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Solutions to Pressure Vessel Failures: A Review

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Abstract— Pressure vessel accidents happen more frequently than they should and cracking is said to be one of the main causes of failure where most of the failures have been traced to surface cracks. To successfully prevent any possible failure of a pressure vessel, one must be able to accurately predict the crack growth behaviour. A lot of studies have been done to provide solution for a range of internal and external surface cracks in pressure vessels. Under normal analysis, linear elastic fracture mechanics (LEFM) approach is mostly applied and therefore majority of these studies have used this approach. However, LEFM is not suitable for elasto-plastic fracture behaviour normally exhibited by the highly tough and ductile material from which pressure vessels are supposedly made from. The branch of fracture mechanics applied to a particular problem depends on the mechanics of fracture of the material and therefore, any wrong assumption of the material's fracture behaviour would lead to some inaccuracies in the final results. Therefore, the actual fracture behaviour of the material is usually overlooked when LEFM is applied in addressing elasto-plastic failure of a pressure vessel. This article presents an overview of the developments made towards addressing the issue of pressure vessel failures, where the correct fracture behaviour of the material is generally found to be missed. This is something believed to have adverse affects on the structural integrity of pressure vessels.

Keywords— Elasto-plastic failure, Linear elastic fracture mechanics. Pressure vessel.

1. INTRODUCTION

A pressure vessel may be defined as a closed container designed to hold gases or liquids at a pressure substantially different from the ambient pressure. The inside pressure is usually higher than the outside, except for some isolated cases, such as in submarine vessels, vacuum pump vessels and vessels containing condensing gas or steam. Pressure vessels are of common use in industrial field where they are used as compressed air receivers, heat exchangers, evaporators, autoclaves, nuclear reactor vessels, steam boiler vessels, pneumatic reservoir, hydraulic reservoir under pressure, rail vehicle air brake reservoir, road vehicle airbrake reservoir and storage vessels for liquefied gases such as ammonia, chlorine, propane, butane and liquefied petroleum gas (LPG) [1], [2]. Pressure vessel accidents happen more frequently than they should, in spite of the rigorous efforts put in attempting to enhance their structural integrity. Fracture is said to be one of the main causes of the failures where most of them have been traced to surface cracks [2].

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Pressure vessels are designed to operate safely at a specific pressure and temperature technically referred to as the "Design Pressure" and "Design Temperature". A pressure vessel has to be able to sustain the stresses imposed on it due to the design pressure, which is the maximum possible pressure the vessel would be subjected to. For most pressure vessels, design temperature is the temperature that corresponds to the design pressure. However, there is a maximum design temperature and a minimum design temperature for any pressure vessel [2], [3]. The most commonly used factor in the design of pressure vessels is that of maintaining the induced stresses within the elastic region of the material of construction in order to avoid excessive plastic deformation or rupture when the yield point is exceeded [2]. This is a traditional design approach where a safe operating pressure is achieved when the maximum stress that exists is less than the strength of the material, suitably reduced by a safety factor. However, the presence of undetected cracks on the walls of a pressure vessel can severely reduce the strength of the structure and can cause sudden failure at nominal tensile stresses less than the material's yield strength.

Crack appearance and growth can seriously endanger the reliability of structures and components in operation [4]. Therefore, it is important to assess their influence on the structural integrity. To ensure the integrity of a structure when a crack flaw is present, the designer should understand and adequately apply the mechanics of fracture, particularly the relation between structure loading (applied stress), the crack size and the fracture toughness. Fracture mechanics quantifies the critical combination of these three variables [5]. Therefore the term "fracture mechanics" refers to a branch of solid mechanics in which the presence of a crack in a solid is assumed and a relationship between the crack length (flaw size), the material's inherent resistance to crack growth (fracture toughness) and the stress at which the crack propagates at high speed to cause structural failure is established [5]. Fracture mechanics can be divided into linear elastic fracture mechanics (LEFM) and elasto-plastic fracture mechanics (EPFM). LEFM gives excellent results for brittle-elastic materials such as high-strength steel, glass, ice and concrete among others. However, EPFM gives excellent results for ductile materials such as low carbon materials, for example, steel, stainless steel, certain aluminum alloys and polymers where plasticity will always precede fracture [4]. However, it is not sometimes possible to set clear boundaries between brittle and ductile (plastic) materials, as one and the same material under certain circumstances may behave as brittle one, while under some other circumstances it may behave as ductile one [6] . For instance, steel materials are generally ductile and their ductility diminishes with decrease in temperature [6]. As the carbon content is increased from 0.1 to 0.8%, the ductile-brittle transition point temperature increases from -45^{o}C to 50^{o}C [6]. Considering pressure vessels are required to operate at a temperature range between -20^{o}C and 600^{o}C [6], then it may be possible to unknowingly apply LEFM in cases where EPFM should have been applied or the other way round. All in all, the branch of fracture mechanics applied to a particular problem depends on the mechanics of fracture of a material and therefore, any wrong assumption of the material's fracture behaviour would lead to some inaccuracies in the final results.

Generally, almost any material with good tensile properties that is chemically stable in the chosen application can be employed in the construction of a pressure vessel [7]. Besides high yield strength, materials for pressure vessels must be tough and ductile, or in other words its resistance to crack growth should be as high as possible. In addition, ductile materials are used in the construction of pressure vessels and piping because their plastic behaviour provides a warning before crack initiation and some amount of stability in crack growth [8, 9]. Therefore, ductile fracture behaviour results in a slow and stable crack growth, which will make it possible for the growing cracks to be detected during routine maintenance by non-destructive testing (NDT) so that corrective measures can be taken before crack growth moves into a high risk regime [10]. Ductile crack growth is characterized by crack blunting occasioned by plastic deformations [5]. EPFM applies to materials that exhibit such kind of failure mechanism, especially whose plastic deformation is no longer small to be approximated by a simple scaling of LEFM solution. On the other hand, LEFM is applicable to brittle fracture, whose fracture behaviour results in the development of rapid and unstable crack growth [11] that can easily lead to sudden catastrophic failure of a pressure vessel. Therefore, EPFM must be applied to elasto-plastic failure analysis of pressure vessels for any reasonable results to be realized. The application of LEFM to deal with the elasto-plastic failure would lead to some inaccuracies whose effects on the structural integrity of a pressure vessel seems not to have been addressed from the available literature findings.

2. LITERATURE REVIEW

2.1 Modes of Failure of Pressure Vessels

Two basic modes of failure are assumed for the design of pressure vessels [6]. These are: Elastic failure, which is governed by the theory of elasticity; and Plastic failure, which is governed by the theory of plasticity. Except for thick-walled pressure vessels, elastic failure is assumed for the design of pressure vessels [6]. When the material is stretched beyond the elastic limit, excessive plastic deformation or rupture is expected.

In a thick-walled pressure vessel, circumferential and radial stresses are initially both maximum on the inner surface. However, failure of the shell does not begin at the bore but in sections on the outer surface of the shell [3]. Although parts on the inner surface reach yield point first, they are incapable of failing because they are restricted by the outer portions of the shell [3]. At a pressure above the elastic-breakdown, the region of plastic flow or "overstrain" moves radially outward and causes the circumferential stress to reduce at the inner layers and to increase at the outer layers resulting to the eventual failure beginning from the outer surface of the vessel where the maximum hoop stress is finally reached [3]. Therefore, plastic failure is assumed for the design of a thick-walled pressure vessel.

The two modes of failure are related to the traditional approach of structural design where the anticipated design stress is normally compared to the flow properties of the material, where the material is assumed to be adequate if its strength is greater than the expected applied stress [5]. This implies that, the most commonly used factor in the design of pressure vessels is that of maintaining the induced stresses within the elastic region of the material of construction [2]. This is done in order to avoid excessive plastic deformation or failure of the material when the yield point is exceeded. However, the presence of undetected crack on the wall of a pressure vessel can severely reduce its strength. That is why there have been incidences of failure of pressure vessels that could not be attributed to strength but to brittle and ductile fracture [12]. Therefore, the fracture mechanics approach to the structural design of engineering components such as a pressure vessel must be applied in order to ensure the structural integrity of the component is guaranteed where there is a real possibility of fracture of the component in service.

2.2 Prediction of Failure in Pressure Vessels

In practice, pressure vessels have a multi-axial stress situation, where failure is not governed by the individual components of stress but by some combination of all the stress components [6]. Many theories of failure have therefore been developed to predict the onset of failure in these complex systems. Among the failure theories, Von Mises criterion is generally accepted to be better suited for common pressure vessels as it is found to be more accurate [6]. Tresca's criterion is commonly used for the design by analysis procedure for two reasons [6]: It is more conservative and it is considered easier to apply. However, with the availability of computers, it has also made it easier to apply the Von Mises criterion. All the same, failure theories approach does not consider the effect of cracks or flaws, which can significantly degrade structural integrity and therefore cannot be applied to deal with failure prediction in cases where fracture of a component is likely to occur and therefore, fracture mechanics method can be adopted instead.

2.3 Approaches to Fracture Analysis

There are two alternative approaches to fracture analysis: the stress intensity approach and the energy criterion [3]. The stress intensity approach applies an important parameter for the intensity of stresses close to the crack tip called stress intensity factor (SIF or K). This parameter completely characterizes the crack tip conditions in LEFM [13], where fracture will occur at a critical stress intensity factor (K_{IC}) which is normally a measure of the material fracture toughness. Therefore, the SIF is compared with the K_{IC} (material fracture toughness value) to determine whether or not the crack will propagate. On the other hand, the energy approach states that, fracture occurs when the energy available for crack growth is sufficient to overcome the resistance of the material. The material resistance may include the surface energy, plastic work, or other types of energy dissipation associated with propagating crack. This approach normally applies the strain energy release rate parameter, G, where fracture will occur at a critical energy release rate, G_C, which is a measure of material fracture toughness just as K_{IC} in LEFM [5], [13]. When dealing with elasto-plastic materials, J-integral is the suitable alternative parameter to apply, where similarly, fracture (fracture initiation) will occur at a critical J-integral value, J_C. However, for the special case of a linear elastic material, J-integral is equal to G where the same definition given for energy release rate (G) for linear elastic materials still holds. That is, strain energy release rate is the energy that is released from a structure when the crack grows in an elastic material. But when applying J-integral to elasto-plastic material, it is important to note that, much of the strain energy absorbed by the material is not recovered when the crack grows or the specimen is unloaded [5], [11]. Therefore, the energy release rate concept has a somewhat different interpretation for elasto-plastic materials. Rather than defining the energy released from the body when the crack grows, in this case, the energy required to extend the crack is dominated by the requirement to extend the plastic zone as the crack grows. The surface energy of the new crack faces is negligible in comparison [5], [14].

Since fracture analysis of pressure vessels commonly applies the determination of SIF [15], [16 it therefore follows that the stress intensity (LEFM) approach is widely used in providing solutions to pressure vessel fracture problems. However, this approach is not applicable to the highly tough and ductile material recommended for the design and construction of pressure vessels.

2.4 Related Research Studies

From the available literature work, it is evident that considerable efforts have been put in the analysis of fracture susceptibility and failure of flawed pressure vessels. Different methods and approaches have been applied in a very rigorous attempt to provide the required solutions. Some of the studies are briefly discussed as follows.

Osama *et al.* [8] studied the behaviour of ductile crack growth in surface cracked pressure vessels. In the study, it was observed that a vastly different crack sequence develops under ductile tearing conditions compared to fatigue and the stress intensity dominated crack growth. The conclusion was that, the crack shapes developed under LEFM conditions would therefore no longer be applicable to ductile tearing scenarios. However, the authors did not establish the magnitude of the inaccuracies bound to occur due to the application of LEFM in solving ductile failure in pressure vessels. In addition, the influence of the resulting errors on the structural integrity of the pressure vessel would need to be examined.

Margolin *et al.* [17] studied modeling of ductile crack growth in reactor pressure vessel steels and presented a method for predicting J_R curves for reactor pressure vessel steels. According to the authors, the J_R curves are used to assess the integrity of reactor pressure vessels in the ductile fracture region. Generally, J_R curves are used for characterizing ductile fracture behaviour of metallic components, where the entire curve can be used to describe the ductile fracture. However, the authors could have also predicted the integrity of the pressure vessel under fatigue loading, which is the most practical failure situation in pressure vessels.

Mundhe and Utpat [13] performed analysis of a cracked cylindrical pressure vessel by using experimental approach. The study applied LEFM approach in determination of SIF of cracked cylindrical pressure vessel made of brittle epoxy. The authors observed that, the strain gauges they used in the experiment gave good results to calculate the required SIFs. Nevertheless, the pressure vessel material used was brittle in nature and therefore it is not recommended for the construction of pressure vessels.

Salam *et al.* [18] carried out a study on crack growth prediction in a thick cylinder under fatigue loading by finite element analysis (FEA) and presented a numerical analysis to predict crack growth under fatigue loading in a thick cylinder made of an aluminium alloy. In the study, experimental crack growth data on middle tension (MT) samples available was applied to simulate and predict crack growth process. It was observed that, in crack growth analysis, FE model provides results optimized for the stress levels of 25 to 40% of the yield stress, but for the stress levels of 15 to 20% the model provides more conservative results. The fatigue crack propagation was simulated based on LEFM determination of SIF method, which is considered unsuitable for the analysis of pressure vessel ductile material fracture behaviour.

Emina *et al.* [19] carried out structural integrity analysis of cracked cylindrical pressure vessel by determining its crack tip stress field state and evaluating the resulting total J-integral. It was noted that, acknowledgement of material fracture behaviour was not only important in order to avoid failures, but also to enable maximum economy of material choice and amount used. For enhanced assessment of structural integrity of a pressure vessel, fatigue loading test was necessary.

Iftikhar [20] carried out analysis of crack propagation in a thick-walled extruded cylinder of an aluminium alloy (AA 6061 T6) under fatigue loading. The fatigue crack propagation was analyzed through detailed experimental work and FEA where fatigue crack growth life of the cylinder with a crack at the bore surface was predicted. The FEA, based on LEFM combined with Pari's law, suitably predicted the fatigue life. The authors found out that, for a stable crack growth prediction under constant amplitude loading, an element size of 0.05mm along the crack propagation was sufficient to produce optimized results. However, slow and stable crack growth is normally exhibited in ductile fracture process, which cannot be addressed by the LEFM technique applied in the study.

Guerrero *et al.* [21] carried out fracture analysis of pressure vessel made of high strength steel P500 (yield strength:

500MPa) assuming the existence of the “worst case” crack allowed by the European Standards in order to demonstrate the safe use of these steels and the too conservative design which was being applied by the pressure vessel manufacturing codes. The three principal stress distributions along the crack tip were presented and it was observed that, the axial stress acted normal to the surface of the crack and was therefore the one that caused the crack to open. A fracture mechanics analysis was conducted to determine the magnitude and distribution of the SIF along the tip of the crack under the design loads. However, structural steel recommended for the construction of pressure vessels need to be of low carbon, which is a ductile material that cannot be accurately analyzed by the LEFM method that was applied in the study. Incidentally, it may be deduced that the actual material of the pressure vessel might have been ductile and therefore probably wrong assumption was made of the material fracture behaviour since a significant crack opening was observed, which is a common phenomenon in ductile materials.

Salam *et al*. [22] did experimental and numerical study of fatigue crack propagation in a thick-walled cylinder under cyclic hoop stress. After finding the anisotropy resulting in dissimilar properties in different orientations of thick-walled cylinder, experimental and numerical study was performed to reveal the fatigue crack growth behaviour of the cylinder under cyclic hoop stress. Fatigue crack growth experiments were conducted on MT samples prepared in an orientation to simulate the hoop stress on the cylinder. The fatigue life analysis results obtained from both the techniques showed that, the fatigue lifetime increased as the stress range decreased. The fatigue crack propagation was simulated, based on LEFM determination of SIF at the crack tip. Since LEFM approach was applied, it implies that, the assumed material fracture behaviour was brittle-elastic, which is not recommended for the construction of pressure vessels.

Adnan *et al.* [23] did estimation of the life of a thick cylinder subjected to internal pressure using FEM with *J*-integral approach. In the study, numerical strain energy release rate was evaluated for the thick cylinder and the resulting SIFs were determined. The authors attempted to demonstrate the proficiency of 2-dimensional (2D) *J*-integral program for LEFM, which they developed in their study for analysis of cracked structures and whose application was proved and verified. It was observed that, the determination of SIF for structures having two or more cracks would never take the total path *J*-integral because it was mathematically illogical and therefore such cases could be determined using superposition. All in all, the *J*-integral application in LEFM can only be reliable in the limit of small scale yielding.

3. THEORETICAL BACKGROUND

3.1 Fatigue Cracks in Pressure Vessels

Pressure vessels are often subjected to fatigue loading due to the cyclic loading by internal pressure which can cause the initiation and the propagation of cracks [24]. The cracks may be initiated from regions of high stress concentration or from defects, which are already present in the vessels. There are generally two possible modes of failure, depending on the load and the toughness of the material: Either the crack grows steadily through the wall by fatigue to form a stable through-crack, or it becomes unstable before or after it has reached the outer surface and spreads rapidly over a large portion of the vessel. In the former case, which is called ``leak-before-break (LBB)", there is a chance for damage to be detected or for the internal pressure to be relieved before sudden catastrophic failure of the vessel [10]. If the primary crack growth mechanism is slow, the cracks will be detected during routine maintenance by non-destructive testing (NDT) so that corrective measures can be taken before crack growth moves into a high risk regime. After the crack reaches a critical size, the ultimate failure may be catastrophic and result at pressures which are even lower than the design capacity of the cylinder [18]. For this reason, there is a need to analyze the crack propagation behavior in pressure vessels to ensure the integrity of the vessel against fatigue failure.

To understand fatigue loading on a pressure vessel, consider an air receiver, which is sometimes called air tank. The air receiver, which is normally connected to an air compressor (air pump), acts as a reservoir for the storage of compressed air which is drawn from the compressor [25]. The air is then taken from the air receiver when it is needed for use. Normally, the compressor is operated on full load for a given period until the pressure reaches a certain set point. The compressor is then restarted when the pressure falls below a certain level [26]. The frequent off-loading and reloading of the air receiver subjects it to a cyclic loading that causes fatigue loading especially within the pressure vessel bore. In a similar manner, a gas cylinder is normally and in oftentimes charged, discharged and recharged with gas and thus subjecting the cylinder to frequent pressure reversals. Generally, you will find that any kind of pressure vessel is subjected to some kind of pressure reversals, implying fatigue loading or cyclic loading which can easily result to the initiation and growth of fatigue cracks.

3.2 Effect of Plasticity on Fracture Mechanics Approach

Fig. 1 illustrates the effect of material plasticity on the crack tip stresses that will also influence the fracture mechanics approach to be applied. Figure 1(a) shows small scale yielding case, where SIF and *J*-integral characterize the crack tip conditions [5]. At a short distance from the crack tip, relative to the size of the structure, occurs a *K*-dominated region. Assuming monotonic, quasi-static loading, a *J*-integral-dominated region occurs in the plastic zone, where the SIF criterion no longer applies [5]. In small scale yielding, SIF uniquely characterizes crack tip conditions, despite the fact that it does not apply all the way to the crack tip. Similarly, *J*-integral uniquely characterizes crack tip conditions even though it does not apply within the finite strain region [5]. *K*-dominated region definitely implies a zone where LEFM is applicable. Simple corrections to LEFM are available to make it applicable in cases where small scale crack tip yielding occurs [5].

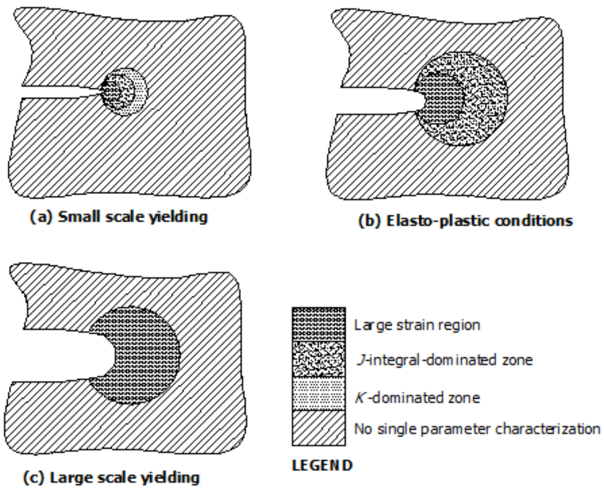

Fig. 1: Effect of material plasticity

For increased plasticity leading to elasto-plastic failure conditions, LEFM criterion is completely not applicable since the *K*-dominated region no longer exists as observed from Figure 1(b). The Figure illustrates elasto-plastic conditions, where *J*-integral is still approximately valid, but there is no longer a *K*-dominated field. As the plastic zone increases in size, relative to the structure size, the *K*-dominated zone disappears, but *J*-integral-dominated region persists in some geometries. Therefore, although SIF has no meaning in this case, the *J*-integral is still an appropriate fracture criterion. Since *J*-integral-dominance implies CTOD-dominance, it follows that; CTOD can also be applied to replace the *J*-integral in dealing with elasto-plastic fracture behaviour [5]. With large scale yielding (Figure 1(c)), the size of the finite strain zone becomes significant relative to the structure size, and there is no longer a region uniquely characterized by *J*-integral. This implies that, a single-parameter fracture mechanics breaks down in the presence of excessive plasticity and fracture toughness will now depend on the size and geometry of the test specimen [5]. Therefore, critical *J*-integral values will exhibit a size and geometry dependence.

Since J-integral deals with both elastic and elasto-plastic material fracture behaviour to some extent; consequently, it makes it a widely acceptable criterion for fracture behaviour comparison of different materials [27].

3.3 Elasto-plastic Failure of a Pressure Vessel

Highly tough and ductile materials are recommended for the construction of pressure vessels [8], [9]. The failure process (elasto-plastic) of these materials is characterized by a phenomenon of crack faces moving apart prior to fracture [5] as illustrated in Fig. 2.

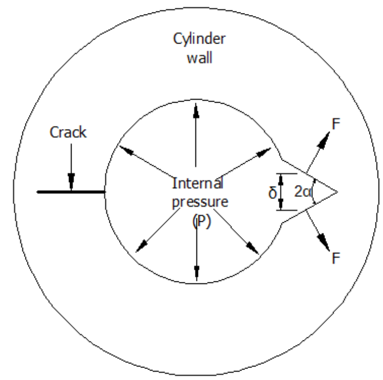

Fig. 2: Elast-plastic Failure

Where: 2α - Crack tip opening angle (CTOA)
δ - Crack tip opening displacement (CTOD)
F - Force normal to crack surfaces
P - Internal pressure

An initially sharp crack is normally blunted by plastic deformation to enable a significant opening of the crack [5]. Consequently, CTOD and CTOA increase from a value of zero to a maximum critical value before fracture occurs. Similarly, the energy absorbed as the crack opening increases is also proportionally increased to a critical value before fracture occurs. This is the energy required to extend the plastic deformation where an insignificant amount of energy is released when the crack grows [14]. *J*-integral is the most appropriate parameter to describe this energy requirement during elasto-plastic failure [28]. The *J*-integral may be defined as a contour integral characterizing strain energy release rate for a material that exhibits plastic deformation or non-linear elasticity during fracture process [5], [11]. The contour describing the *J*-integral is a path-independent line integral which can be drawn around the crack tip and viewed as an energy release rate parameter and sometimes as SIF [5]. When the material behaviour is linear elastic, calculation of *J*-integral is relatively straightforward because *J*-integral is equal to the strain energy release rate (*G*), and *G* is uniquely related to the stress intensity factor (SIF). Computing *J*-integral is somewhat difficult when the material is nonlinear or elasto-plastic. In this case, one option for determining *J*-integral is to apply the line integral definition, where its value is evaluated by mathematical integration along the arbitrary contour around the crack tip [5].

As the pressure increases and the crack opening relatively increases, the direction of forces (F) normal to the crack surfaces changes continuously. In normal analysis (LEFM approach), it is assumed that no plastic deformation takes place and therefore no blunting occurs of the initially sharp crack. LEFM applies in the limit of small scale yielding of low toughness materials [5], where a slight blunting of the sharp crack tip occurs and causes a relatively small crack opening that does not significantly alter the initial direction of F as the crack grows. For low toughness materials, brittle fracture is the governing failure mechanism which is characterized by a rapid and unstable crack growth [5]. At high fracture toughness, LEFM is no longer valid and it requires the application of EPFM which is a nonlinear fracture mechanics approach. In this case, failure is governed by the flow properties of the material [5], which results to slow and stable crack growth. Therefore, EPFM approach becomes suitable in addressing realistically expected steady crack growth behaviour in pressure vessels.

3.4 Surface Crack Shape Variation in Pressure Vessels

Most of the failures of pressure vessel are said to have been traced to surface cracks occurring on the walls of the vessel. A surface crack with any arbitrary shape becomes semi-elliptical after its formation [29], [30]. An axial crack will experience the maximum stress present in the vessel. Therefore, an axially oriented crack becomes more critical than a circumferential crack.

Most of the pressure vessels are cylindrical in shape with 2:1 semi-elliptical heads or end caps on each end [1], [7]. For the purpose of fracture analysis of cylindrical geometries, such as cylindrical pressure vessels, large diameter structures may be generally regarded as "Pipes" while small diameter structures may be called "Tubes" [21]. The failure pressure of a cracked pipe against elasto-plastic failure may be assessed based on the relationship between fracture toughness of the material and the *J*-integral, which represents the driving force for elasto-plastic failure [24]. The energy *J*-integral distribution along the presumed semi-elliptical crack front (defined by the elliptic angle ϕ) can be applied for the assessment of the internal surface crack propagation in a pressure vessel. The initial semi-elliptical crack geometry is as shown in Fig. 3.

Where: $\boldsymbol{a}$ is the crack depth, $\boldsymbol{2c}$ is the crack length and ϕ is the crack elliptic angle.

In general, the *J*-integral is expected to be a function of the non-dimensional quantities [21]: $\boldsymbol{R/t}$, $\boldsymbol{a/t}$, ρ and material parameters. $\boldsymbol{R}$ and $\boldsymbol{t}$ are the inner radius and wall thickness of the cylinder respectively and ρ is given by the following equation:

$$\rho = \frac{2c}{\sqrt{Rt}} \tag{1}$$

Equation 2 [31] can be used to provide the required *J*-integral distribution along the crack front during elasto-plastic failure of the pressure vessel.

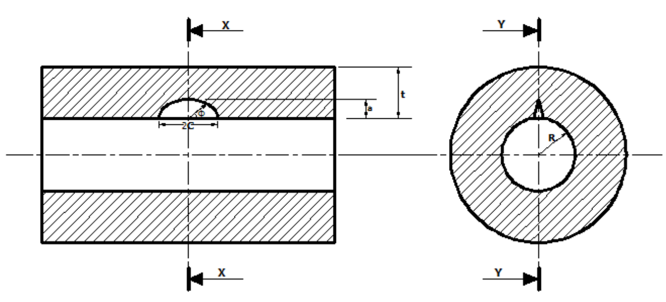

Fig. 3: Geometry of Semi-elliptical Crack

$$J(\phi) = \alpha \frac{\sigma_y}{E}(t-a)h_1\left(\frac{R}{t}, \frac{a}{t}, \rho, \phi; n\right)\left(\frac{P}{P_L}\right)^{n+1} \tag{2}$$

Where: σ_y – Yield stress of the material
E - Material young's modulus
α - Dimensionless material constant
P - Internal pressure
P_L - Limit pressure
h_1 - Dimensionless function of geometry and material conditions
n - Strain hardening exponent

A finite element analysis of the semi-elliptical surface crack can be carried out to estimate the solution of *J*-integral distribution along the crack front (according to Eq. 2) as a parameter for different crack extensions. Appropriate FEA softwares that can be applied are currently available, which can provide the *J*-integral solution with reasonably high accuracy. The results to be obtained can be used to simulate the crack propagation in a pressure vessel.

4. CONCLUSION

Highly tough and ductile materials are recommended for the construction of pressure vessels. In the normal failure analysis of pressure vessels, LEFM approach is applied, though it is not suitable for addressing failures that are associated with ductile materials. LEFM is suitable and appropriate when dealing with failures of brittle-elastic materials. Sometimes, it is not possible to set clear boundaries between brittle and ductile materials, as one and the same material under certain circumstances may behave as brittle one, while under some other circumstances it may behave as ductile one. Therefore, it is possible to unknowingly apply LEFM in cases where EPFM should have been applied or the other way round. For this reason, it becomes important to consider the extension of the available research work in a new direction of study that requires the understanding of the errors and effects that occur due to wrong assumption of material fracture behaviour during fracture analysis. In so doing, this will lead to enhancing the structural integrity of engineering components such as pressure vessels.

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