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Cracked scuba panel safety valve disc fracture analysis

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1. Introduction

Flaws in material, appearing because of imperfections, manufacturing faults or severe service conditions, can easily threaten the structural integrity of engineering components. This is particularly dangerous when concerning equipment whose purpose is to protect larger systems, e.g. pressure safety valves (PSV) that protect pressure vessels and equipment of overpressure. Catastrophic consequences can occur [1] if a weakened pressure safety valve fails to function properly, especially if some its components are susceptible to crack growth. Therefore, it is crucial to assess design of such components according to fracture mechanics principles.

Assuming isotropic linear elastic material behavior or dealing with materials that exhibit small-scale yielding at the crack tip, linear elastic fracture mechanics parameters can be used to assess mentioned fracture behavior [2]. One of such parameters is stress intensity factor (SIF), a parameter that completely defines crack tip conditions, i.e. stress, strain and displacement values. Among the first efforts in that direction were pioneer works of Irwin [3] and Williams [4] that deal with stress and strain analysis around the crack.

Closed-form solutions for SIF have been derived for a number of simple configurations [5, 6], but the research of the topic is ongoing, especially for the applied solutions. Latest efforts include SIF calculation for a tension plate and study on potential transferability on bended pipe [7]. Least-square method was used to analytically find SIFs of finite elastic disk in polar coordinates [8], while the similar approach used the Hamiltonian formulation to analyze edge cracked cylinder in 3D domain [9]. Weight functions found use in analyzing edge cracked semicircular disk under compressive loading [10], while same authors studied possible use of mentioned disk as a specimen for fracture toughness assessment of brittle materials using compressive loading [11]. As for the crack occurrence in safety valves, only few works have been reported, dealing with a semi-elliptic crack appearing in valve body [12], or intergranular corrosion and fracture of a steel stud used in safety valve assembly [13].

Regarding all mentioned here, it is easy to understand the need for the research of pressure safety valve behavior when a crucial part, disc, is through or partially cracked. This paper is a step in that direction combining experimental investigation of functionality and numerical determination of stress intensity factors.

2. Theoretical background

Stress intensity factor is a significant parameter in linear elastic used in fracture mechanics predict the stress state near the tip of an arbitrary crack caused by a remote arbitrary load. Depending on the crack opening mode, there are three types of SIFs – Mode I (opening), II (in-plane shear) and III (out-of-plane shear) with Mode I being most common for fracture problems found in structural engineering components. Several methods developed to find SIF include singular integral equations [14], weight functions [15], finite element [16] or extended finite element methods [17]. Closed-form SIF solutions are developed for a number of different geometries and loads. For a single edge cracked circular plate subjected to uniformly distributed edge stress, Fig. 1, a, Mode I SIF is [18].

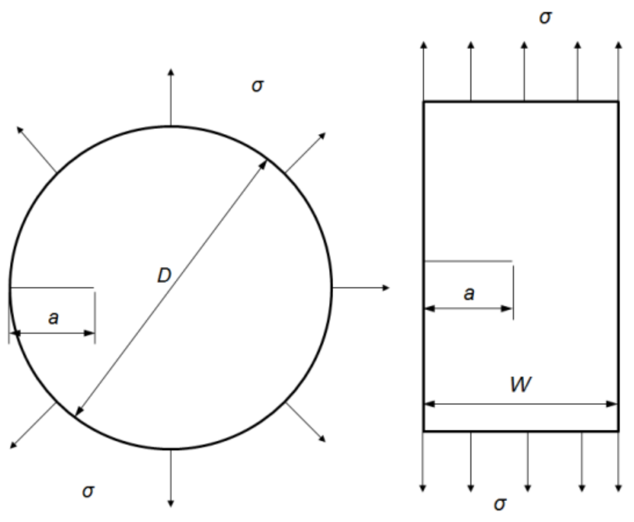


Fig. 1 a - Single edge cracked circular plate; b - Single edge notched rectangular specimen

$$K_I = \sigma\sqrt{\pi a}\, F\left(\frac{a}{D}\right), \tag{1}$$

$$F\left(\frac{a}{D}\right) = \frac{1.122 + 0.14\left(\frac{a}{D}\right) - 0.545\left(\frac{a}{D}\right)^2 + 0.405\left(\frac{a}{D}\right)^3}{\left(1-\frac{a}{D}\right)^{\frac{3}{2}}}, \tag{2}$$

with σ - representing stress; a - being crack length and D - plate diameter.

Example of single edge cracked circular plate is chosen since it is similar in geometry and load to cracked safety valve disc later investigated in this paper. Another way of determining SIF for the single edge cracked circular plate is by using symplectic expansion method [8]:

$$K_{\mathrm{I}} = lim\sqrt{2\pi r} \cdot \sigma_{r|\theta=0} = \frac{3\sqrt{2\pi a} \cdot a_1^{(1)}}{1+\nu}, \tag{3}$$

where ν stands for Poisson's ratio.

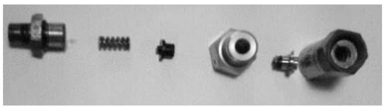
If trying to validate Eqs. 1 and 3 for the single edge cracked circular plate, an empirical solution [19] for single edge notched rectangular specimen, Fig. 1, b, could be used:

$$K_{\mathrm{I}} = \sigma\sqrt{\pi a}\left[\begin{array}{l} 1.12 - 0.23\left(\dfrac{a}{W}\right) + 10.55\left(\dfrac{a}{W}\right)^2 - \\ -27.72\left(\dfrac{a}{W}\right)^3 + 30.39\left(\dfrac{a}{W}\right)^4 \end{array}\right], \tag{4}$$

with W being specimen width.

3. Cracked safety valve disc

Pressure safety valve studied here is of a classic double-spring construction with steel body and aluminum bonnet. It is usually used on pressure equipment intended for filling scuba tanks with air, e.g. air compressors, filling panels, pressure reducers. Opening pressure is typically set on 22.5 MPa or 30 MPa. Eight of them were taken off pressure equipment in a regularly scheduled maintenance process. Typical setup of a disassembled pressure safety valve can be seen in Fig. 2, a.



a

b

Fig. 2 a - Typical setup of a disassembled pressure safety valve; b - Upper disc containing edge crack (in circle).

Of particular interest is upper disc on which, in one PSV, an edge crack has been detected, Fig. 2, b. Fracture behavior of this disc is a topic of further investigation since, because of constructional demands, flaws in it can produce malfunctioning of entire PSV, endanger the process of air filling and eventually cause pressure burst of the attached equipment.

Table 1

Mechanical properties of CuZn39Sn1, $\sigma_{0.2}$ - yield tensile strength, σ_m - maximum tensile strength, E - modulus of elasticity, ν - Poisson's ratio

Material	$\sigma_{0.2}$, MPa	σ_m, MPa	E, GPa	ν
CuZn39Sn1	207	427	100	0.28

Material of considered disc is given in Table 1; it is a type of brass with good corrosion resistance that finds applications in marine structures like bolts, nuts, propeller shafts, rivets, valve stems, etc. Geometry of the considered disc is given in Fig. 3.

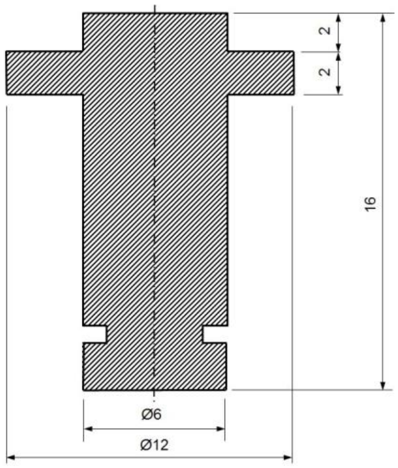


Fig. 3 Dimensions of the considered disc (in mm)

4. Experimental procedure

Functionality of PSVs containing uncracked and cracked disc was examined on a Wika hydraulic test bench equipped with analog pressure gauge and digital pressure transmitter while the results were recorded using Wika Easy Cal software, Fig. 4.

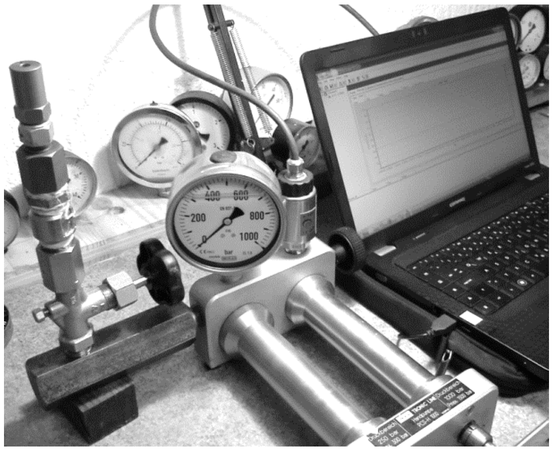


Fig. 4 Experimental setup

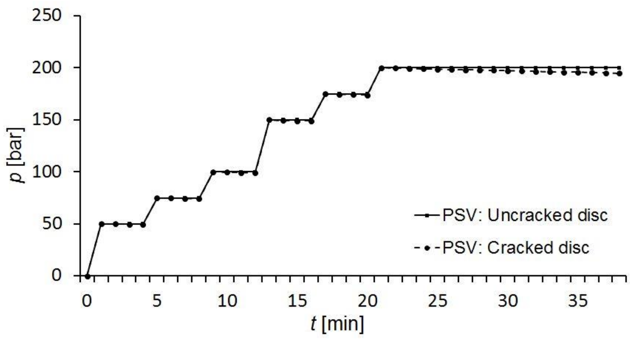


Fig. 5 Pressure drop caused by fluid leakage through a PSV containing cracked disc

Using experimental setup, functionality, opening pressure, full opening pressure and fluid leakage were examined [20]. Results showed that a PSV with a cracked disc exhibited test fluid leakage resulting in a pressure drop, Fig. 5. That kind of malfunctioning would be unallowable for a PSV in service because it would endanger attached pressure equipment and bring significant losses. Also, it clearly marked the problem of PSV containing cracked disc so the next step was to numerically investigate the fracture behavior of disc with different shapes of crack.

5. Finite element analysis

In order to build a numerical model of a cracked PSV disc, finite element (FE) method was used. Material behavior was considered linear elastic isotropic with properties according to Table 1. Disc FE model was defined according to geometry in Fig. 3, but due to symmetry, only half of the disc is modelled, Fig. 6. Symmetric boundary conditions are applied on the cross-section surface, except of the cracked portion of symmetry plane. Crack tip is constrained in the direction of *x* axis to avoid rigid translation. Additional totally constrained points at the bottom of the valve prevent rigid body motion in the direction of *z* axis. Pressure of 22.5 MPa is applied on the areas of disc below the cracked ring and it is assumed to fully penetrate the crack cavity.

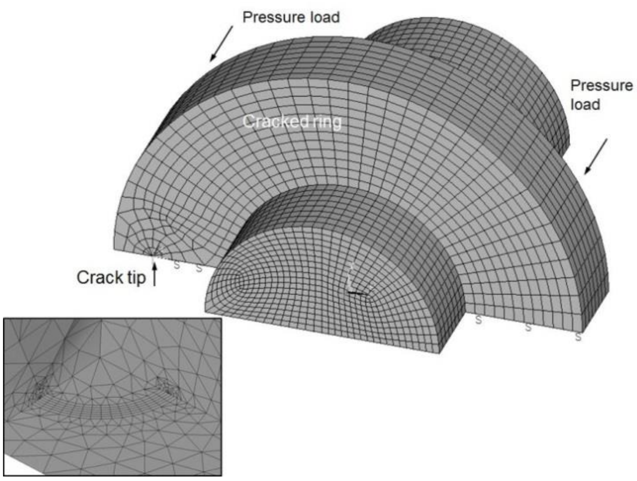


Fig. 6 FE model of disc with a detail of edge crack

To accommodate the singular stress field in the vicinity of the crack tip, this area was meshed with 20-node isoparametric brick elements collapsed to wedges. Rest of the model consists of 20-node isoparametric brick elements. Particular care was taken when meshing area around the crack tip ensuring mesh fine enough to properly capture stresses and deformations. Around 25.000 elements are used to mesh the model; this number gave balance between accuracy in SIF calculation and economy in terms of computer process time. Models with around 18.000 and 31.000 elements were tested, but the lack of accuracy or economy was noted.

The FE method is employed in order to obtain SIFs because of its versatility when dealing with vast array of different cracked structures, being standardized specimens [21] or real structures [22]. It was proved [23] that the theoretical strain/stress singularity at the corner of a 20-node isoparametric element can be achieved by moving the mid-side nodes of the elements to 1/4-point positions toward the crack tip. SIF can then be estimated for plane strain conditions from the crack-surface displacements at these 1/4-points:

$$K = \frac{E}{4\left(1-\nu^2\right)}\sqrt{\frac{2\pi}{r_{1/4}}}\,u_{1/4}, \tag{5}$$

where $r_{1/4}$ is the distance of the 1/4-point from the crack tip and $u_{1/4}$ displacement of the 1/4-point.

5.1. FE model validation

Prior to obtaining SIFs for studied case, FE model is validated. Validation is done by comparing SIF obtained for FE model of the disc containing through edge crack, Fig. 7, with similar models presented in Fig. 1.

Loads are distributed according to Fig. 1, while SIF for FE model is determined through Ansys routine, Eq. (5), and compared to SIFs calculated using Eqs. (1-4).

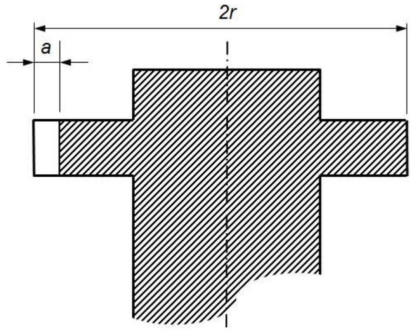


Fig. 7 Geometry of an edge through crack used for validation

Resulting SIF are obtained for plate diameter $2r = 12$ mm, crack length $a = 1$ mm, specimen length $W = 12$ mm, stress $\sigma = 30$ MPa. Obtained results, Table 2, show good correspondence between SIFs calculated by different methods. Greater difference is seen when calculating SIF according to Eq. (4), but that can be accounted to different geometry, Fig. 1, b.

Results give confidence in further use of PSV cracked disc FE model when real, in-use, pressure loads are applied along with real, part-through crack.

Table 2

Comparison of SIFs obtained by different methods for a plate containing through edge crack

	Eq. (1)	Eq. (3)	Eq. (4)	FE model
K_I, MPa·mm$^{1/2}$	68.466	66.391	61.841	65.641

6. Results and discussion

Using proposed FE model and procedure, SIFs are calculated for an array of different crack dimensions (*a/c* = 0.2, 0.4, 0.6, 0.8, 1), crack lengths (*a/r* = 0.01, 0.025 and 0.05) and crack front angles (α = 0°, 30°, 45°, 60°, 90°), Fig. 8. Values of SIFs are normalized according to relation [24]:

$$K_N = \sigma\sqrt{\frac{\pi a}{Q}}, \tag{6}$$

where:

$$Q = 1 + 1.464\left(\frac{a}{c}\right)^{1.65}, \quad \frac{a}{c} \le 1; \qquad Q = 1 + 1.464\left(\frac{c}{a}\right)^{1.65}, \quad \frac{a}{c} > 1. \tag{7}$$

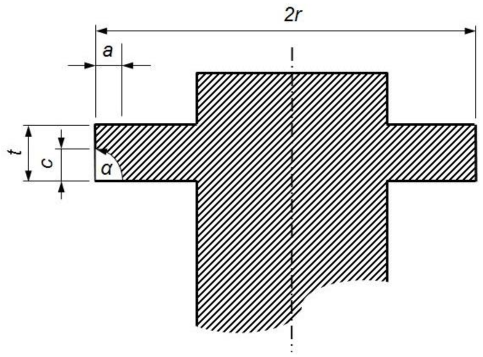
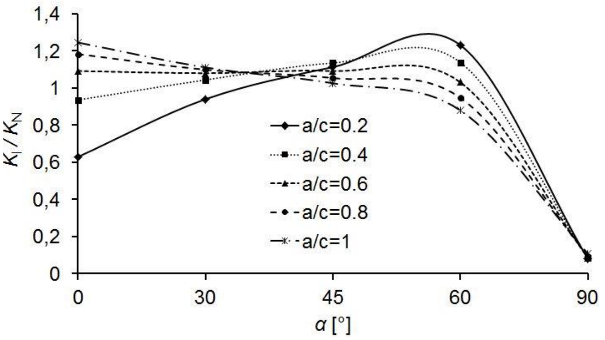
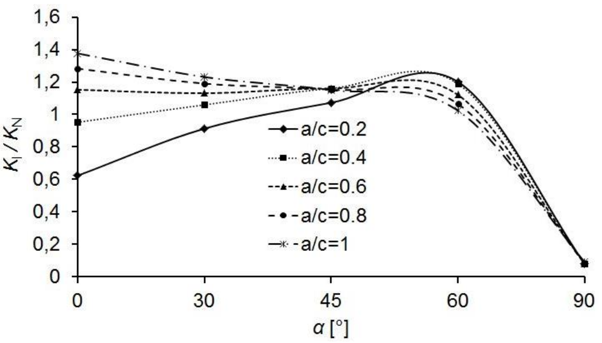


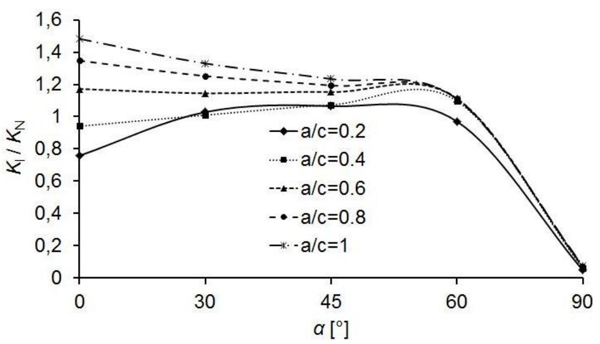
Fig. 8 Geometry of examined cracks



a



b



c

Fig. 9 Calculated SIFs: a - a/r = 0.01; b - a/r = 0.025; c - a/r = 0.05

Results are given in Fig. 9, for a/r = 0.01, 0.025 and 0.05, respectively, and for different crack shapes a/c = 0.2, 0.4, 0.6, 0.8, 1, depending on crack front angle α = 0°, 30°, 45°, 60°, 90°.

It can be noted that smaller cracks correspond to lower SIF values and vice versa. Also, SIF values on the outer edge, α = 90°, are significantly lower than the ones on the inner edge, α = 0°.

7. Conclusion

In this paper fracture behavior of a cracked pressure safety valve disc mounted on scuba tank filling panel has been studied. By using experimental procedure, functionality check of PSV with uncracked and cracked disc was carried and malfunctioning of PSV with cracked disc has been recorded. SIF solutions for different crack configurations located in PSV disc have been obtained then using FE methodology. The procedure is validated for a through edge crack in a circular plate using available analytical and empirical solutions. Good correspondence of results in validation process gave confidence in using the FE methodology for a case of PSV edge cracked disc. Obtained results give insight into the fracture behavior of such cracked disc and can be used in the design process or inspecting PSV condition assessment.

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CRACKED SCUBA PANEL SAFETY VALVE DISC FRACTURE ANALYSIS

S u m m a r y

Fracture behavior of a cracked safety valve disc mounted on scuba tank filling panel is studied in this paper. Experimental comparison of functionality between the safety valves with uncracked and cracked disc was done and, following that, cracked disc was further numerically investigated. Stress intensity factor (SIF), an important fracture mechanics parameter, was calculated for an array of edge crack dimensions, crack lengths and crack front angles using finite element (FE) analysis. Prior to that, FE model was verified according to available solutions for similar problems. Obtained results are valuable for predicting fracture behavior of a safety valve with cracked disc and as a reference in the design process of such discs.

Keywords: cracked disc, safety valve, stress intensity factor, FE analysis.

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