INFLUENCE OF THE PRESENCE OF SURFACE CRACKS ON THE DYNAMIC RESPONSE AND FAILURE OF PIPES UNDER PIPE WHIP CONDITIONS

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Abstract

This study investigates the influence of cracks, of semi-elliptical shape according to ASME III rules, which is assumed be located near the pipe region where tensile stress is expected. The investigation refers to pipe whip conditions. Pipe whips are a high-energy phenomenon resulting from sudden rupture in pressurized piping systems and poses a significant threat to structural integrity and safety. This research focuses on how the presence of semi-elliptical cracks alters stress distribution, deformation and failure modes during such dynamic accidental events. With the applications of numerical simulations and principles of fracture mechanics, the manuscript presents the interaction between crack geometry, pipe curvature, and dynamic loading conditions. Key findings include the amplification of stress intensity factors in the cracked regions which exacerbate local plastic deformation due to their curvature under whipping forces. Additionally, this study highlights the critical role of crack dimensions and orientation in determining failure and provides insights into the energy dissipation caused by such defect. The results will contribute to the advancement of understanding of pipe behaviour during the postulated accident scenario. Moreover, insight could allow to enhance predictive models for pipe failure assessment and adopt design strategies for mitigating risks associated with pipe whip. This study significantly enhances pipeline safety by rigorously integrating fracture mechanics into dynamic response modelling, providing a comprehensive basis for strengthening the structural robustness of piping systems operating under high-energy dynamic loads.

Keywords: Semi-elliptical crack, SIFs, pipe whip, sub-model

1. INTRODUCTION

Pipe ruptures in nuclear power plants (NPPs) due to pipe whips occur when a pressurized piping system experiences a sudden break, resulting in rapid fluid discharge with an associated reaction force which induces the severed pipe segment to undergo uncontrolled high-velocity motion, imparting substantial dynamic loads to the adjacent structures, systems, and components (SSCs). The International Atomic Energy Agency (IAEA) mandates the postulation of such high energy pipe breaks which can compromise the structural integrity of the SSCs [1]. Conventional pipe whip investigations typically model intact pipes using finite element method (FEM) to predict their trajectory and impact forces, but they often overlook pre-existing flaws. This neglection can significantly affect failure initiation and progression, leading to potential inaccuracies in safety assessment and design measures.

This study investigates the critical influence of surface cracks (semi-elliptical) on certain regions of pipes undergoing high-energy pipe whip phenomenon. Semi-elliptical cracks shape are common defects in piping, as defined by the ASME section III rules [2], and are characterized by localized surface separation with a distinct geometric profile.

In the present study, time-dependent analysis of pipe whip phenomena for a pipe-on-wall-impact (POWI) model was performed in ANSYS Workbench, wherein the blowdown force generated by a severed pipe segment was applied as a dynamic loading boundary condition, in accordance with the approach detailed by Pate et. al [3]. To enhance computational efficiency, a sub-modelling technique was employed to incorporate semi-elliptical cracks at significant locations, namely the intrados, extrados, and plastic hinge regions of the pipe. The study systematically examines the effects of these cracks on the pipe's dynamic response under whipping conditions. Stress Intensity Factors (SIFs) were computed and analysed for a range of crack aspect ratios, providing quantitative insight into the influence of crack geometry and positioning on the fracture mechanics parameters during pipe whip events that alter traditional failure prediction models, with implications for both regulatory frameworks and engineering design practices. The dynamics of the whipping pipe are often governed by rotation about the hinge regions that develop near restraint locations, potentially leading to deformation.

2. METHODOLOGY

This research presents the computational modelling of the pipe whip phenomenon, and it is carried out in the transient structural module of ANSYS Workbench where the pipe and the impacting slab are conventionally modelled [3] with a conservative material modelling approach to efficiently utilize the Linear Elastic Fracture Mechanics (LEFM) principles to obtain the SIFs for the aim of this study.

2.1 Material properties

The pipe material properties are those of the A106 Grade B steel (see **Table 1**) with a bilinear isotropic hardening to represent the plasticity at impact and a fracture toughness (K_{IC}) of 40 MPa√m. A conservative approach is carried out for the concrete slab model with the following properties: density of 2400 kg/m^3, Young's modulus of 27000 MPa, Poisson's ratio of 0.2 [4].**Table 1** Material properties of the steel pipe

Density (kg/m^3)	Young's Modulus (MPa)	Poisson ratio (-)	Yield Stress (MPa)	Ultimate Stress (MPa)
7850	200000	0.3	250	550

2.2 Numerical modelling with sub-modelling approach

The POWI model is numerically modelled in ANSYS Design Modeler GUI, as taken from [5] which uses the EUROPLEXUS model to numerically validate it with the Aquitaine II experimental data. This model is effective to represent the deformation at the intrados, extrados along with the hinge formation near to the fixed end where the introduction of the semi-elliptical cracks would gain much benefit. The data (time-dependent force) of the fluid blowdown force of a severed pipe from the experimental tests as extracted from [3] is used as input boundary condition to facilitate the pipe whip phenomenon under fast transient conditions. The POWI model and the corresponding necessary sub-models for further simulations are shown in **Figure 1.** The model was implemented with hexahedral elements capable of simulating fast transient conditions, i.e., 0.02 s, with a minimum time step size of 0.0001 s. The resultant von Mises stress distribution at the impact region as shown in **Figure 2** validates well the previous research study under the same conditions for the schedule 80 pipe thickness of 7.62 mm [3, 5]. The displacement based sub-modelling approach was implemented in the ANSYS Workbench for the transient model to adequately refine the mesh in the regions of interests where the crack is assumed to obtain efficiently the SIFs based on the principles of LEFM [6, 7]. Two different sub-models, one at the plastic hinge region and the other at the elbow as shown in **Figure 1,** are used for modelling the semi-elliptical cracks. These sub-models are selected based on their significance in undergoing the deformation state (see **Figure 2**) which induces the opening mode of the crack to effectively study the SIFs to the maximum extent.

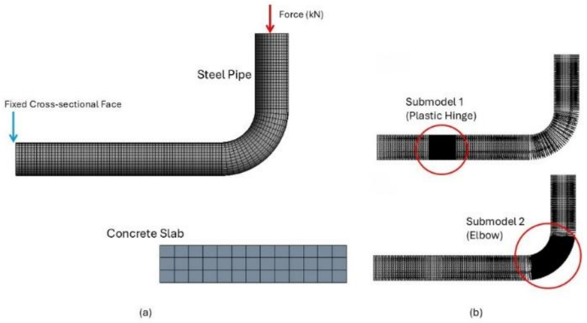


Figure 1 (a) - The POWI global model, (b) – the two sub-models

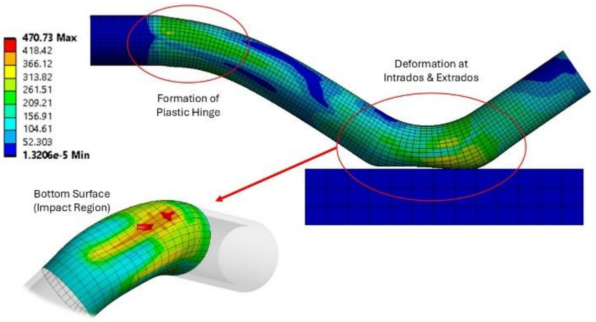
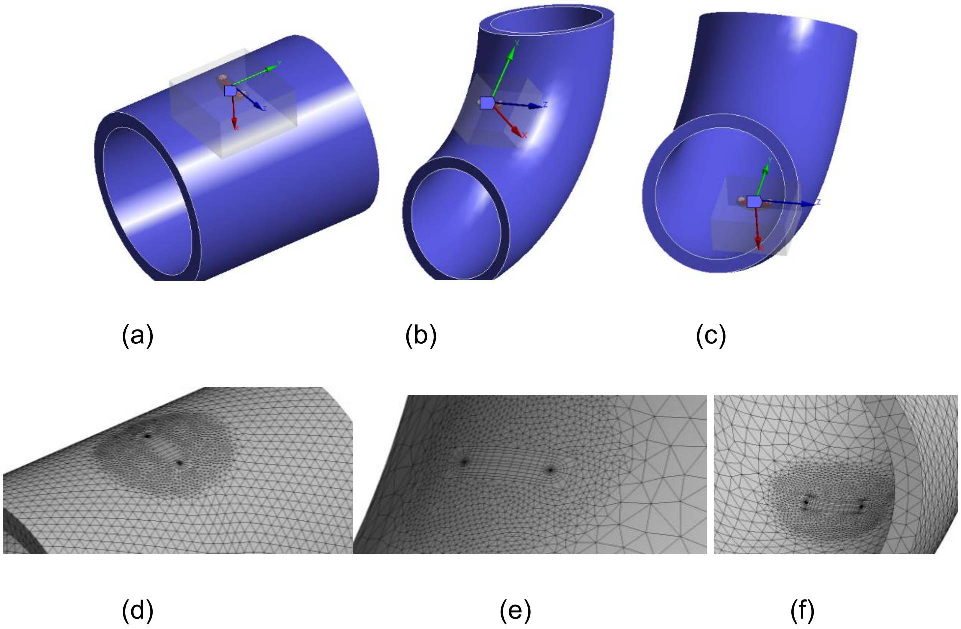


Figure 2 The equivalent von Mises stress distribution contour at the impacting region

2.3 Semi-elliptical crack model

A semi-elliptical crack was introduced in the hinge region, extrados and intrados (see **Figure 3**) where large bending deformation and potential plastic hinge formation occur during pipe whip to obtain the stress intensity factors (K) which is a function of the stress level (σ), crack depth (a), angle defining the position at the crack front (ϕ) and correction factor $(f(\phi))$ [8].

$$K = \sigma\sqrt{\pi a} f(\phi) \tag{1}$$



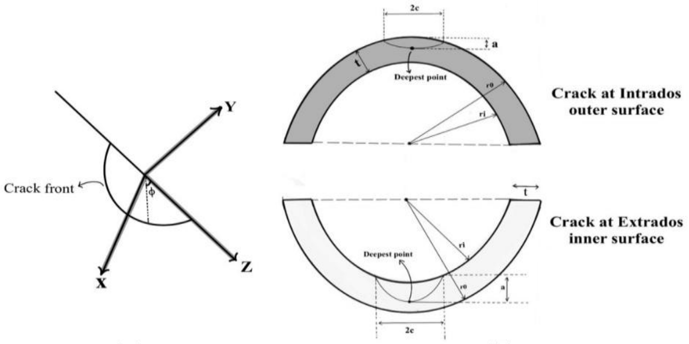
(a) (b) (c)

(d) (e) (f)

Figure 3 (a), (b), (c) – Semi-elliptical crack assumed regions (plastic hinge, intrados and extrados respectively), (d), (e), (f) – mesh around the crack (plastic hinge, intrados and extrados respectively

Although this region is subject to localized plasticity, the use of LEFM-based SIFs is justified as a conservative estimate of crack driving force under the assumption of small-scale yielding when the plastic zone estimate parameter (r_p) is less than the crack depth (a) [8].

$$\boldsymbol{r_p = \frac{1}{2\pi}\left(\frac{K_I}{\sigma_y}\right)^2} \tag{2}$$



(a) (b)

Figure 4 (a) - Semi-elliptical crack front, (b) - crack geometry at the intrados and extrados

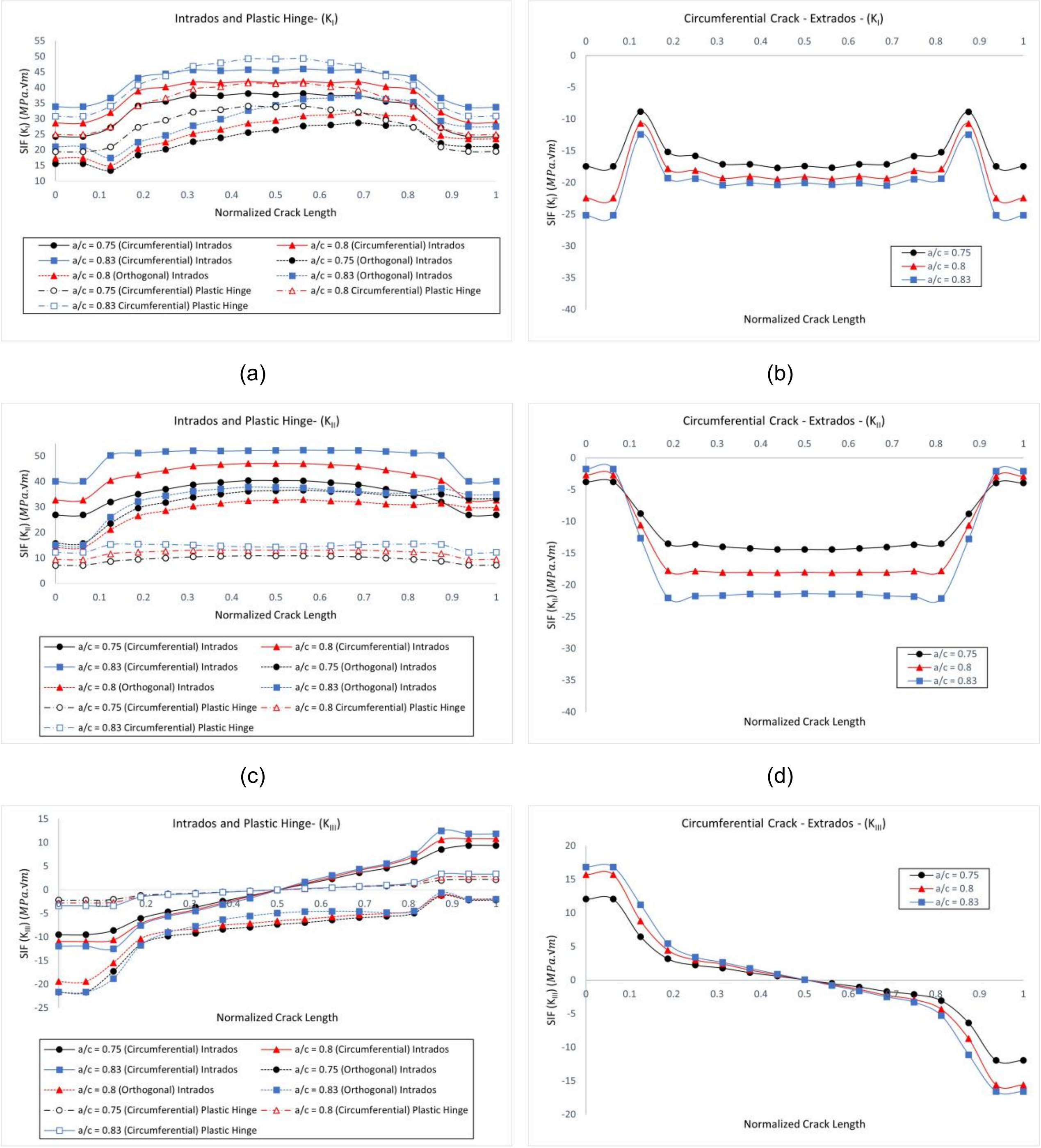
Both circumferential and orthogonal cracks are investigated at the intrados while the effect of circumferential crack alone is studied at the plastic hinge and extrados. Varied crack geometries based on the crack depth and length were considered (see **Figure 4, b**). The crack depth (a) varies across 3, 4 and 5 mm along with variations of the length of crack (2c) being kept at 8, 10 and 12 mm respectively. The relationship of critical crack length (a_c) to the fracture toughness (K_{IC}) is given by,

$$a_c = \left(\frac{K_{IC}}{f(\phi)\sigma}\right)^2 \frac{1}{\pi} \tag{3}$$

Tetrahedral elements are utilized in this SIFs-based fracture analysis owing to their capability for accurately modelling complex surface defects, such as semi-elliptical cracks, in three-dimensional components (see **Figure 3, a**) [9]. Furthermore, this tetrahedral element-based approach aligns with the flaw characterization methodologies outlined in ASME Boiler and Pressure Vessel Code, Section **III**, which prescribes semi-elliptical cracks as a conservative assumption for evaluating fracture behaviour in Class 1 components [2] actively.

3. RESULTS AND DISCUSSIONS

The SIFs (K_I, K_{II} and K_{III}) at the deepest point of the semi-elliptical cracks are plotted against the normalized length of crack parameter (2Φ/π) for the different aspect ratios (a/c = 0.75, 0.8 and 0.83) of the crack geometry (see **Figure 5**). The results show that K_I (crack opening mode) typically peaks at the normalized crack length 0.5 for all cases (**Figure 5, a**), consistent with expected behaviour in surface cracks due to stress concentration at the deepest point. Circumferential cracks at the intrados exhibit the highest opening mode values, indicating greater susceptibility to crack propagation under bending loads, whereas cracks at the plastic hinge show lower opening mode values, suggesting that local plasticity may alleviate some crack tip stress. On the contrary, results from **Figure 5, b** demonstrate that circumferential cracks at the extrados undergo primarily compressive loading during pipe whip events due to the negative parameters which are consistent with the bending-induced stress state in the region. The circumferential cracks at the intrados exhibit the highest K_{II} values (see **Figure 5, c**) indicating the presence of significant in-plane shear near the pipe curvature under bending in contrary to the cracks located at the plastic hinge where lower K_{II} values are recorded, representing nearly flat distribution, indicating limited in-plane shear development. The K_{III} values exhibit distinguishable variation along the crack front, with pronounced negative values observed toward the normalized crack length ends indicating significant shear-induced tearing (see **Figure 5, e**). As the crack front progresses toward the centre, K_{III} transitions toward zero or slightly positive, consistent with mode-**III** at the deepest crack point. Cracks at the plastic hinge exhibit much smaller K_{III} magnitudes throughout the crack front, suggesting reduced out-of-plane shear effects. The difference between intrados and plastic hinge behaviour underscores the influence of local curvature and deformation mode on mode-III fracture mechanics parameters. In contrast to the intrados, the plots in **Figure 5, d and f** reflects a reversal of in-plane and out-of-plane shear stress direction along the crack front during pipe whip loading due to the bending-induced curvature at the elbow.



(a) (b)

(c) (d)

(e) (f)

Figure 5 (a), (c), (e) – K_{I}, K_{II} and K_{III} of circumferential and orthogonal crack at the intrados and at the plastic hinge, (b), (d), (f) - K_{I}, K_{II} and K_{III} of circumferential crack at the extrados respectively

4. CONCLUSION

The numerical simulations were performed to investigate the pipe whip phenomenon and with the help of sub-modelling approach, the introduction of semi-elliptical cracks at critical regions was implemented effectively. The presence of semi-elliptical cracks significantly alters the local stress state during pipe whip, with SIFs strongly dependent on crack location and geometry. Variation in crack aspect ratios demonstrated a pronounced influence on SIF magnitudes, where increasing crack depth relative to length consistently amplified the SIFs. Higher aspect ratio cases consistently yields the highest K values, reflecting increased opening and shear concentration with deeper cracks. Crack aspect ratio influences the magnitude but not the general distribution of SIFs, highlighting the importance of crack geometry in assessing the risk of crack opening, in-plane and out-of-plane shear-driven crack propagation under dynamic loading scenarios. The coexistence of positive and negative SIF values implies alternating shear directions during whipping conditions and emphasizes the need for mixed-mode fracture criteria in assessing failure conditions involving pipe whip phenomenon.

SIFs are used in this study as conservative indicators of crack driving force to evaluate comparative fracture trends under dynamic loading. The results contribute to improved and predictive pipe failure models under dynamic behaviour and support the development of enhanced design and inspection strategies aimed at mitigating pipe whip risks in safety-critical infrastructure. Subsequent research should involve full-scale pipe whip simulations or reference validated benchmark experiments to rigorously correlate numerically computed SIFs with experimentally observed crack initiation and propagation behaviour under dynamic loading conditions.

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