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Numerical Analysis of explosion effects on the redistribution of residual stresses in the underwater welded pipe

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Abstract

Structural health monitoring of cracked structures is one of beloved subject of researchers recently. Consider of crack behavior in the water and energy pipeline is important because of environmental problems. In this paper consider of crack parameters in the underwater pipe subjected to mechanical transient load is investigated. For this purpose, three-dimensional parametric model of cracked pipe has been presented for calculation of J integral values. Underwater explosion load model has been used for applying the transient load and J integral values have been obtained in circumferential and axial semi-elliptical internal cracks. Obtained results is shown that under mentioned condition, pipe isn't safe and crack grow is happening in the inner surface of crack. According to results for integrity of structure must be safe stand-off distance (distance of charge with respect to pipe) greater than previous state. Obtained values in this paper is used for estimation of structure life and Repair and maintenance are useful.

Keywords:

Cracked pipe, Finite element analysis, Transient loading, Dynamic stress intensity factors, Dynamic J Integral

1. Introduction

In the field of structural health monitoring, the dynamic loading plays a very important role, with respect to static loads. Although the presence of many static loads, such as, creep and primary stress into the material can be as important as the dynamic loads, but time-dependent loads, such as, transient and harmonic types of forces can be quite critical in the failure of structures. Since the structures contain one or several defects, the effects of dynamic loads are quite important. This is because most attention is focused on the structures containing the defects. One of the most important defects, on which many analyses have been performed, are cracks. In the presence of cracks in the structures, their threshold tolerance is reduced. Up to now many experimental, analytical, and numerical activities are performed.

These activities are performed to determine the fracture parameters caused by static loading that show good results, while dynamic loads are more important. The analysis of time-dependent loading started 40 years ago. In1971, Freund investigated the crack propagation in elastic solid subjected to uniform and non-uniform loading. Most of the performed activities

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in the fields of dynamic crack analysis is related to dynamic elasticity. In this state the materials' behavior is assumed linear elastic, while the real behavior of materials is a combination of elastic and plastic state.

The appropriate criterion for the analysis of elasto plastic crack problems is J Integral. In fact, this criterion is based on the mere linear elastic assumption, but the empirical activities show that J Integral is a very good parameter for the analysis of elasto plastic stress fields around the crack. It is proven that the elastic strain energy release rate G is equal to J. One of the differences between G and J is in the application of these criteria. G is used for linear elastic materials and J for linear and non-linear ones.

There have been activities on the dynamic crack analysis which have been performed using the finite element and boundary integral equation methods (BIEM). Considering and Comparison of the finite-element method for 2D and 3D cracks subjected to impact loads have been investigated by Enderlein et.al [1]. In this study the dynamic stress intensity factor has been obtained, based on 2D and 3D finite element, by three methods, containing dynamic J integral, modified crack closure integral method, and crack tip near the displacement field. Obtained results have very good agreement.

The dynamic stress intensity factor in a homogeneous and non-homogeneous functionally graded material, using interaction integral, has been investigated by Song et.al [2]. In this study the dynamic fracture behavior of homogeneous and non-homogeneous functionally graded material, as variation of dynamic stress intensity factor and relation between initiation time and the domain size (for integral evaluation), and the contribution of each distinct term in the interaction integral have been investigated using finite element and interaction integral.

Dynamic stress intensity factor in an infinite continuum weakened by a cylindrical crack subjected to impact loading has been investigated by Itou [3]. In this paper transient stresses around a cylindrical crack in an infinite elastic medium subjected to impact loads have been investigated. Stress intensity factors were defined in the Laplace transform domain and were numerically inverted to a physical space. Numerical calculations were carried out for the dynamic stress intensity factors corresponding to some typical shapes assumed for the cylindrical crack. Dynamic fracture analysis for a penny-shape crack in an FGM interlayer between dissimilar half spaces has been investigated by Chunyu Li et.al [4]. Comprehensive description of deformation and fracture of solids as wave dynamic investigated by Sanichiro [5].

Dynamic stress intensity factors in a thick wall cylinder, weakened by semi elliptical internal crack subjected to transient loading have been investigated by Shahani and Nabavi [6]. In this study initially dynamic elasticity relation has been calculated by applying the finite Hankel transform and then the weight function of crack has been calculated using three-dimensional finite element methods and finally dynamic stress intensity factors have been obtained. In the different method, using distributed dislocation method, the dynamic stress intensity factors in an infinite plane, weakened by multiple cracks subjected to impact loads have been investigated by Ayatollahi et.al [7].

In this paper effects of underwater transient pressure loading on the two semi elliptical surface crack in the internally and externally pressurized pipe are investigated. Time-dependent J integral on each contour is obtained, and using the J integral parameter, the dynamic stress intensity factors have been derived.

2. Method section

In this paper main aim is analysis of underwater transient pressure loading effects on the cracked pipe. Two pipe with same diameter and with two separate crack directions have been considered as modeling in this paper. X70 steel has been applied as pipe material. Mechanical properties and chemical composition of X70 steel has been presented in the table (1). Generally; according to figure (1), pipe has been located in depth of 30 meter and distance of dynamic loading source with respect to pipe is 10 meter. Crack direction in the one of the pipe is circumferential and in the other pipe is opposite of circumferential direction. For exact analysis, semi-elliptical surface crack in the internal surface of the pipe has been considered. Finally; by interaction of shock wave induced by dynamic loading with cracked pip, the dynamic stress intensity factors and dynamic J-integral have been obtained. For validation of obtained results, a case study example according to ref. [1] has been considered. In this example dynamic stress intensity factors for an elliptical embedded crack into the rectangular bar has been obtained. Good agreement is observed between obtained result and references.

3. Time-dependent fracture parameters

3.1. *Three-dimensional dynamic J- integral*

In the previous section, kinetic energy was not seen, but in the presence of dynamic loads, the standard form of J-Integral changes into another form. By applying the transient pressure load to the structure, J-Integral parameter is obtained as J, in terms of time. In the static loading, J parameter has a constant value in each node around the contour, while in the dynamic loading, the obtained graph, is a form of energy release rate per time. Finite element analysis of the dynamic J-Integral using virtual crack closure method (VCCM) has been investigated by Enderlin et al [1]. Using this method, the convergence and precision of J value has been increased.

According to Eqs (1), by the selection of the weight function q and applying it to the Eqs (2), the dynamic J-Integral for linear elastic material is obtained as follows:

$$J^d = \int_S \left(\sigma_{ij} u_{i,k} - U\delta_{kl}\right) m_j q_k \, dS - \int_{S^+ + S^-} \left(\sigma_{ij} u_{i,k} - U\delta_{kj}\right) m_j q_k \, dS \tag{1}$$

where q_k three-dimensional weight function, and m_j unit normal vector at the contour, shown in Fig. (2). According to Fig (2), $S=S_r+S^+ + S^- + S_0$. Applying divergence theorem to the integral over S yields:

$$J^d = \int_V \left[\begin{matrix} \left(\sigma_{ij} u_{i,k} - U\delta_{kj}\right) q_{k,j} + \\ \rho \ddot{u}_i u_{i,k} q_k \end{matrix} \right] dV \tag{2}$$

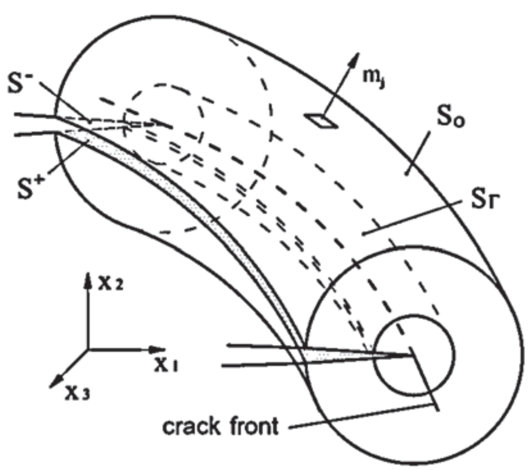

Fig 2. Three-dimensional integration contours [1]

4. Finite element modeling

In this section, two pipes with the same length, diameter, and determined load, with two different cracks shown in Fig. 3, are analyzed. As can be seen, an elliptical three-dimensional crack on the inner surface of the two pipes, one of which is along the circumferential of the pipe and the other one is located along the axis of pipe, too. The main purpose of this study is to investigate the dynamic J integral parameter and stress intensity factors. In this regard, the behavior of materials is being considered in the form of elasto plastic, and for this reason, the J integral parameter has been reviewed and analyzed. Considering the state of elasto plastic behavior of the material, the effective parameter is J integral; and on the other hand, obtaining dynamic stress intensity coefficient parameter of cracks is desired, so in the process of solving the problem, SSY (Small Scale Yielding) conditions are assumed. Modeling the elliptical cracks on the pipes is done in a quarter of it, while coextensive with shortening the time of solution, governing conditions of the issue is simpler. The analysis of cracks in pipes, which is performed by using the Contour Integral method has been done by Abaqus finite element software.

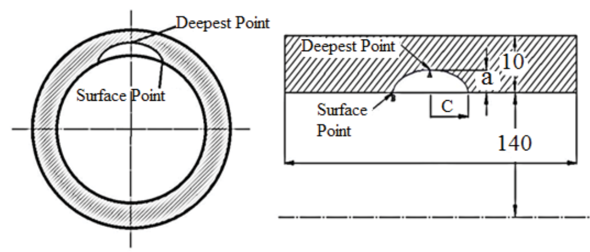

Fig 3. Different crack directions in pipe

As can be seen in Fig. 4, five contours have been used around the crack tip front, each of which has nine nodes. J integral values at each node have been calculated in terms of time. Because of the type of loading that is underwater transient pressure, therefore, it is expected that the crack closure phenomenon, under this type of load, is unavoidable. In the analytical issues, this phenomenon can be studied by applying one condition, but because of difficulties in software modeling, the crack closure can be considered from the results of the stress intensity factor at the parameter negation moments.

5. Underwater transient pressure loading

All underwater transient loading phenomena are caused by the detonation of a stuff-containing explosives, too. The heat generated in the process of the underwater explosion of TNT material is approx. 1050 *kcal/kg*. The temperature created in the gas is approx. 3000°c, with a pressure equal to 5000 *MPa*. Sudden energy released by the detonation of a potent explosives is led to the formation of high-temperature, high-pressure bubble pulse and production of shock waves in the water environment. Propagation speed rapidly reaches a

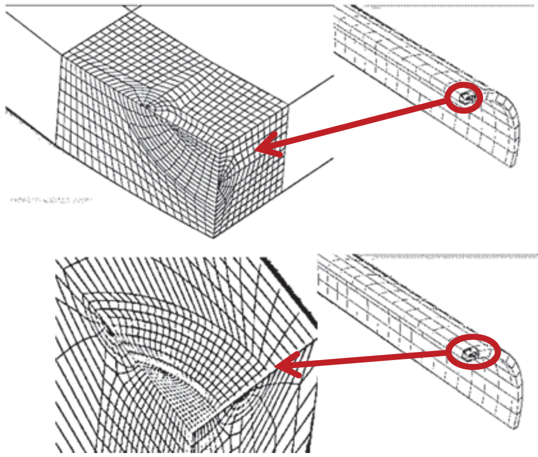

Fig 4. Contour of integration in two different cracks

speed equal to the speed of sound, which is approx.1440 *m/s*. in water [8].

The underwater shock wave created by the explosion is added to the hydrostatic pressure. The pressure-time history diagram starts with a sudden pressure and increases to maximum pressure Pm in less than 10-7 second. Exponential function for the distribution of the pressure has been presented by Cole as follows:

$$p(t) = P_m e^{-t/\theta} \tag{3}$$

where θ is delay time for $0<t<\theta$. Maximum and constant pressure of the delay, depends on the size of the explosive and its distance to the demand position as follows:

$$P_m = 52.16\left(\frac{w^{1/3}}{s}\right)^{1.13} \tag{4}$$

$$\theta = 96.5\left(w^{1/3}\right)\left(\frac{w^{1/3}}{s}\right)^{-0.22} \tag{5}$$

where P_m in terms of MPa, θ in terms of microsecond, and W has been measured by per kg of TNT, and the stand-off s is in meters. These formulas are applied for any amount of explosives, any depth of explosion and shock waves description, except in cases where the explosives are close to the target. In this simulation, the time-freeze technique has been used to study the effects of explosion transient pressure loading of the pipe during which the dynamic load has been applied to the structure at a demand time. In fact, in this article, the dynamic behavior of materials in which the dependency of strain on time is assumed, has not been used, and instead, the effect of dynamic loading on the structure in a certain timeframe is examined.

In this study, the pipe is located at a depth of 30 meters underwater, and the stand-off distance has been considered 10, 5 meters, and the explosive mass is equal to 20 kg of TNT. The pressure-time curve of the material reaction against this amount of explosives, at a distance of 30 meters, has been shown in Fig 5.

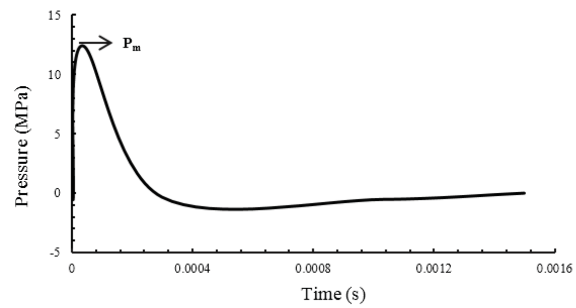

Fig 5. Pressure-Time response of the pipe due to underwater explosion

In order to simulate and apply underwater dynamic loading, the implicit dynamic method has been used, too. Due to the high depth of the location of the explosives and the pipe, the cavitation's effect can also be ignored. Another part of the underwater transient loading is related to the secondary pressure pulse or the bubble pulse. This type of load can be spread over long distances that because of the high destructive power of maximum pressure of the peak, pulse bubble is ignored in this article [10]. As noted before, the distance of explosives to pipe is 10, 5 meters. When the shock wave traverses this distance and reaches the pipe, it almost has the same effect on both sides of it. On the other hand, since the pipe's diameter is not large, the effects of shock waves on both sides of the pipe are identical [8]. That's why the explosive loading on pipes have been considered symmetrical and it is assumed that the propagated shock wave affects the entire surroundings of the pipe, identically.

6. Case study

In this section, in order to demonstrate the appropriateness of the implemented method, by using the finite element software, a problem was calculated and validated according to Ref. [1]. For this purpose, a rectangular shaft with an internal elliptical crack and specified dimensions, shown in Fig.6, is also analyzed under an impact load. The properties of materials used are displayed in Table 1 below. In order to simulate the internal elliptical cracks, the wedge-shaped stage 2 elliptical elements have been used, and for other parts of the material, stage 2 Sweep elements have been used. Dynamic stress intensity coefficient values in the first contour nodes that are related to crack front are shown in Fig. 7.

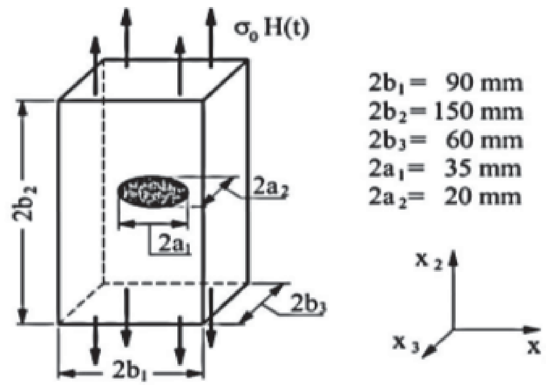

Fig 6. Fully elliptical embedded crack in a rectangular bar [1]

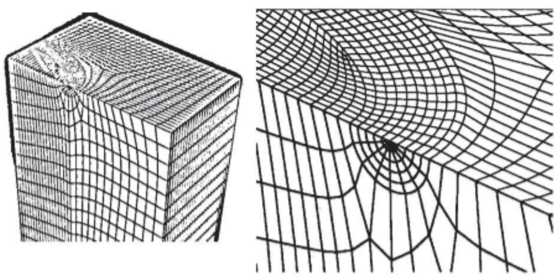

Fig 7. Geometry and meshing of the internal elliptical crack [1]

Table 1. Mechanical properties of materials used in Ref. [1]

μ	ρ	υ
$77\times10^9\ Pa$	$7900Kg/m^3$	0.126

Regarding the complexity of dynamic phenomena that must be considered, in order to precisely verify the answers to various parameters, so, the obtained diagrams can be admissible. As mentioned before, negation of the stress intensity factor on a part of the diagram means the closure of the crack. The reason being, when the transient load is applied to the material, the propagation of stress waves within the material leads to the displacement of materials around the crack and vibrates them, as a result of which, the crack surfaces are opened and closed against each other, and finally, leads to the negation of stress intensity factor values in parts of the diagram.

The number of elements used in this study is 5790 and there are only 2304 cracks in the area containing crack. The dynamic stress intensity factor obtained in Fig (8) where K_d by Eqs (8) is dimensionless:

$$K_I = \frac{\sigma\sqrt{\pi a}}{\Phi}\left(\sin^2\theta + \frac{a^2}{b^2}\cos^2\theta\right)^{\frac{1}{4}} \tag{6}$$

where a and b are half of the ellipse dimensions and θ, is measured at point B, shown in Fig 10, in counterclockwise direction, and Φ is elliptical integral of second type which is definition as follows:

$$\Phi = \int_0^{\pi/2}\left(1-\frac{b^2-a^2}{b^2}\sin^2\theta\right)^{\frac{1}{2}} d\theta \tag{7}$$

By solving the above integral, the final form of dimensionless making relation used in this problem is as follows [11]:

$$K_I = \frac{\sigma\sqrt{\pi a}}{\frac{3\pi}{8}+\frac{\pi a^2}{8b^2}}\left(\sin^2\theta + \frac{a^2}{b^2}\cos^2\theta\right)^{\frac{1}{4}} \tag{8}$$

By substituting θ=0 in Eqs (8), dynamic stress intensity factor is obtained as follow:

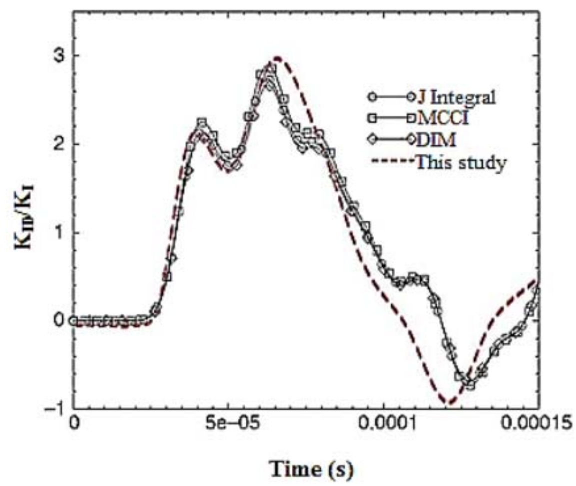

Fig. 8 Verification of dynamic stress intensity factor diagram, calculated by various Refs.

As shown in Fig 8, the obtained result has very good agreement with Ref [1]. In the above Figure. In the 0.1 millisecond, dynamic stress intensity factor is increased and with continuing dynamic loading K_{Id} has reaches the positive part of the graph. This type of loading leads to crack closure and then the negation of stress intensity factors.

7. Numerical results

In this part, we consider the numerical results for the cracked pipe used in this study. According to Fig 4, two cracked pipes are shown, containing two cracks with different directions analyzed by ABAQUS finite element software. Transient pressure loading has been applied on the outer surface of both pipes. The main goal in this paper is to study the direction of two cracks on the J integral and stress intensity factor values. In Figs. 9 until 16, the J integral and dynamic stress intensity factor are shown in the deepest, as well as, surface points, respectively where This fracture parameter have been plotted for deepest point and surface point.

8. Numerical results

In this section the results of J integral and dynamic stress intensity factor of two semi-elliptical cracks shown in Fig. (4) have been analyzed and investigated. All around the crack tip, shown in Fig. (4a), 6 contours and for crack (4b), 5 Contours have been considered. The two important points on the semi-elliptical crack are the Deepest Point and the Surface Point, so that J and dynamic K values have been calculated at these points. Dynamic J integral values for the two-aforementioned cracks are shown in Fig. 9 and 10.

As shown in Fig. 9, values of J for the Deepest Point are more than the ones for the Surface Point. The reason why J increases in the Deepest Point state is that the amount of energy, released at loading time is more on the inner tip of the crack and since that Surface Point is located on the free surface of the pipe, so, due to the dynamic load, less energy is pumped into it. Therefore, since at the Surface Point the outer tip of the crack is located on the free surface of the material, it can release less energy. Thus, the dynamic J integral values or energy release rate around the crack, where it reaches the free surface, is less than the crack tip within the material. The J integral values for the crack shown in Fig. (4b), have been presented in Fig. 10.

As in the previous state, in this type of crack, also, J integral values for the crack tip (Deepest Point) is more than the crack tip on the free surface. The reason for J values decreasing at the tip of the outer crack of the material is also the same as before. It is important to note that if the loading is of a static type, the J at the crack tip has the maximum values. In this case, which the loading is of a dynamic type, the releasing of energy rate is considered that it has the highest value at the inner tip of the crack and at the tip of the crack on the free surface, has the lowest value.

The values of dynamic stress intensity factor for the two cracks shown in Fig. 4, have been analyzed in Figs. (11) and (12). When transient dynamic loading effects the pipe, through the stress wave propagation inside it, causes the crack surfaces open and close [12], in this respect, when dynamic loading leads to crack closure, the stress intensity coefficient values will become negative, during the closure, which is due to compressive stress. In Fig. (11) and (12) this matter is quite noticeable.

Dynamic stress intensity factors and J integral are shown in Fig. (13), (14), (15), and (16). According to this mentioned figures, all of the fracture parameters increases with decrease of the stand-off distance. While, behavior of each parameter is same with state of 10-meter stand-off, but, maximum and minimum value is different with previous stand-off. As a result, fracture parameters as, stress intensity factors and J integral, and failure of cracked pipe strongly increase, when underwater transient pressure loading source is near to cracked pipe. In other words, effects of stand-off distance are more than explosive charge. In fact, with approaching the charge with respect to cracked pipe, the dynamic stress intensity factors and dynamic J integral are increases.

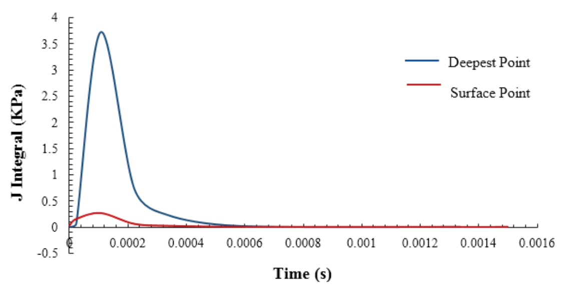

Fig. 9 Dynamic J Integral for circumferential Internal crack for 10-meter stand-off

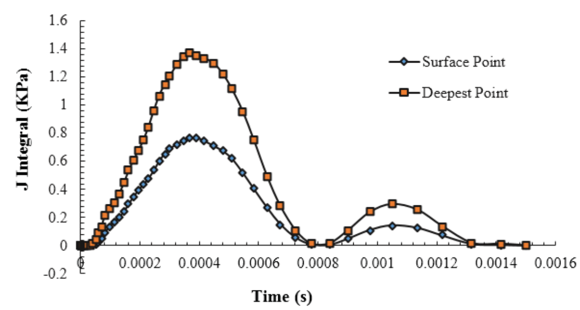

Fig. 10 Dynamic J integral for the axially crack for 10-meter stand-off

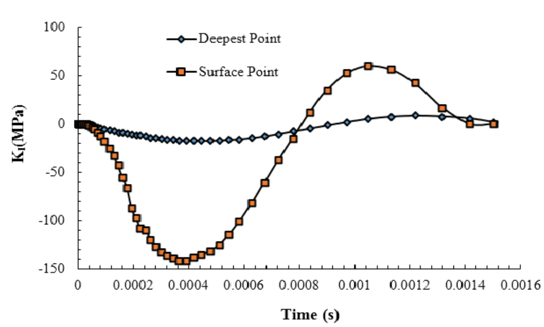

Fig. 11 Stress intensity factor for the axially crack for 10 meter stand-off

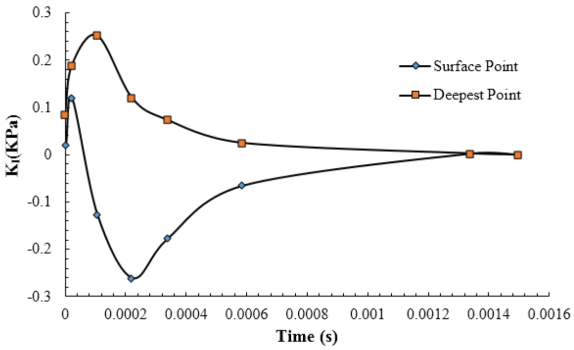

Fig. 12 Stress intensity factor for the circumferential crack for 10-meter stand-off

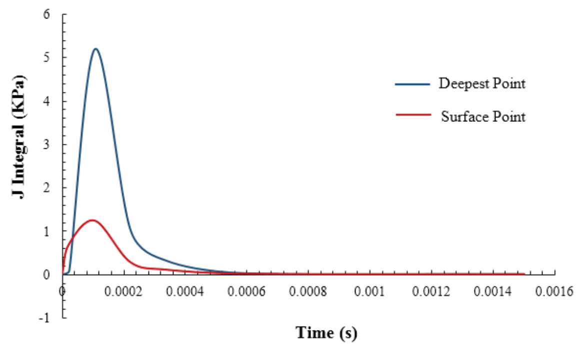

Fig. 13 Dynamic J Integral for the circumferential Internal crack for 5-meter stand-off

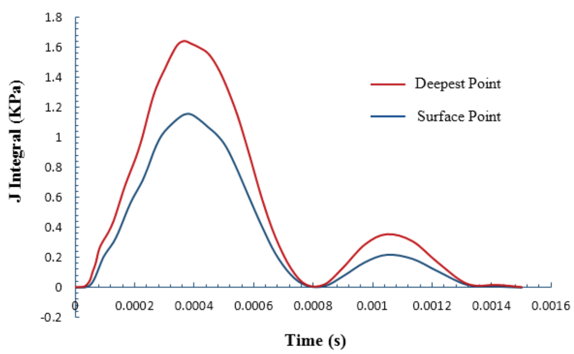

Fig. 14 Dynamic J Integral for the axially Internal crack for 5-meter stand-off

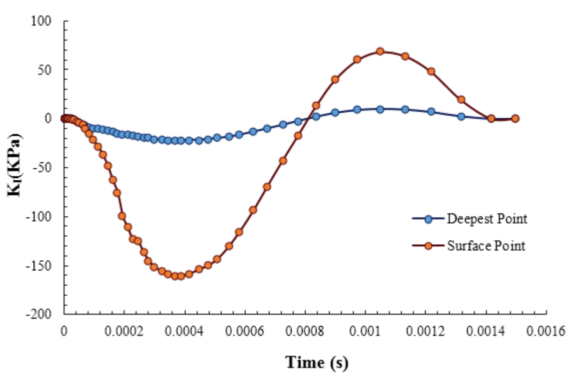

Fig. 15 Dynamic Stress intensity factor for the axially crack for 5-meter stand-off

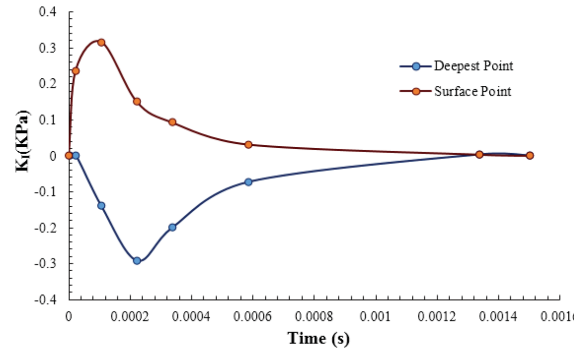

Fig. 16 Dynamic Stress intensity factor for the circumferential crack for 5-meter stand-off

9. Conclusion

In this paper, the effect of underwater dynamic transient pressure loading on dynamic J integral values was investigated. Initially, the dynamic J integral relation, based on Ref. [1] was introduced, by the use of which, the dynamic J values can be obtained for each node of the contour around the crack. At first, a problem, containing a rod with a rectangular cross section with a complete elliptical internal crack was modeled and the dynamic stress intensity factor for the crack tip was obtained. The results obtained from this problem was compared with the results of Ref. [1], in which, good agreement can also be seen between the obtained results. In continuation, two semi-elliptical cracks were introduced, one of which being parallel with the circumference of the pipe and the other one being perpendicular to the previous direction.

A dynamic underwater pressure transient loading was applied to the entire surface of the pipe throughout which the pressure distribution function, introduced by Cole [8], was used to simulate and apply dynamic loading to the pipe surface. The results of this analysis show that under the effect of this type of loading, the J integral in the Deepest Point has Lower values than the Surface Point. In addition to the J integral values, obtained diagrams for the dynamic stress intensity factor also shows that sometimes the crack, during dynamic loading, is closed for a moment and leads to the negation of the stress intensity factor at a particular time.

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Competing interest

The authors declare that they have no competing interest.

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