Service Life Prediction of Type III Hydrogen Storage Cylinders

[1]Rajat Shrivastava, [2]Vikash Kumar Yadav, [3]Yeswant Kumar

[1]M.Tech. Scholar, [2,3]Assistant Professor
Department of Mechanical Engineering
BM Group of Institutions, Gurugram

***Abstract*: Hydrogen storage cylinders are key element in expanding hydrogen energy-based technologies to various stationary (telecom towers, power systems at various remote location) and mobile (vehicular) applications. Type III hydrogen cylinders are the promising candidate due to their large volumetric storage capacity at high pressure. They have thin liner as core made of Aluminium alloy, to control the hydrogen permeability andto provide strength, that is wrapped with thick carbon fibre reinforced plastic composite toprovide majority of the strength required to hold high pressure gaseous hydrogen (of the order of 350 bar or more). Type III cylinders are advantageous due to their corrosion resistance, light weight and operational efficiencies. For operational safety and estimating the service life of these cylinders (filling and refilling cycles), it is important to understandthe fatigue behaviour of a cylinder material under high pressure hydrogen conditions. To this end, a simulation framework for modelling the fatigue crack growth behaviour in Type III composite cylinder material under high pressure hydrogen is developed within 2-D finite element framework enhanced with fracture mechanics concepts to predict service life of cylinder. The framework is developed within Abaqus finite element program coupled with python scripting using quarter point method to obtainthe stresses at the crack tip that govern crack growth behaviour. The stress intensity factor(SIF) and energy release rate value plays the role of important fracture mechanics parameters which is used in simulation to get fatigue crack propagation direction. In this work, focus is on the LEFM theory that is used for crack growth study in Aluminium liner.Analysis is performed in small steps, where in the first step stress intensity factor, crack propagation direction is calculated for an initially cracked liner of composite cylinder. In further small steps, the stress intensity factor (SIF) and crack propagation direction is calculated for the propagating crack while taking care of the liner-wrapping interface strength and stacking sequence of the composite wrapping. It is found that the stacking sequence plays a vital role in achieving improved service life of Type III cylinder.**

***Keywords*: Hydrogen storage cylinder, hydrogen energy, stress intensity factor, Type III cylinder**

I. INTRODUCTION

Engineering structure are always designed in such a way that it can sustain loads above permissible limits while in actual service. High end factor of safety should be considered for high stress concentrations because microscopic flaws which generally present in a structure or occur during production can fail structure catastrophically anytime which are assumed to be safe previously. Earlier if any structure encompasses any flaw either wholestructure use to be rejected or repaired, but in present scenario it is not possible from the point of view of material and energy conservation. By using fracture mechanics as a tool to predict life it has become easy to analyse structure containing cracks [1]. Since last 150years, engineers are devoted their selves in the analysis of fatigue failure. Designing and analysing the failures due to fatigue are mainly divided into three best possible approaches. i.e. strain based approach, stress based approach and the best one fracture mechanics approach. The strain-based approach uses the deformation or yield stain accumulated nearthe area of interest with notches and edges are considered as a stress raiser. The stress basedapproach uses von Mises stress near area of interest for the calculation of fatigue life of anycomponent [2]. The last approach is fracture mechanics approach which uses methods available in fracture mechanics on which this thesis is based on.

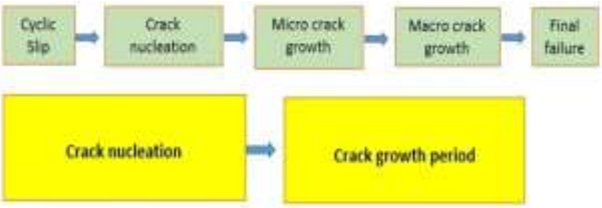

Fig. 1: Different periods of fatigue life in metals [3]

The fracture mechanics approach of fatigue failure can be further classified into two ways

i.e. fatigue crack growth approach or lifetime approach. In fatigue crack growth approach,damage tolerance is observed in the analysis [4]. Damage tolerance term itself is a propertyof a structure that dictate ability to sustain defects until proper rectification done and it is used by aircraft components manufacturing industries. In lifetime approach, minimum number of cycles is calculated before actual failure due to cyclic loading on any structure.This approach is used in this work to predict total number of cycles before failure of liner material. Further this lifetime approach is classified into two different cases i.e.

Low cyclefatigue and High cycle fatigue [5]. Low cycle fatigue is defined as the case where large overload can be seen in low number of cycles and typical example of this case is the elements of control systems in mechanical devices. High cycle fatigue is the case where material is subjected to lower loads less than 2/3rd of yield stress and fatigue damage startsafter at least 1000 cycles. Failure due to fatigue is because of discontinuity present in structure and crack initiation period is very short in this case while crack growth period is most significant phase. The discontinuity area where stress reached maximum value and causes cyclic plastic strain is the reason for crack propagation and failure. Low cycle fatigueis studied in terms of cyclic strain developed. In high cycle fatigue analysis, crack initiationperiod is most significant while crack growth is for very short time. This applied to mostlymachine parts which are subjected to cyclic stress and this can be evaluate using S-N curve.One of the basic difficulty associated with these two criteria are observation of transition phase that is crack nucleation to crack growth period. This difficulty is solved by Paris in 1961 [6] which gives relation between crack growth with change in stress intensity factor range and this is briefly explained in Chapter 2. Different types of cylinders used in literature are as follows

Types of cylinders

1. **Type I cylinders**: It is made up of total metallic material (steel/aluminium) and pressure cannot be more than 175-200 bar is bearable by this cylinder [7].
2. **Type II cylinders**: It is made up of metal tank with filament windings like aramid or glass fibre or carbon fibre on the outer surface of cylinder to provide better strength which sustain somewhat more pressure (250-300 bar) inside the cylinder in comparison to Type 1 cylinders [7].
3. **Type III cylinders**: It is made up of composite material with a metallic liner whosebasic purpose is to control permeation and strength is provided by composite material wrapped over it. Pressure limits for different-different composition is givenbelow:

- Aluminium/glass combination - up to 305 bars
- Aluminium/aramid combination - up to 438 bars
- Aluminium/carbon combination- up to 700 bars [7]

a. **Type IV cylinders:** This cylinder is as same as Type III cylinder only change whichcan be observed in this is polymer liner instead of metallic liner which gives zero permeation to hydrogen gas due to which operational efficiency is increases. It can also survive 700 bars of pressure. No change in pressure limit is observable here because liner is only getting changed because of permeation quality enhancement [7].

b. **Type V cylinder:** This cylinder has one noticeable thing that it doesn't compose ofany liner part. It is totally based on composite material. But right now, it is in development phase so not of much concern with practical use of it at present [7].

II. LITERATURE REVIEW

History and Background

Whenever failure of any structure is concern, there are only two types of failures comes into picture i.e., due to the negligence during operation, construction, design of structure itself or any design which comes in application and shows unexpected results [9]. Althoughin the application of fracture mechanics, polymers give an overwhelming response as an alternate of metallic liners due to which operational efficiency enriched and permeation is close to zero. Polyethylene as a polymer is popular material in the world which is used fornatural gas storage or transportation systems [10]. But due to some limitation with contour integral method in FE package, this research is restricted up to metallic liners only. Fracture mechanics has two approaches, the stress intensity factor (K) approach and energy criterionapproach. Both approaches are quite equivalent in various circumstances [10]. In this study,only focus is laid on stress intensity factor approach. When structures are subjected to anyloading, there are three ways available which a crack can experience i.e. Mode I, Mode II,Mode III illustrated in Figure 2, Figure 3, and Figure 4.

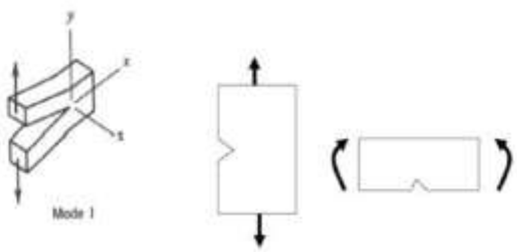

Fig. 2: Mode I fracture [11]

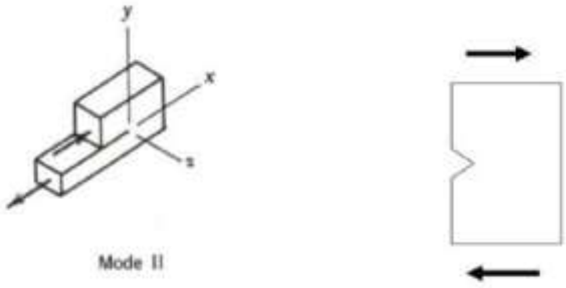

Fig. 3: Mode II fracture [11]

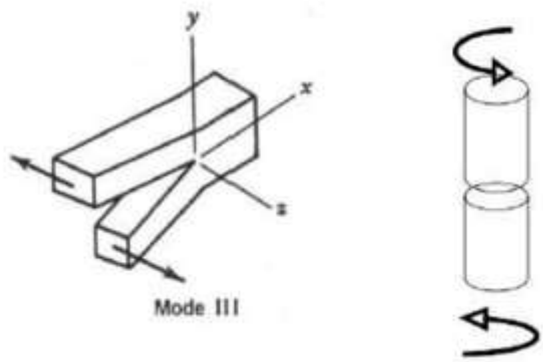

Fig. 4: Mode III fracture [11]

Mode I fracture: Another name of this fracture is crack opening mode which can be defined as a load acting normal to the crack plane which tends to open the crack.

Mode II fracture: This is also known as sliding mode which is defined as a shear stress acting parallel to the crack plane and perpendicular to crack front corresponds to in plane shear stress loading and tries to slide one face of crack with respect to another.

Mode III fracture: This fracture is known as Tearing mode in which shear stress is actingparallel to both plane of crack as well as crack front. It is a pure shear condition like roundbar subjected to torsion [11].

Fracture parameter are governed by type of loading as discussed above but they also changewith respect to the geometry of the problem and angle of initial propagation direction of crack which has to be investigated. Two approaches here also available of which one is singular integral equation basically for problems related to two parallel cracks interaction under mode II loading and another approach is implementation of this problem into Finiteelement method software i.e. Franc2D/L code [12]. For a crack which terminates at interface, the stress field generated there quite complicated and not possible or can say difficult to analyse through above two discussed approaches. So, after numerous studies itis evaluated that these problems can be handled either analytically or numerically. Due to complex mechanical state of stress fields near crack tip, it is difficult to find solution with finite element method therefore alternate approach is adopted which is termed as contour integral method. Contour integral method describes behaviour of fracture in terms of far field loading which is appears to be quite impressive. Once the J-integral is computed fromthis formula, general stress intensity factor (K) and asymptotic mixed mode stress fields can then be arranged properly [13]. This contour integral method is applicable to only homogenous materials but when non-homogenous material comes into picture then this method goes fail and then a new method is introduced which is known as Interaction (energy) integral method. This method is implemented for the computation of stress fieldsfor non-homogenous materials with continuous and discontinuous properties. But the limitation of this method is still stick to it like for contour integral method limitation i.e. itcan only be applicable to linear elastic materials

Engineering structures in general may fail due to fatigue loading and fatigue damage. Fatigue crack initiation and its propagation is regularly being modelled using finiteelement method [15]. As far as composite cylinders are concern, it plays a vital role in automotive industry for paying intensive attention towards storage of hydrogen for their hydrogen vehicles. However, the advantage of use of these cylinders in automobiles is weaken by manufacturing defects like flaw which leads to development and propagation ofcrack. Therefore, fracture behaviour seems to be an important tool for studying crack phenomenon on the surface of liner but side by side this can also be achieved that the service life gets increased by using any method and this method in the history of fracture mechanics is known as Autofrettage effect. Basically, this is nothing but deforming the liner up to plastic limit to store some plastic strain in it, due to which tensile stresses generates in the composite material. From next time, onwards whenever a load is applied

again, then this load must have to cross that residual stress stored due to plastic deformationearlier then after crossing this limit liner material start behaving for applied load. The wholescenario is applied on Type III cylinder having a semi elliptical crack exist on the surface of liner. In this manner, application of load intensity is increased leads to enhance the capability of liner material to sustain higher loads. This method gives immense results whencompared to results achieved without Autofrettage effect [16]. The problem arise up to thistime is like how to get service life or predict service without having a proper finite elementtool which can fulfil this fatigue crack growth problem in elastic or elastic plastic material.A numerical solution gives fine results for this problem by using re-meshing algorithm developed at TWI to simulate crack propagation. The flexibility, accuracy and stability of this method is analysed and compared on several examples. All the things starting from model generation to final crack propagation is programmed with python programming language with having some algorithm used for crack propagation [17].

When talk comes around method used which has to implement on finite element software then a huge list is available behind this scene. The best method available is J- Integral approach from the available methods like Stress intensity factor approach, T- stresscalculation and J- integral. For crack to be propagate, stress intensity factor (K) plays pre- eminent role in defining crack growth direction which is indirectly obtained from J-Integral.Both CTOD extrapolation method and J-integral approach are used in Abaqus finite element models for both 2D and 3D CT specimen and round bars which are pre-cracked. SIF are calculated along the crack front and where this value is larger, crack increment 'da'is propagated in that direction. Then according to Paris crack growth law only parameter left is no. of cycles which is associated with directly incremental crack length 'da'. On thisnew crack front, same steps are implemented and crack growth study has been done. Results obtained are in good agreement with literature surveyed results [18].

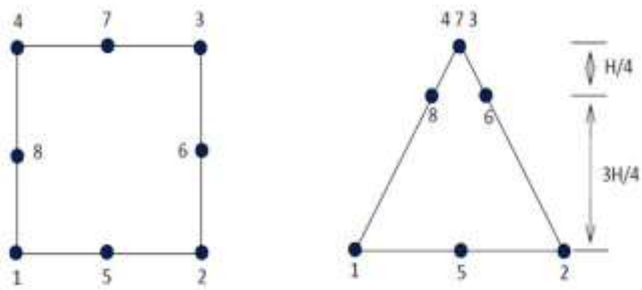

Fig. 5: Quadrilateral iso-parametric and collapsed Quarter Point Element

Quadrilateral iso-parametric and collapsed Quarter Point Element near crack tip can be observed in Figure 5. But one of the problem is also associated with quarter point elementsis meshing but have certain advantages in generating finite element code. Similarly stress intensity factor can also be calculated by Displacement Correlation technique, which usedmost of the times instead of simplicity to apply Finite element quarter point method [19]. To introduce crack propagation in cylinders is important because of the ample applicationsassociated with these cylinders. Crack propagation due to fatigue which is created due to fluctuating internal pressure is studied in this work where 6063-T6 and 6061-T4 aluminiumalloys cylinders are introduces for initial longitudinal cut problem. Stress intensity factor may be used as a correlation parameter and a modified model is mainly described to account bending effect. A shell and a plate model is analysed in order to investigate the crack propagation data comparison for both cases with different geometries and loading. Data obtained shows us that crack propagation in shells are much faster than in plates because initially crack propagations is due to plain strain (flat fracture) which changes to shear fracture later when stress intensity factor reaches a certain value. Results shows that stress intensity factor proves itself to be an important parameter for correlation in elastic solution [20].

Now after reaching this stage before moving to any step, it's time to discuss that what are the available methods available in literature especially for crack propagation framework. These methods consist of Finite element Quarter point method, mixed mode critical energy release rate, virtual crack closure technique (VCCT), extended finite elementmethod (XFEM), phantom node approach and level set method which are discussed. In ourcase mixed mode critical energy release rate method is used which is basically known contour integral method in Abaqus finite element software. This method has some limitations too that it is only applicable to linear elastic material if crack propagation direction is trying to be evaluated and elements must be quadrilateral in contour integral region. Contour integral method also allowed us to analyse elastic-plastic material but in this case J-integral value is only available and crack propagation direction is achieved fromsome other means like formulation available to get stress intensity factor from J-Integral value.

Fatigue crack growth is developed using numerical technique in which crack growthis assumed to be in that direction where plastically dissipated is accumulated more in plasticzone near crack tip. Then this accumulated energy is compared with critical value (materialproperty) required for growth of crack in a 2-D finite element model for compact tension specimen. Two types of polymer are used, one are those which depend upon frequency of loading and another those which do not depend on frequency of applied loading. A particular methodology is adopted here for manual crack growth which is helpful for further proceeding this work [21].

In [22] analytic method have been developed to assess fatigue crack growth whichproves their application in prediction of behaviour of crack growth under cyclic and thermalcombined transient loading. A non-linear fracture mechanics parameter evaluation isdeveloped by means of path integral method using finite element method in which stress and strain fields gives value required for fracture mechanics parameter calculation. Later asimplified crack growth behaviour is simulated by using stress intensity factor which is obtained by method of superposition. Both of the analysis are done on pre-flaw specimen to validate above code with experimental result available in literature. To observe more accurate behaviour of crack growth, it is required to reconsider the setup used in experiments. This is clear that J-integral prove itself to be promising parameter for non- linear fracture mechanics study. When non-linear material is concerned then two integral comes into picture i.e. Domain integral and contour integrals. These integrals are defined

on a vanishingly small contours which are normal to the crack front and providing the pointwise value of the energy release rate required for J-Integral study. Domain integral arenothing but integral over the volumes of element present in a contour and contour integralis the method in which line or area integral is associated within the contour defined. Both approaches have its unique values then what is the problem, geometry, element meshing and matter of convenience is only concern. Problem found in literature survey after analysing it may conclude that many papers are putting more focus on plate problem, CT specimen problem, modified cylinder problem but it has not ever seen who has developedcrack growth behaviour in proper cylindrical models. It is obvious that analysing a 3D problem is a bit long and hectic task which need a long duration of research and may not be possible to complete in 8 months of duration, so this work is restricted to 2-D cylinder model which may be extended to 3D problem.

Cylinders are not only made up of metallic liners, then it is required to go through the literature again for collecting information about the crack growth in polymers or composites. Study of fatigue behaviour made an intense point of concern due to the failureshappening in structure which basically starts in composite material because of the non- homogenous constituents. Local damage is the cause of failure in isotropic material usuallydevelops ramp loading leads to failure. In [23] carbon fiber reinforced composite is studiedfor high frequency fatigue. It has been proved that stacking sequence in efficient manner may increase the strength of composite therefore a parametric study is described in this work to compare different sequence of composite behaviour on the application of fatigue loading. Micromechanical analysis is also performed to see the small-scale yielding using scanned electron microscopy. Experimental results provide the information of actual failurereasons which are due to matric crack combination in a structure, splitting longitudinally, fracture in fiber and the last one is delamination.

In [24] carbon fiber reinforced polymer (CFRP) composite bonded material is testedfor different patch configurations, thickness of reinforcement and initial damage levels areinvestigated. In CFRP fatigue crack propagation may be prevented: (a) by decreasing the stress range around crack tip; (b) by decreasing crack tip opening displacement and (c) by promoting crack closure. For the analysis of non-linear materials, a special method is implemented in Abaqus to promote the CFRC based stress field evaluation which is knownas XFEM method. This method has some limitation but it can also fulfil other requirements which other method cannot be able. A user subroutine is required to incorporate the

capabilities of this method for non-linear analysis. On comparing with method available for finite element study i.e. XFEM, it provides numerous advantages in numerical modelling of crack growth behaviour. In conventional methods available for finite element,existence of crack is only modelled by or restricted by element edges means that if crack wants to tear out elements then it cannot be able to do same but in XFEM it is possible which enhance results by greater margin.

In contrast, crack geometry in XFEM don't want to follow element edges which provides versatility and freedom to model a crack globally [25]. XFEM is based on the enrichment of the FE model in which extra degree of freedom is provided to the nodes of elements associated directly to the crack. In addition, nodes which are surrounded by cracktip are also enriched by DOFs associated with functions of LEFM asymptotic stress fields [26]. This method holds well when accuracy of stress intensity factor is concerned due to the crack discontinuity within crack tip element. Cylinder may fail under normal application of pressure irrespective of any fatigue loading for that case a Type IV cylinderhaving HDPE, LLDPE and blend of HDPE/LDPE as a liner material and effect ofmechanical behaviour is investigated. Also the effect of circumferential winding on sequence of stacking used is discussed [27]. It provides exact solution of deformations andstresses on cylindrical section subjected to thermo- mechanical loading. Burst pressure canbe improved by circumferential windings with optimum stacking sequence [28].

Methods available for fatigue study is done but if this study has to move further forthe life prediction study then it is necessary to learn models available for crack growth. There are numerous models available like Paris model, Walker Model, Forman model andmany more. Paris model is effective model if stress ratio is not the key aspect of analysis. If stress ratio is not varying or parametric study not based on stress ration is done then Parismodel plays a successful candidate. These model gives no. of cycles for incremental crackgrowth. So a cumulative sum of these number of cycles provide us idea of total number ofcycle up to critical length. There are some criteria's available on which crack propagation direction is based which are as following [29],

- Maximum Tangential Stress Criteria (MTS)
- Maximum Energy Release Rate Criteria (MERR)
- $K_{II} = 0$ Criteria
- Maximum Circumferential Stress Criteria (MCS)

Out of above 4 criteria's, only first three are available in Abaqus simulation finite elementsoftware and if fourth-one is used in any study then python coding is the alternate way to indirectly use it in numerical software. The crack propagation direction criteria's give almost same direction except for marginal difference due to the formulation used for each method is different. It is up to the researcher that which method is suitable to choose for getting direction of crack propagation for their research[29]. After having all this data in our hand now we can start thinking to design a problem based on literature survey.

III. PROCEDURE OF NUMERICAL SIMULATION FOR CRACKGROWTH

Fatigue crack growth study is of major concern for civil and mechanical engineers and it issubjected to further research in this field because most of the structures are either failing due to fatigue loading or creep loading. As this work is dealing with fatigue loading insidecylinder with a frequency of 5Hz for 400 bar of pressure, a framework is designed and procedure to execute it is given in next section of this chapter.

Method of Contour Integral implementation in Abaqus

In fatigue crack growth study, number of methods are available in Abaqus namely XFEM,Virtual crack closure technique and contour integral method. Out of mentioned methods, contour integral method is used for our analysis because it have advantages over other twomethods with limitations. The Contour Integral method is introduced in Abaqus recently which is a tool used to predict crack growth direction with stress intensity factor information for mixed mode crack growth. This method gives solutions with high precisionand accuracy if meshing near crack is done properly. It has some advantages over other methods available in Abaqus and has some limitations too. Here limitation must behighlighted before going further. First limitation is that it needs only quadrilateral elementsin the contour region for the sake of Finite Element Quarter Point method fulfilment as discussed in literature part and no triangular or hexagonal meshing can be created in the contour region. Literature give the idea of meshing near crack region and this should be about 3% of the crack length to get accurate and acceptable results [3]. This method doesn'tcompute for J-Integral value near crack tip directly but indirectly from the computed one stress intensity factor values. Another limitation associated with this method is that if crackpropagation direction is to be find then it is not possible to use material other than linear elastic material. It is true that if crack propagation direction is not required for any case andonly we need is J-Integral then non-linear elastic material can be used by using Romberg- Osgood Model which is given by deformation plasticity theory in Abaqus. A re-meshing criteria is used in simulation framework. Fine seed is given to crack geometry by picking a variable edge associated with crack tip and as the crack geometry changes at eachsimulation re-meshing is done.

Procedure for 2D fatigue crack growth simulation

In previous section it is discussed that contour integral method is able to give crack propagation direction and stress intensity factor values for a single step of simulation i.e. for an initial crack present in a model. This work requires propagation of the same crack. For propagation purpose python scripting is used here. Each step in Abaqus is saved in journal file and by utilising this journal file python scripting is prepared to update crack geometry for next steps of simulation. A python script is developed for two dimensional fatigue crack propagation which is given in Appendix A. The method used known as contour integral for our work is mesh dependent and this dependency can be reduced to some extent bydoing various partition to differentiate crack from global area. This partitionstrategy also helps in reducing computation time with a significant margin.

The procedure for 2D crack growth simulation in Abaqus is given as below:

- Create a 2D model with initial crack in Abaqus having model configuration,Inner diameter of cylinder=217mm Outer Diameter of Cylinder=229mm.

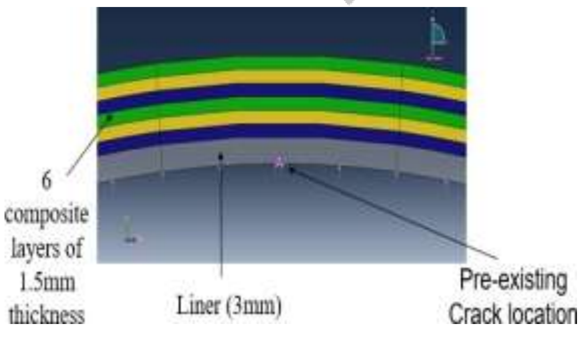

Fig. 6: Computational model of 2D Type-III Cylinder

- Created model should be partitioned for liner material assignment, compositematerial assignment and to create a crack.
- Crack length is 0.25mm at the periphery of Aluminium liner.
- Properties of material are given in Abaqus using Table 1 and assigning thesematerials accordingly.

- Creating instance for prepared model.
- Define interaction of crack as a seam with model.
- Create step to apply load and boundary conditions.
- Create partition for various regions and small partition near cracked region to meshit finely with quadrilateral shape elements.
- Geometric order should be quadratic for FEQP technique.
- 8-Node biquadratic plane strain quadrilateral element-CPS8R with reducedintegration is used.
- Saving model and find .cae file and .jnl files in the working directory to start playingwith python script.
- Fill/modify the details needed for crack propagation in journal file.
- Execute .py extension file which is python file and after completion of job obtain results and necessary details from output database file which is automatically doneif script is written accordingly.
- Running modified python script gives all necessary outputs in text file created on every iteration which are saved in working directory and however the crack propagation animation is not provided by Abaqus itself, for that purpose a video maker tool is used which collects all snapshots of every last frame of each iteration and play it to see how crack is actually propagating.

IV. RESULTS AND DISCUSSION

Stress Vs. Thickness of Cylinder

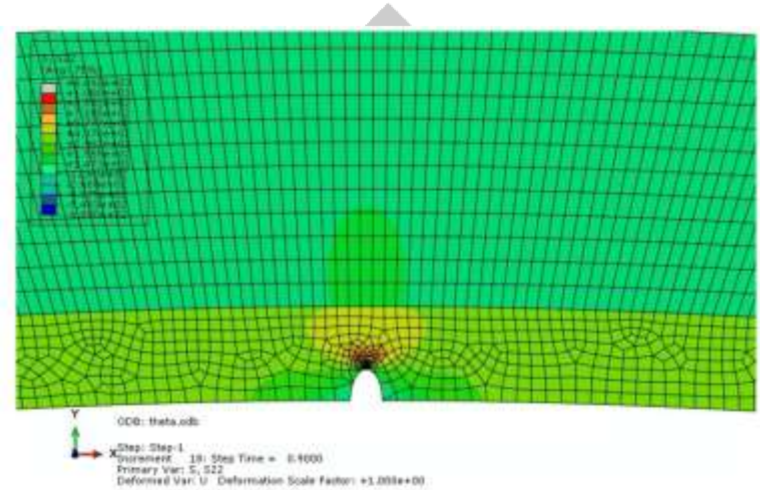

Fig. 7. Stress Vs. Thickness of Cylinder

When the results obtained from output database file and implemented into Paris law, itgives Number of cycles before failure which are available in below Table 1.

Table 1: Number of cycles before failure for Traction crack surfaces and Traction freecrack surfaces

S.No	Load (Bar)	F(Hz)	Stacking Sequence	Total no. of Cycles	
				Liner (Traction crack surface)	Liner (Traction Free crack surface)
1.	400	5	AAAAAA	3704	4152
2.	400	5	ABABAB	4735	5163
3.	400	5	ABCABC	5785	6118

When results are compiled with Paris law, Number of cycles are obtained by integrating Paris equation and found that ABCABC stacking sequence used cylinder will fail its liner material in 6118 cycles which is highest among other two and whole cylinder will fail in 116349 cycles but this is not of our interest because as soon as liner material got failed permeation of hydrogen gas starts which is not required. From above data it can be assumedthat Type III cylinder can be manufactured for bearing 400 bar of pressure for up to 6118 filling and un-filling cycles with ABCABC stacking sequence.

Effect of Autofrettage in Composite Cylinder

There is one important method also available in literature which enhances the service life or reliability of composite hydrogen storage cylinders which is known as Autofrettage effect. A simple crack free cylinder is simulated to encounter this effect and foundsuccessful in achieving positive results which basically implementation of residual effect inside cylinder due to plastic deformation of it. The yield stress for Al7075 is 420 MPa. InFigure 21, radial stresses are observed for autofrettaged cylinder and non-autofrettaged cylinder in which 450MPa of Autofrettage pressure is used to deform aluminium liner for

The residual stress encountered for whole thickness is beneficial for our case as the black curve is throughout above the red curve which depicts that the difference associated with these two curves are directly showing the available residual stress in the cylinder. Withouthaving an Autofrettage effect stress generated is around 43MPa (compressive) at the surface of liner while in case of Autofrettage, marginable difference is observed of about 4MPa which obviously enhances the fatigue life of cylinder as this is directly depends on the tangential stress of cylinder because during Autofrettage this tangential stress is converted into tensile residual stresses.

This chapter summarizes no. of cycles before failure of liner in Type III cylinder for tractionenabled and traction free surfaces and it is found that traction enabled case give significantdifference in total no. of cycles. Stacking sequence used on wrapped composite layers gaveimpressive results for [90, -10, 10] sequence. The Autofrettage process implemented on Type III cylinder enhanced service life of cylinder with the help of residual stress present in cylinder.

V. CONCLUSION AND FUTURE SCOPE

This chapter summarizes the work done and presents the conclusions reached. The aim of this work is to predict the service life of Type III cylinder using finite element framework based on fracture mechanics. Fatigue crack propagation in metal liner of Type III cylinderis studied using this framework using the contour integral method in Abaqus and customized python scripting. Paris crack growth model has been selected to estimate the fatigue crack growth rate however this model does not consider the role of stress ratio but this can be extended easily for more complicated models. Development of such a simulation framework allows us to simulate fatigue crack propagation in a Type III cylinderwhich can be extended for Type IV cylinder with suitable modifications. The framework is validated by fitting service life prediction data using a standard Franc2D code for a traction free crack face case. The framework is extended by including the possibility of simulating a growing crack with pressure acting on the crack face. It is envisioned that a crack face cannot be assumed to be traction free in case of high pressure hydrogen cylindersas hydrogen can penetrate itself in any small opening which leads to pressure loading of crack face. The analyses of fatigue crack growth is then performed for a traction enabled crack. Service life prediction using traction free model and traction enabled model showedsignificant decrease in service life for a traction enabled analysis.

The framework thus developed is then used for understanding the role of stacking sequence of composite wrapping on service life of cylinder. A strong role of stacking sequence is observed in controlling the service life with ABCABC (90,-10,+10) kind of stacking giving the best results. Lastly, it is shown that Autofrettage of Type III cylinder can be used in controlling the stress levels generated in metal liner and composite wrapping.

Future scope

The framework presented in this thesis based on LEFM which is limited to metals. In orderto extend the framework for predicting the service life of Type IV cylinders it is essential to include the EPFM based model for crack propagation. This can be done using XFEM based approach instead of contour integral. This work can be further proceeded to 3d models and for more than one crack in cylinder. At last parametric study can be done for different composite materials.

References

[1]. Chun H. Wang. Introduction to Fracture Mechanics: Defence Science and TechnologyOrganisation; 1996.
[2]. Vethe S. Numerical Simulation of fatigue crack growth 2012.
[3]. Vethe S. Numerical simulation of fatigue crack growth 2012.
[4]. Safarian P. Fatigue and Damage Tolerance Analysis.
[5]. Suresh S. Fatigue of materials, 2nd ed. Cambridge [u.a.]: Cambridge Univ. Pr; 2006.
[6]. Cherepanov GP. Crack growth under cyclic loads. Journal of Applied Mechanics and Technical Physics 1968;9(6):674–86.
[7]. Wikipedia. Hydrogen tank - Wikipedia. [July 25, 2017]; Available from: https://en.wikipedia.org/w/index.php?oldid=785840433.
[8]. Wikipedia. Hydrogen storage - Wikipedia. [July 25, 2017]; Available from: https://en.wikipedia.org/w/index.php?oldid=790369807.
[9]. Peacock A. J. Handbook of polyethylene: Structures, properties and applications. NewYork, Marcel Dekker Inc.
[10]. Hsuan, Y.G., Zhang, J. Stress crack resistance of corrugated high-density polyethylene pipes in different test environments and temperatures.
[11]. Wikipedia. Fracture mechanics - Wikipedia. [July 26, 2017]; Available from: https://en.wikipedia.org/w/index.php?oldid=788512923.
[12]. Petrova VE, Marsavina L, Sadowski T. Revisit of compact Mode II crack specimen: Analysis and fracture interpretation. Theoretical and Applied Fracture Mechanics2012;59(1):41–8.
[13]. Chang JH, Wu DJ. Calculation of mixed-mode stress intensity factors for a crack normal to a bimaterial interface using contour integrals. Engineering Fracture Mechanics 2003;70(13):1675–95.
[14]. Yu H, Wu L, Guo L, Du S, He Q. Investigation of mixed-mode stress intensity factors for nonhomogeneous materials using an interaction integral method. International Journal of Solids and Structures 2009;46(20):3710–24.
[15]. Ding Z, Gao Z, Ma C, Wang X. Modeling of I + II mixed mode crack initiation andgrowth from the notch. Theoretical

and Applied Fracture Mechanics 2016;84:129–39.
[16]. Hu J, Chandrashekhara K. Fracture analysis of hydrogen storage composite cylinders with liner crack accounting for autofrettage effect. International Journal of Hydrogen Energy 2009;34(8):3425–35.
[17]. Tyler London,Dr Simon D. Smith,Dr Şefika Elvin Eren. Three dimension finite element simulation of elastic and elastic plastic material using automated remeshing technique.
[18]. Courtin S, Gardin C, Bézine G, Ben Hadj Hamouda H. Advantages of the J-integralapproach for calculating stress intensity factors when using the commercial finite element software ABAQUS. Engineering Fracture Mechanics 2005;72(14):2174–85.
[19]. Naoto Sakakibara. Finite Element Method in Fracture Mechanics.
[20]. W.M.Catanach* & F.Erdogan. Fatigue crack propagation in cylindrical shells.
[21]. Ding G, Karlsson AM, Santare MH. Numerical evaluation of fatigue crack growthin polymers based on plastically dissipated energy. International Journal of Fatigue 2017;94:89–96.
[22]. Takashi WAKAI and Morito HORDORI. Development of Simplified Methods forFatigue Crack Growth Assessment under Cyclic Thermal Loadings.
[23]. S. Putiæ, P. S. Uskokoviæ,and R. Aleksiæ. Analysis of fatigue and crack growth incarbon fiber epoxy reinforced composites.
[24]. Colombi P, Fava G, Poggi C, Sonzogni L. Fatigue Reinforcement of Steel Elementsby CFRP Materials: Experimental Evidence, Analytical Model and Numerical Simulation. Procedia Engineering 2014;74:384–7.
[25]. Giner E, Sukumar N, Tarancón JE, Fuenmayor FJ. An Abaqus implementation of the extended finite element method. Engineering Fracture Mechanics 2009;76(3):347–68.
[26]. Gordana Jovi, Miroslav Živkovi,Katarina Maksimovi,Nenad. The crack Growth Analysis on a Real Structure Using the X-FEM and EFG Methods.
[27]. Bertin M, Touchard F, Lafarie-Frenot M-C. Experimental study of the stacking sequence effect on polymer/composite multi-layers submitted to thermomechanical cyclic loadings. International Journal of Hydrogen Energy 2010;35(20):11397–404.
[28]. A.Hocine, A. Ghouaoula, F. Kara Achira and S. M. Medjdoub. Analysis of failurepressure of composite cylinders with a polymer liner of Type IV CNG vessels 2013.
[29]. Beden SM, Abdullah S, Ariffin AK. Review of fatigue crack propagation models for metallic components.
[30]. Miguel Patr´ıcio, Robert M.M. Mattheij. Crack Propagation Analysis.
[31]. Erdogan F, Sih GC. Closure to "Discussion of 'On the Crack Extension in Plates Under Plane Loading and Transverse Shear'" (1963, ASME J. Basic Eng., 85, pp. 525–527). J. Basic Engineering 1963;85(4):527.
[32]. Matthew J. Pais. Variable amplitude fatigue analysis using surrogate models and exact XFEM reanalysis.
[33]. F. Trieb, J. Schedelmaier, M. Poelzl. Autofrettage - Basic information and practicalapplication for waterjet cutting 2005.