Journal of Stress Analysis
Vol. 5, No. 1, Spring − Summer 2020, 99-106

Bu-Ali Sina University

ORIGINAL RESEARCH PAPER

Three-dimensional Fracture Analysis of Defected Tubes under Detonation

H. Eskandari*

Abadan Institute of Technology, Petroleum University of Technology, Abadan, Iran.

Article info

Article history:
Received 20 June 2020
Received in revised form
11 September 2020
Accepted 16 September 2020

Keywords:
Finite element simulation
Structural fracture analysis
Detonation loading
Thick walled cylinder

Abstract

The main purpose of this article is three-dimensional finite element analysis of defected tubes under gas detonation loading. The variation of stress intensity factor through the semi elliptical crack front for different defect profiles versus the simulation time is studied. The structural linear elastic response of tube in presence of an embedded defect is considered. The results show that the traveling pressure loads can affect the distribution of fracture factors along the defect shape. It can be seen that the moving pressure loads lead to occur the mixed mode stress intensity factor in thick walled tubes. The dependency of the stress intensity factors on the crack configuration, time period of loading and typical pressure-time profile is investigated. It can be seen that the schematic of stress/strain-time trace profiles strongly dependents on the location of points through the wall thickness. The capability of finite element modeling in analysis of three dimensional dynamic transient problems has been shown.

Nomenclature

a(mm)	Depth of the deepest point on the crack front	DCT	Displacement correlation technique
c(mm)	Semi axis of the elliptical crack	E(Pa)	Elastic modulus
K_I, K_{II}, K_{III} (Pa$\sqrt{\text{m}}$)	Conventional modes I, II, III stress intensity factor	$K_{i,non}$	Non dimensional modes I stress intensity factor
K_O(Pa$\sqrt{\text{m}}$)	Nominal stress intensity factor	H	Heaviside step function
η(mm/mm)	Relative depth of the crack	Q	Shape factor
r_i(mm)	Inner radius of the vessel	P	Pressure of the gas mixture
r_o(mm)	Outer radius of the vessel	T	Exponential decay factor
u_x, u_y, u_z	Displacement in x, y and z directions	V_{cj}	Chapman-Jouguet velocity
$LS-DYNA$	Livermore software-dynamics	L	Tube length
ξ(mm/mm)	Aspect ratio	t_{cj}	Traveling shock time
$APDL$	ANSYS parametric design language	FEM	Finite element modeling
X_G(mm)	x-coordinate of corner point on the crack front	SIF	Stress intensity factor

*Corresponding author: H. Eskandari (Associate Professor)
E-mail address: eskandari@put.ac.ir
http://dx.doi.org/10.22084/jrstan.2020.22345.1154
ISSN: 2588-2597

1. Introduction

The problem of fracture analysis and design of tubes, pipes and vessels due to mechanical loading of shock has continued to attract attention for reason of their mechanical importance and the intellectual challenge [1-3]. An accidental explosion can produce a detonation wave propagating through tubes or pipes [4]. Flexural shock wave in tubes produces moving pressure loading which provides the driving force for crack extension and resulting oscillating strain.

The vessels, tubes and pipes with the probability of the accidental burst or explosion are employed in a wide variety of industrial applications such as oil and gas transmission and distribution pipeline systems, pressurized aircraft fuselages, and Compressed Natural Gas (CNG) fuel cylinders/tanks [1, 5]. If a defect is detected in a pressurized vessel or pipe, it is vital to know its residual strength to withstand a detonation loading.

In analyses of suddenly exploded structural parts, much attention is being paid to investigating the transient response of vessels to gaseous detonation. Unfortunately, most studies are focused on two dimensional works. For example, the problem of gaseous detonation-driven fracture of tubes is examined by Chao [1]. He developed the fracture threshold model for gaseous detonation-loaded tubes with different flaw sizes.

Mirzaei et al. [5] investigated the fracture analysis of a CNG fuel tank under explosion through the finite element simulation. The elasto-dynamic transient structural response of a finite length tube under detonation loading is investigated by Mirzaei et al. [6]. Zhou et al. [7-8] studied the mechanical and thermal responses of sandwich tubes under internal dynamic load.

Malekan et al. [2] analyzed a cylindrical tube with internal shock loading through the numerical approach. In this work, we considered a cracked cylinder and analyzed the elastic response to the resulting load from a detonation shock wave traveling along the cylindrical tube axis starting from the closed end.

Here a wealth of quantitative data on the nature of gaseous detonation driven fracture of tubes in three dimensional, which has not been addressed to date available in the literature, is obtained. The contribution of the current work is to provide 3D finite element analysis of fractured cylindrical tube due to shock loading (Fig. 1).

The configuration of internally semi-elliptical arc crack in middle of tube is depicted in Fig. 1. The semi-elliptical internally surface defect is described by non-dimensional parameters $\eta = a/t$, and $\xi = a/c$, the so-called the relative depth and aspect ratio of the defect, respectively. As shown in Fig. 1, any arbitrary point located on the front of the crack in local coordinate system is normalized by the x-coordinate of the corner point (X_G).

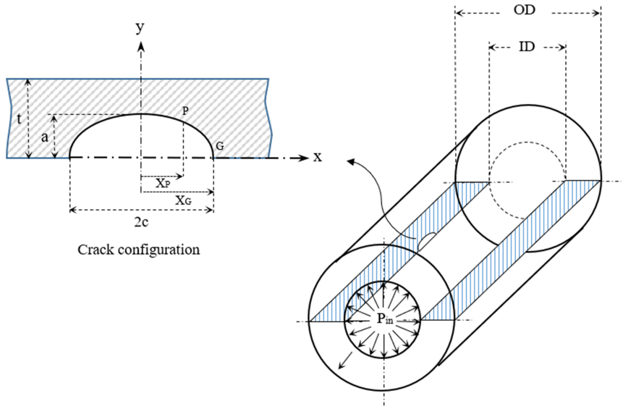


Fig. 1. The schematic diagram of a cylindrical pressure vessel with an embedded elliptical defect.

2. Gaseous Detonation and Pressure Loading

A detonation consists of a shock wave with the supersonic speed of the wave front and a reaction region that are coupled together tightly [4]. Depending on the fuel-oxidizer combination, an ideal gaseous mechanical shock travels at speed of Chapman-Jouguet velocity, V_{cj}, in range of 1500 to 3000m/s [4]. The maximum value of mechanical wave pressure near the detonation is 20–30 times the value of ambient pressure [4].

Here an exponential approximation known as Taylor–Zeldovich model is adopted to describe the pressure history for shock dynamic loading [9]:

$$P(t) = P_1 - P_{atm} + [P_2 - P_1 + (P_2 - P_3)e^{-\frac{t_{cj}}{T}}] \times (1 - H(x - V_{cj}t)) 0 < x < L \quad (1)$$

Where P_1, P_2, P_3 and P_{atm} are the initial values of the gas mixture pressure, the peak value of the pressure, the post shock and atmospheric pressures in the cylinder, respectively. Here T is a factor with the exponentially decaying trend, distance x is the variable which is measured from starting point of the shock, t is the time variable, H is the Heaviside step function, t_{cj} is the traveling time it takes for a shock wave to arrive the x location in a cylinder with length L. From the structural point of view, the tube will experience transient deformations for the reason of moving load arising from the detonation.

Here it is assumed that the displacement of cylindrical tube is constrained at both ends and the time dependent pressure is applied to the inner surface of the tube.

3. Finite Element Simulation

The work has been done through the LS-DYNA commercial package employed as a powerful Finite Element

(FE) solver for non-linear dynamic problems. The singular elements are used around the front of the crack and the Explicit 3-D structural solid elements (8 nodes solid 164) are used for other parts (Fig. 2). In order to achieve the structural response of the cylinder to transfer pressure loads, several transient linear-elastic analyses were carried out.

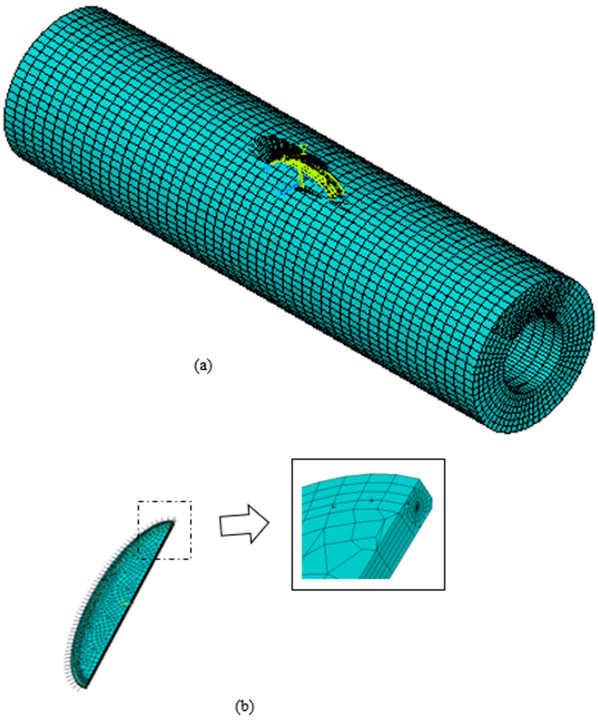


Fig. 2. Finite element mesh model; a) Whole volume, b) Crack region.

A tube of length 700mm with the inner and outer diameters of 90mm and 135mm, respectively, is considered. Over a time-period, 1000 linear segments were employed to approximate the shock wave decay in the discretized Taylor–Zeldovich model. The configuration and material properties of the tube and the parameters used in the pressure loading history are shown in Table 1.

After a trial and error process, 10, 64 and 90 elements are used in radial, circumferential and longitudinal directions, respectively. The cylinder is assumed to be clamped ($u_x = u_y = u_z = 0$) at both ends.

3.1. The Work Validation

Due to lack of reported studies in the literature for linear elastic response of cracked cylindrical tubes to internal shock in 3-dimensional cases, the finite element model of a 2D tube under detonation with simply supported boundary condition is considered. A schematic illustration of a 6061-T6 aluminum tube under denotation loading is shown in Fig. 3a. The material property and detonation parameters are listed in Table 2. The results which are depicted in Fig. 3b are compared with the analytical ones (Fig .2c) in a study by Mirzaei [10] and are shown to be in a relatively good agreement. The reliability of analytical results have been previously proved by experimental data [4].

4. Result and Discussion

In this work, we considered a semi-elliptical defect located at the inner surface of cylinder (Fig. 1a). We examined our study for a wide variety of crack profiles. Modeling the traveling pressure loads is one of the most important part of the finite element simulation which is done using the ANSYS Parametric Design Language (APDL) code. The ANSYS-LS DYNA solver is also employed for reasons of high capability for solving the non-linear explicit transient problems. The SIF's are calculated by using the displacement correlation technique (DCT).

The resulting time dependent stress intensity factors through the crack front for a wide variety of crack profiles are shown through Figs. 4-6. The obtained SIFs are normalized with K_O as follow:

$$K_{normalized} = \frac{K}{K_o}, \quad K_o = \frac{2P_2(r_o)^2}{(r_o)^2 - (r_i)^2}\sqrt{\frac{\pi a}{Q}}$$

The shape factor Q is estimated as: $Q = 1.464(a/c)^{1.65} + 1$.

Variation of the K_I along the crack front for a constant value of aspect ratio ($\xi = 0.4$) and different depths of the crack i.e. $\eta = 0.2$, 0.4, 0.6 and 0.8, versus the computational time of 0.5ms is shown in Figs. 4a to 4d.

Table 1
Material property and pressure loading history parameters of 3D tube.

ρ (kg/m^3)	E (N/m^2)	ν	σ_y (MPa)	V_{cj} (m/s)	T_{exp} (s)	P_1	P_2 (pa)	P_3
7800	210×10^9	0.3	300	1699.7	4.34×10^{-4}	0	1.7×10^6	0

Table 2
Material property and detonation parameters of 2d tube.

ρ (kg/m^3)	E (N/m^2)	ν	V_{cj} (m/s)	T_{exp} (s)	P_1	P_2 (pa)	P_3
2780	69×10^9	0.33	2643	1.5×10^{-4}	0	1.9×10^6	0

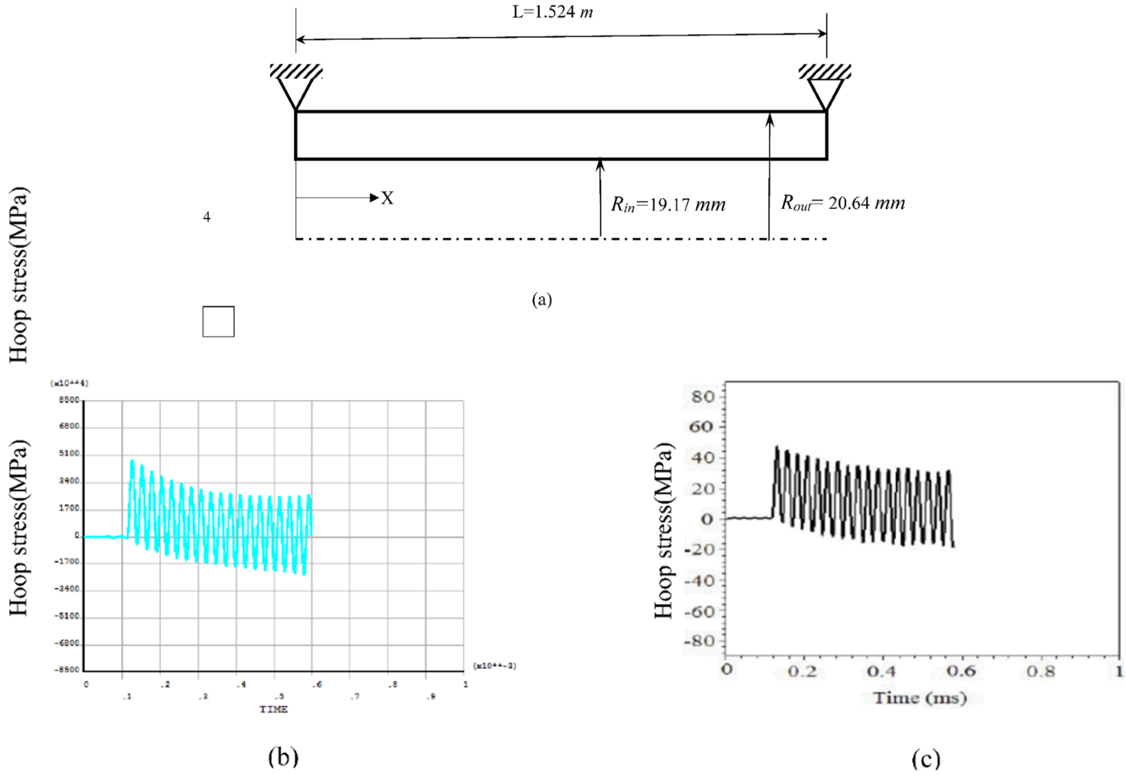


Fig. 3. The hoop stress versus time at $X = 0.3038$m from the ignition side of a 2d tube under denotation, a) Schematic representation of detonation tube, b) Finite element prediction, c) Transient analytical approach results.

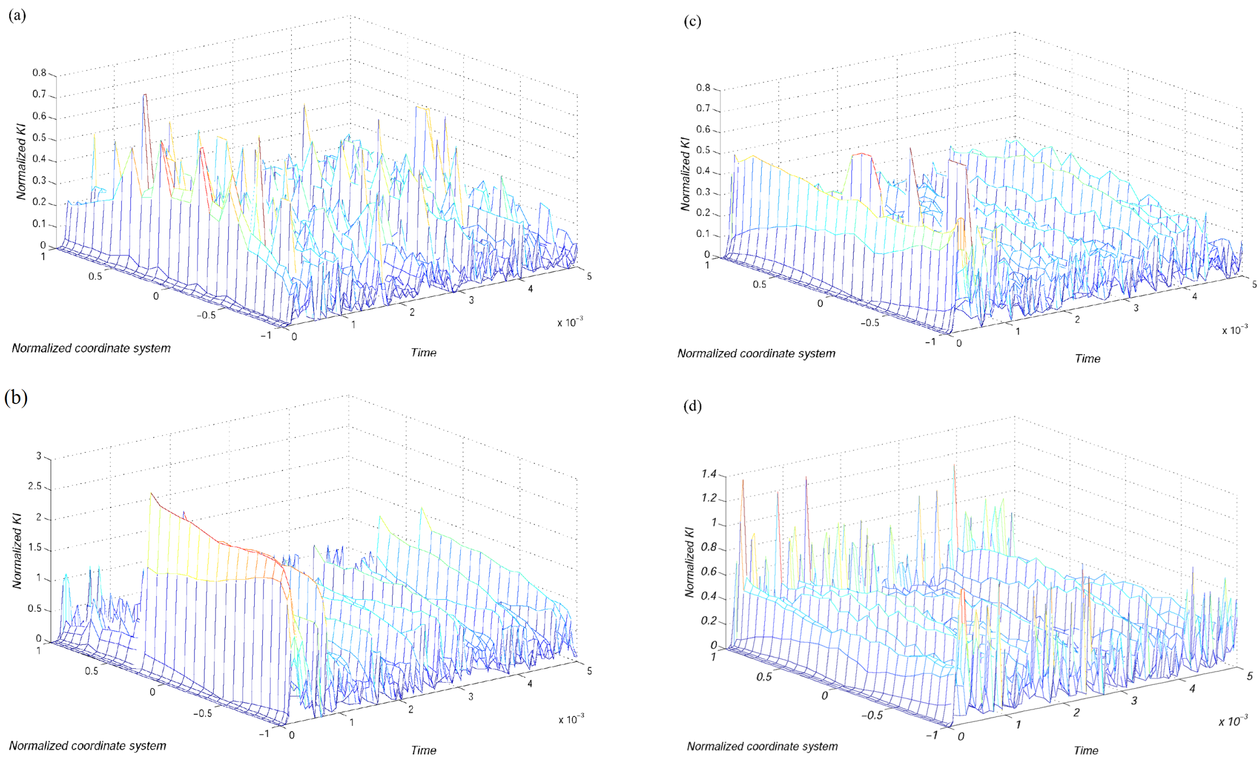


Fig. 4. Variation of K_I along the crack front versus time for constant $\xi = 0.4$ and different crack depths i.e., a) $\eta = 0.2$, b) 0.4, c) 0.6, d) 0.8.

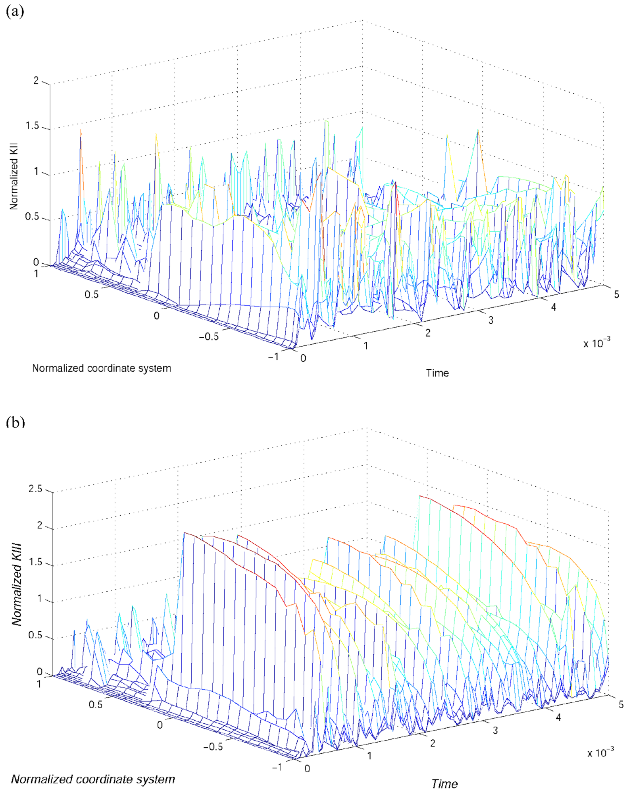


Fig. 5. Distribution of a) K_{II} and b) K_{III} through the crack line vs. time for a semi elliptical shape defect with $\xi = \eta = 0.4$.

As seen, for reasons of traveling pressure, the stress intensity factor along the crack front at a fixed time is distributed with no symmetry line. Due to moving structure of pressure loading, the SIF variation due to moving structure of pressure loading increases initially with time and then decreases. It can be observed from Figs. 4a to 4d that the level of stress distribution through the crack line as time passes strongly depends on the crack profile. For cracks with constant aspect ratio ($\xi = 0.4$), maximum SIFs happened for configuration with crack depth of 0.4. In other words, the cracks with $\eta = 0.6$ experienced the minimum value of stress intensity factors. The time which the maximum SIFs happened depends on the crack profile. As shown, the deeper the crack, the shorter the time required to reach the maximum SIF. In all crack configurations, right tip points are critical ones. Any probable crack growth will start from right side of the crack profile through the inner surface.

Distribution of K_{II} and K_{III} through the crack line vs. time for a semi elliptical shape defect with $\xi = \eta = 0.4$ is depicted in Figs. 5a to 5b.

As can be seen, the mixed mode of stress intensity factors occurred. The out of plane shear mode of SIF is dominant relative to the sliding mode. Maximum K_{III} is repeated as time passes. For cracks with $\xi = \eta = 0.4$, the critical SIFs are happens initially in modes II, I and III, respectively. The dominant mode of SIF changes over tme.

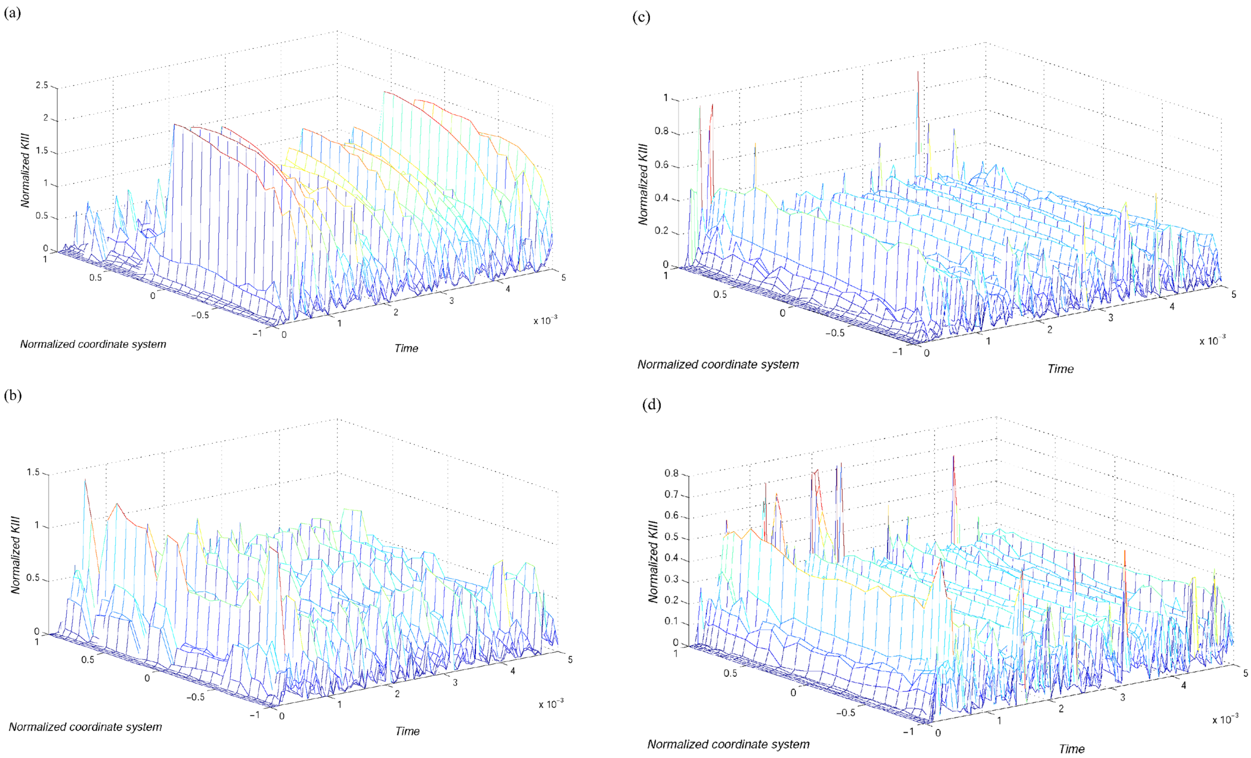


Fig. 6. Variation of K_{III} vs. time along the crack front for constant $\eta = 0.4$ and different aspect ratios, i.e., a) $\xi = 0.4$, b) $\xi = 0.6$, c) $\xi = 0.8$, d) $\xi = 1$.

Figs. 6a to 6d illustrated the variation of K_{III} vs. time along the crack front for a constant crack depth ($\eta = 0.4$) and different aspect ratios, i.e., $\xi = 0.4$, 0.6, 0.8 and 1. As illustrated, in defects with the same crack depths, the tearing mode in narrower cracks is higher than others and have more susceptibility for out of plane growth. While time is passing, the crack with $\xi = 0.8$ reaches a relatively constant value of K_{III} for points between corner points.

The global coordinate system as seen in Fig. 7, located at the mid side thickness of left side of thevessel is applied to evaluate the strain and stress fields in different points of the cylindrical vessel.

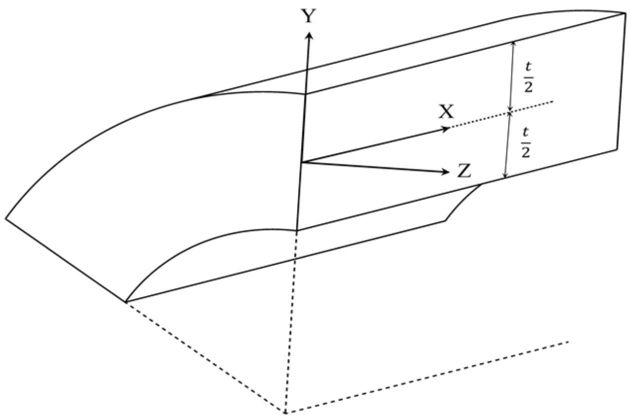


Fig. 7. Global coordinate system defined in cylindrical pressure vessel.

The effect of wall thickness on values of time histories of hoop and radial stresses for points located at positions ($X = 100$mm, $Z = 0$) and $Y = \pm 22.5$mm, ± 13.5mm, 0mm is depicted in Figs. 8a and 8b, respectively. As seen, the maximum amplitude of radial and hoop stresses for points through the thickness varied according to their radial positions. The points located at inner and outer radius of tube experienced the minimum values of radial stresses. Maximum stress in radial direction happened in position $Y = -13.5$mm (near to the inner radius of tube). It can be deduced from Fig. 8b that the variation of hoop stress is relatively symmetric with respect to the points located at the mid plane of wall thickness as time passes. The higher the distance from the mid plane of wall thickness, the higher the maximum values of hoop stresses. It may be observed that the vibrational spectrum value of hoop and radial stresses decays to zero.

The strain and stress histories at position of 600mm from the right side of the cylinder ($X = 100$mm, $Y = Z = 0$) is shown in Fig. 9.

An oscillatory graph for both stress and strain in axial, radial and hoop directions for reason of vibrational phenomenon of loading can be seen. According to Fig. 9, the maximum amplitude for axial, radial and hoop stresses are about 2.8, 1.1, 0.57MPa respectively. This should be attended to in the designing tubes against the failure due to structural fatigue loading produced by shock. The maximum values for axial, radial and hoop strains are 13, 5.8 and $-4.3(\times 10^{-5}$m/m) respectively. As can be seen, the maximum deformation occurs in the longitudinal direction at $t = 0.5$ms.

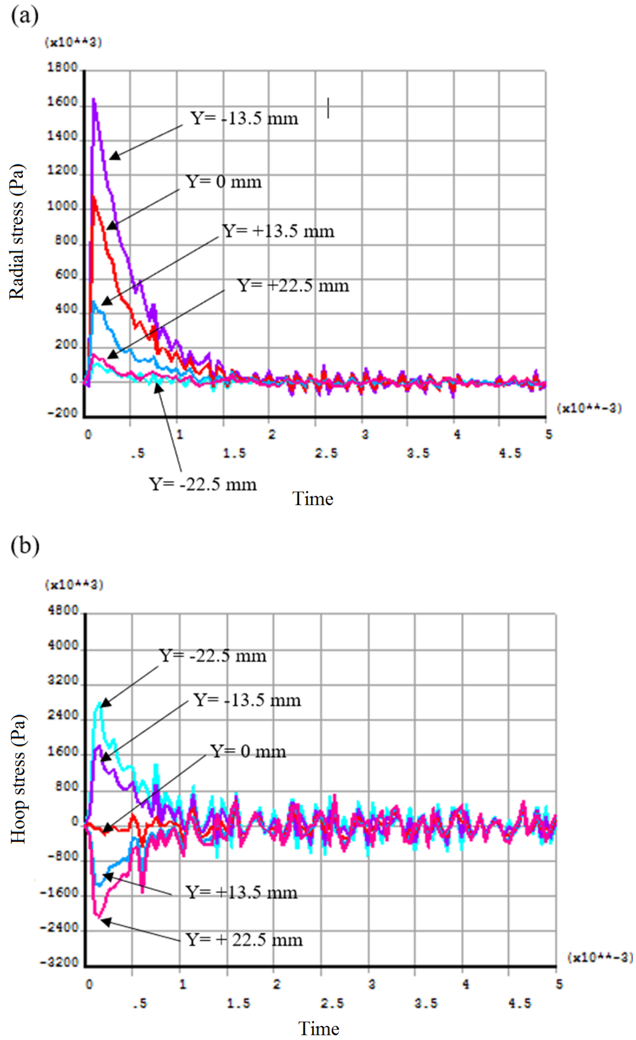
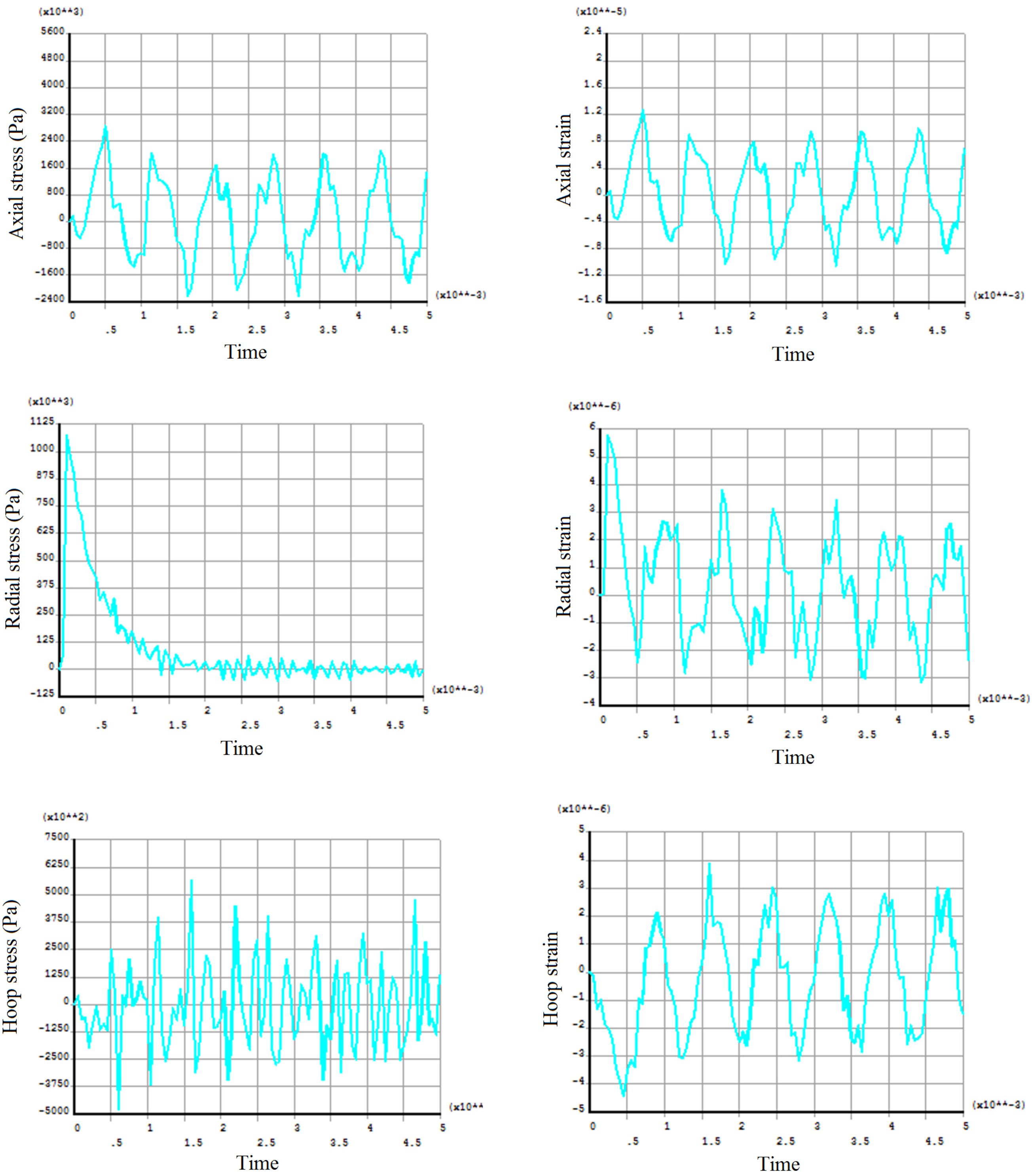


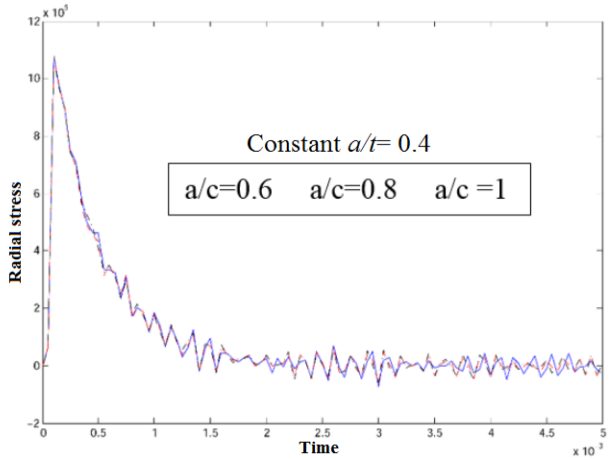
Fig. 8. The values of time historical of a) Radial, b) Hoop stresses for nodes located at ($X = 100$mm, $Z = 0$) and $Y = \pm 22.5$mm, 13.5mm, 0mm.

The history of radial stresses for points far away the defect location ($X = 100$mm) in cylindrical vessels with different crack profiles is illustrated in Fig. 10. As shown, for constant value of crack depth, changing the aspect ratio has no considerable effects on the variation of radial stress with time. In other words, crack profiles with different depths can affect the radial stress distribution over time.

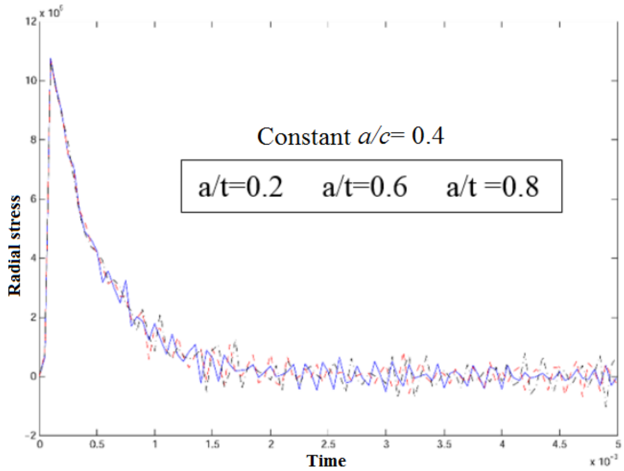


(a) **(b)**

Fig. 9. The histories for axial, radial and hoop a) Stress, b) Strain for node located at (X = 100mm, $Y = Z = 0$).



(a)



(b)

Fig. 10. The history of radial stress for points far away the defect location in cylindrical vessels with different crack profiles, a) Constant $\eta = 0.4$, and different $\xi = 0.6$, 0.8 and 1; b) Constant $\xi = 0.4$ and different $\eta = 0.2$, 0.6, and 0.8 .

5. Summary and Conclusions

The 3D-FE fracture analysis of the thick walled tubes under detonation loading for different crack profiles is considered in this paper. The following summarized results can be drawn from the present work:

- Moving pressure loads leads to the mixed mode stress intensity factor in thick walled tubes.
- The distribution of SIFs through the crack line depends on the crack configuration, time period of loading and typical pressure-time profile.
- The schematic of stress/strain-time trace profiles strongly depends on the location of points through the wall thickness.
- The capability of finite element modeling in analysis of three dimensional dynamic transient problems has been shown.

References

[1] T.W. Chao, Gaseous Detonation-Driven Fracture of Tubes, Ph.D. Dissertation, California Institute of Technology; Pasadena, California, (2004).

[2] M. Malekan, F.B. Barros, E. Sheibani, Thermo mechanical analysis of a cylindrical tube under internal shock loading using numerical solution, J. Braz. Soc. Mech. Sci. Eng., 38(8) (2016) 2635-2649.

[3] H. Eskandari, Three-dimensional investigation of cracked tubes coated with functionally graded material under shock loading, J. Braz. Soc. Mech. Sci. Eng., 40 (2016) 432.

[4] W.M. Beltman, J.E. Shepherd, Linear elastic response of tubes to internal detonation loading, J. Sound. Vib., 252(4) (2002) 617-655.

[5] M. Mirzaei, M. Malekan, E. Sheibani, Failure analysis and finite element simulation of deformation and fracture of an exploded CNG fuel tank, Eng. Fail. Anal., 30 (2013) 91-98.

[6] M. Mirzaei, H. Biglari, M. Salavatian, Analytical and numerical modeling of the transient elastodynamic response of a cylindrical tube to internal detonation loading, Int. J. Press. Vessels Pip., 83(7) (2006) 531-539.

[7] J. Zhou, Z. Deng, T. Liu, X. Hou, Elastic structural response of prismatic metal sandwich tubes to internal moving pressure loading, Int. J. Solids Struct., 46(11-12) (2009) 2354-2371.

[8] J. Zhou, Z. Deng, T. Liu, X. Hou, Optimal design of metallic sandwich tubes with prismatic cores to internal moving shock load, Struct. Multidiscipl. Optim., 41 (2010) 133-150.

[9] W.M. Beltman, J.E. Shepherd, The structural response of tubes to detonation and shock loading, Parts I and II, Technical Report FM98-3, California Institute of Technology, Pasadena, CA, (1998).

[10] M. Mirzaei, On amplification of stress waves in cylindrical tubes under internal dynamic pressures, Int. J. Mech. Sci., 50(8) (2008) 1292-1303.