service (FFS) Procedure – Volume 1, Revision MK8. Joint Research Centre, GKSS Research Centre Geesthacht, 2008.
5. Koçak M., Hadley I., Szavai S., Tkach Y., Taylor N.: FITNET Fitness-for-Service (FFS) Annex – Volume 2, Revision MK8. Joint Research Centre, GKSS Research Centre Geesthacht, 2008.
6. Neimitz A., Fracture Mechanics [in Polish], PWN, Warszawa, 1998.
7. Kossakowski P.: The Evaluation of Load-Carrying Capacity of Elements of Steel Structures Using R-6 And FITNET Methods [in Polish], Proceedings of 56th Annual Conference of KILiW PAN i KN PZITB on Scientific Problems of Civil Engineering, Kielce 19-24 September 2010, Kielce-Krynica, 667-674.
8. PN-EN 10002-1:2004 Metallic Materials – Tensile Testing – Part 1: Method of Test at Ambient Temperature.
9. PN-88/H-04336 Metals – Test method of fracture toughness by measurement critic value J integral.