Fracture Toughness Material Characterisation Based On Direct Measurements Of Displacement Field

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INTRODUCTION

The term "fracture mechanics" refers to a vital specialization within solid mechanics in which the presence of a crack is assumed, and we wish to find quantitative relations between the crack length, the material's inherent resistance to crack growth, and the stress at which the crack propagates at high speed to cause structural failure. Based on analytical analyses and mathematical models of variously shaped bodies with cracks, experimental methods have been developed to determine essential fracture mechanics' parameters such as the critical value of stress intensity factor KIC, crack tip opening displacement (CTOD), and Rice's contour integral J. [2]

These parameters are used to calculate the power of a crack formation and predict when and how it will propagate. [2]

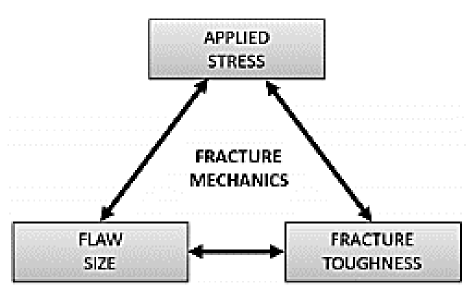
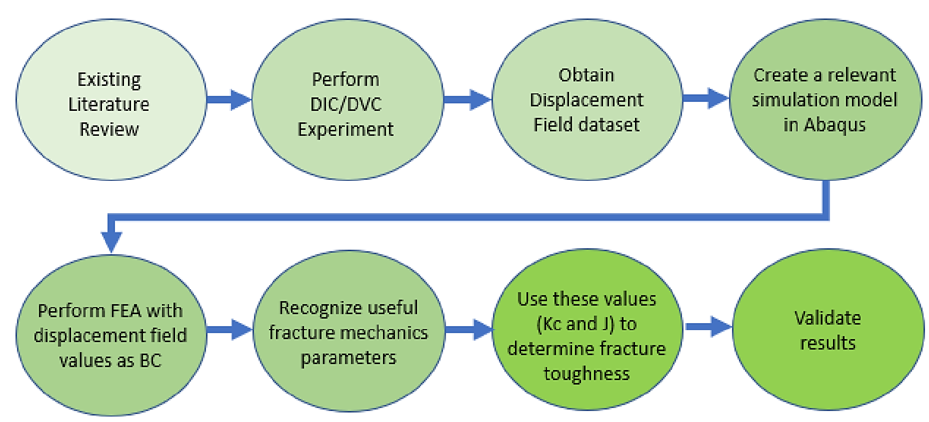


Figure 1. Fracture mechanics overview (simplified) [1]

OBJECTIVES

- To review existing literature on material characterisation based on the measurements of displacement fields as well as the state-of-the-art image processing tools and techniques available
- To review the advancements made in recent years in the field of fracture mechanics for monitoring and detecting crack formations and propagations
- To use an image processing technique such as DIC or DVC to measure surface or volume displacement fields respectively
- To use obtained data as boundary conditions for FEA
- To employ a complex engineering simulation software, such as Abaqus, to calculate fracture toughness parameters (Kc, J/CTOD) for material characterisation to from the displacement field using FEA.
- To establish the validity of the results through post-processing and further relevant research

METHODOLOGY



AIM

The goal of this dissertation project is to review fracture mechanics and cutting-edge imaging processing techniques like DVC and DIC with the integration of FEM to extract fracture mechanics' parameters from surface and volume displacement fields for material characterisation [3]

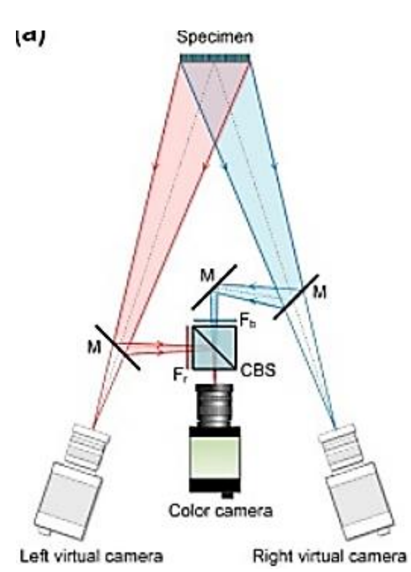


Figure 2. Stereo-DIC setup which enables DVC when combined with internal imaging [4]

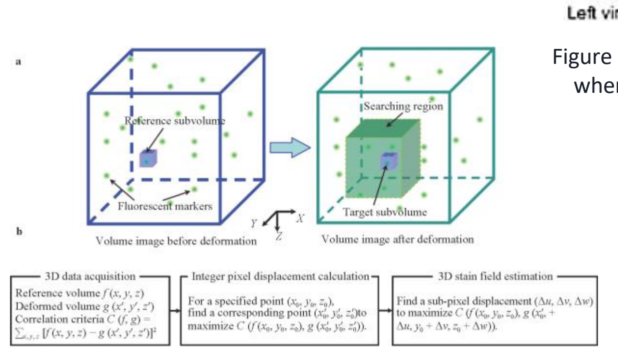


Fig. 3. a General format of digital volume correlation calculation . b Schematic diagram of the overall process of DVC [5]

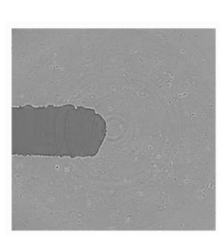


Figure 4. X-ray tomographic image of aluminium alloy AA2139 [5]

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Failure characterisation of PEEK polymers used in extruded pipelines

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Introduction

In the 1980s, PEEK (poly-ether-ether-ketone) was initially made available for industrial use in the production of, among other components, bearings, turbine blades, piston parts, cable insulation, and compressor plate valves. PEEK polymers are used in the manufacturing of extruded pipes and offer an outstanding ability to withstand the harsh conditions encountered in both oil-field production and offshore exploration.[1]

In Implant engineering, PEEK has emerged as a significant substitute for metal implant parts, particularly in traumatic applications, orthopaedics, and spinal implants.[2]

The impact of stress concentration and inclusion on the fracture behaviour of PEEK, however, has not received much attention. An important aspect of implant design is to ensure a long-term reliable performance under various loading situations, as implant components frequently fail under static or repetitive loading due to stress concentration.

It is well known that, besides the strain intensity, the most important factor that controls initiation of ductile fracture is stress triaxiality.[3] Therefore, to effectively design pipelines and jointed connections, as well as implant materials characterising the mechanical properties and the fracture locus according to stress triaxiality is essential to support finite element analysis.

Aim

The aim of this current work is to find the appropriate model for modelling PEEK and perform a tensile test to ascertain mechanical properties to necessitate the Characterisation of the failure behaviour of 650G PEEK polymer. This vital information would be needed to support the fracture locus construction for 650G peek polymer in a stress triaxiality of range -1/3 to 1.1

Objectives

- Conduct an extensive literature on stress triaxiality and procedure for fracture locus characterisation.
- Mechanical properties determination using (dumbbell vs cylindrical specimens) to characterise the extruded properties of PEEK 650G
- Experimentally test and validate various PEEK coupons under quasi static loading, requiring digital image correlation for accurate surface strain measurements.
- Achieve correlation with experimental results for the uniaxial tension specimen using FEA, and test robustness of FE model by extending it to all coupon designs
- Using finite element data and experimental data to determine the fracture locus from a stress triaxiality range of -1/3 to 1.1

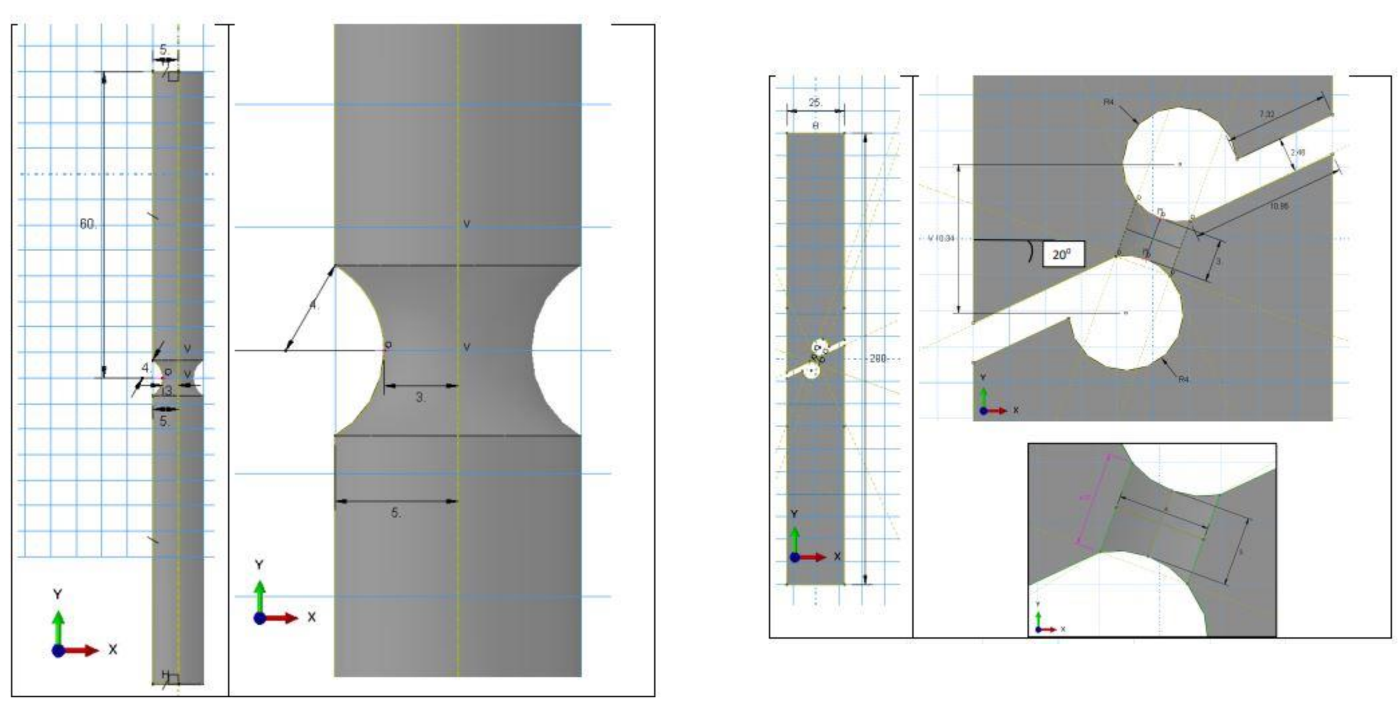

Figure 1: Some selected geometry specimens

Methodology

Initial stress triaxiality calculations and procedure

Experiment
- Materials
- Testing
- Results and discursion

FEM
- FE analysis
- Post processing
- Correlation and validation of results with experimental data

Results and discursion

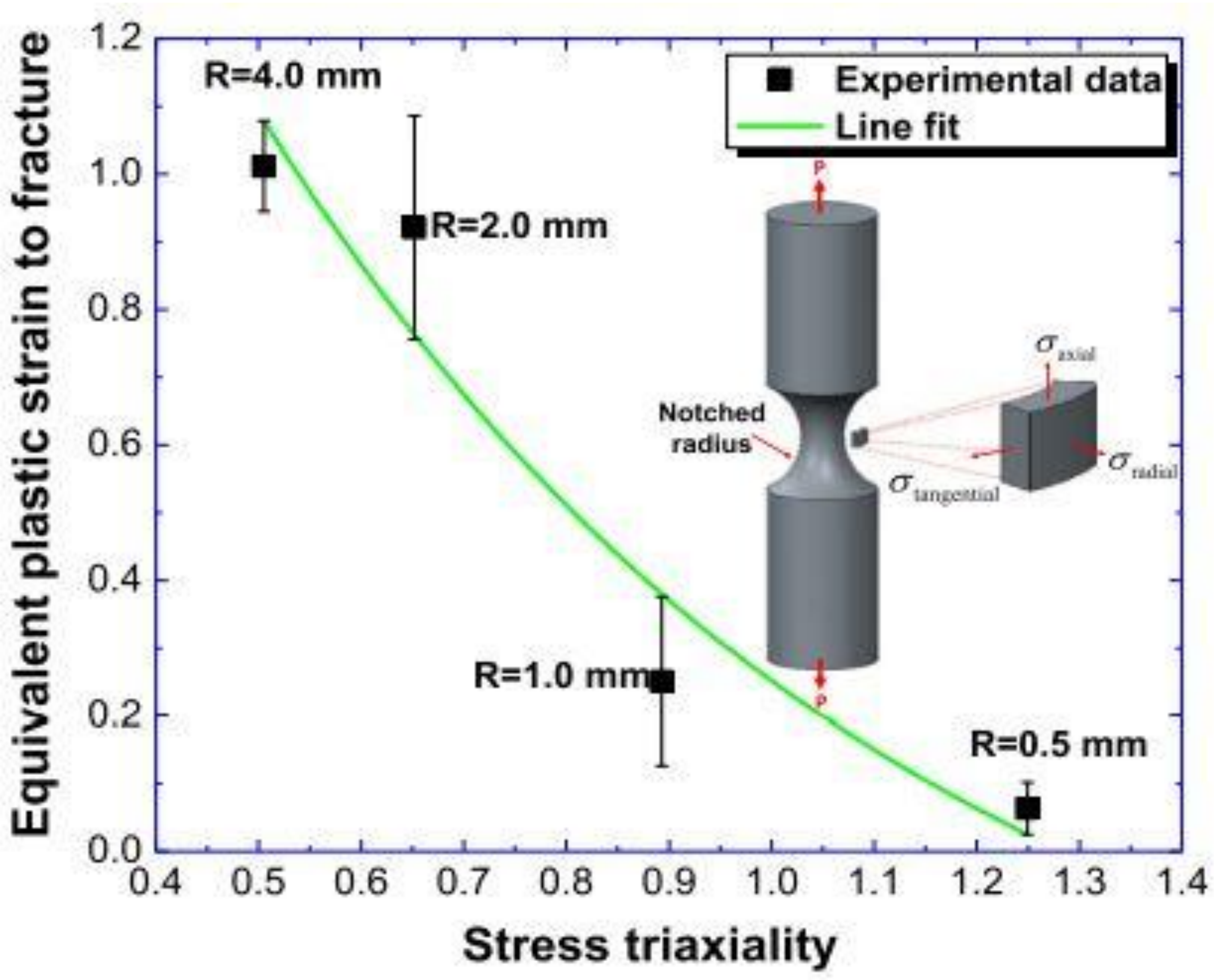

Figure 2:Equivalent plastic strain to fracture with the change of stress triaxiality. (source Chen et al. 2016)

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Modelling Blast Loading from a Hydrogen Explosion

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INTRODUCTION

Hydrogen has become attractive as one of promising green energy candidates in this era. Explosions of hydrogen pose a serious risk. When combined with ambient oxygen, hydrogen gas can generate flammable or explosive mixtures at concentrations between 4.0 and 75 percent and 18 and 59 percent, respectively. Hence safety of adjacent structures can not be ignored.

In a scenario of hydrogen gas explosion, the effect of the overpressure (blast loading) on surrounding adjacent structure is the consideration for this research work. That is, analysing structural response of equipment subjected to potential blast loading from conventional detonation is of great interest to the engineer.

RESEARCH AIM

The study is aimed at evaluating safety requirements for hydrogen storage containers and investigating blast loading on surrounding structures following a hydrogen – air explosion. The CONWEP blast loading model in ABAQUS is used.

OBJECTIVE

- Review properties of hydrogen air explosion
- Ascertain safety requirements for hydrogen storage containers.
- Review CONWEP blast loading modelling approach.
- Developing two blast loading model for hydrogen detonation and deflagration.
- Carrying out a blast loading test case for mechanical structures around a hydrogen- air explosion and running it on CONWEP blast loading model to ascertain if similar results can be obtained.
- Allowable safety distance on a structure adjacent to a hydrogen- air explosion.

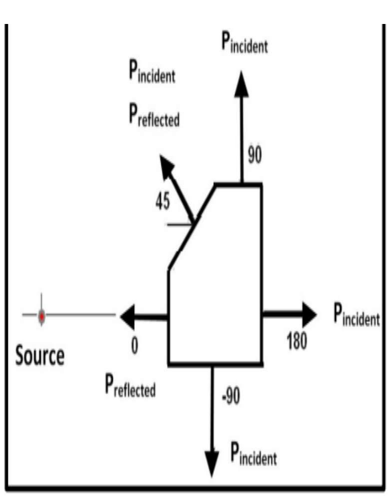
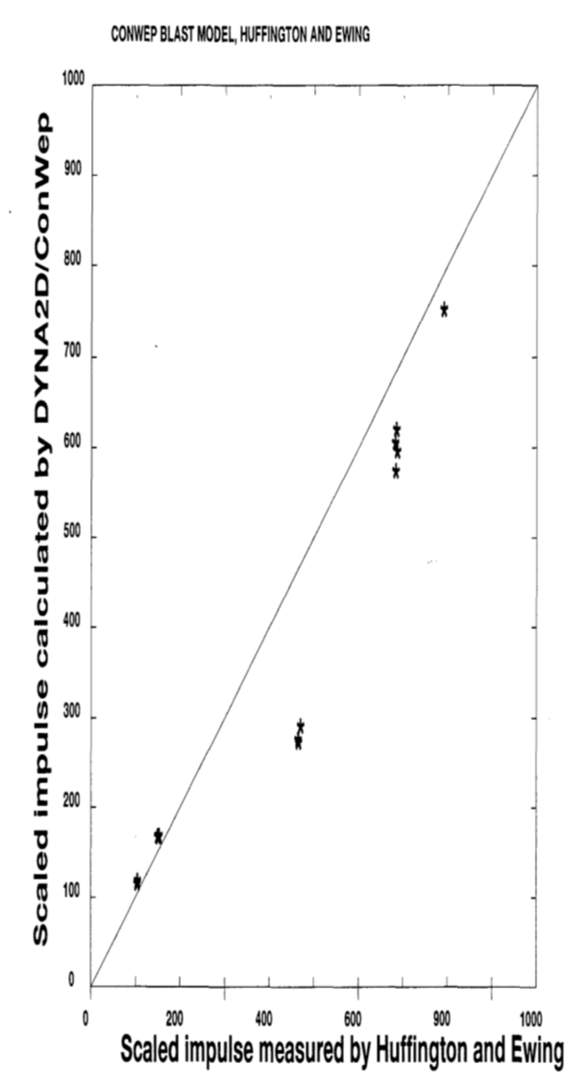


Figure 2. Blast wave reflection formulation built into the CONWEP charge property (Simulia, 2010)

LITERATURE REVIEW ON CONWEP BLAST LOADING

A significant challenge associated with computational blast modelling is appropriately accounting for reflection effects. The peak blast pressure that a structure is subjected to is greater than the peak incident overpressure and is referred to as the reflected pressure. This pressure is a function of the peak incident overpressure and the angle of incidence; that is, the angle between the loading direction and the surface normal of a given point on the loading surface.

The main advantage of using CONWEP over the incident wave loading approach is that realistic overpressure amplitudes and other blast wave parameters are inherently calculated based on a user-defined amount of TNT at a given distance from the explosion source. Furthermore, the CONWEP blast loading model does not require modelling the fluid medium (air in this case) to account for reflection effects. The reflection formulation employed in the CONWEP charge property is depicted in Figure 2



METHODOLOGY

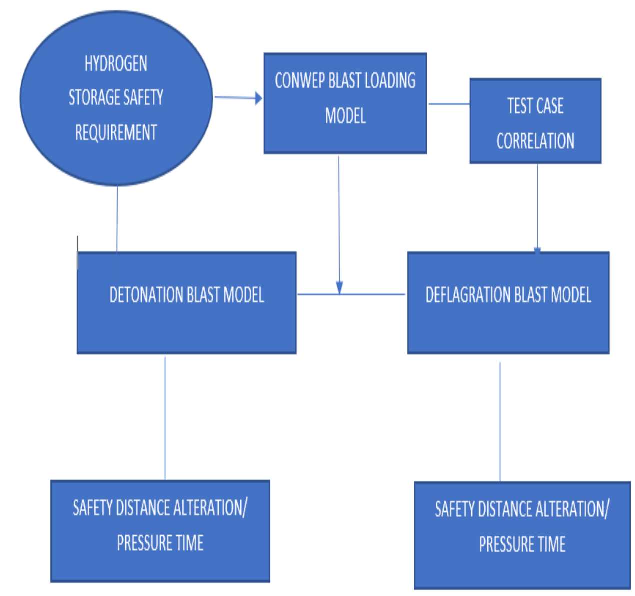


Fig. 1.0 Research Methodology

HYDROGEN EXPLOSION

Hydrogen explosion represents a considerable hazard. Hydrogen gas forms combustible or explosive mixtures with the atmospheric oxygen over a wide range of concentrations in the range 4.0%–75% and 18%–59%, respectively. Vapor cloud explosions involve a large release of hydrogen outdoors that mixes with air to form a large flammable cloud before ignition occurs (Pasman and Rogers, 2010).

The strength of the explosion depends on the magnitude of confinement which in turn depends on the degree of confinement and could generate blast wave that can produce damages to the surrounding buildings and people (Baraldi et al., 2009). Many of the studies on hydrogen stations have dealt with explosion, deflagration, or detonation of hydrogen (Yamanaka et al., 2004; Fukuda et al., 2004; Xu et al., 2008).

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Integrity Of composite pressure vessel

Background to the Problem:

- Fuel Cell Electric Vehicles have a high potential in the decarbonisation of the transport industry by using Hydrogen as an energy carrier.
- Composite pressure vessels are designed to store hydrogen at pressures between 35MPa and 70MPa.
- Numerical simulations are used to study the behaviour of composite pressure vessels in different failure cases.

Aim:

- The aim of this project is to study the integrity of composite pressure vessels used in FCEV to store hydrogen.

Objectives:

- Literature review on hydrogen as an energy carrier
- Studying the obstacles of using hydrogen in FCEV
- Studying different possible failure cases
- Performing Numerical simulations to study the failure cases

Methodology:

Literature review

- Introduction to hydrogen as an energy carrier
- Storage of hydrogen in FCEV
- Analysis of experimental results

Numerical
Analysis

- Designing the base cylindrical model
- Burst failure model
- Burst failure
- Burst and Impact Model
- crack propagation model (Optional)

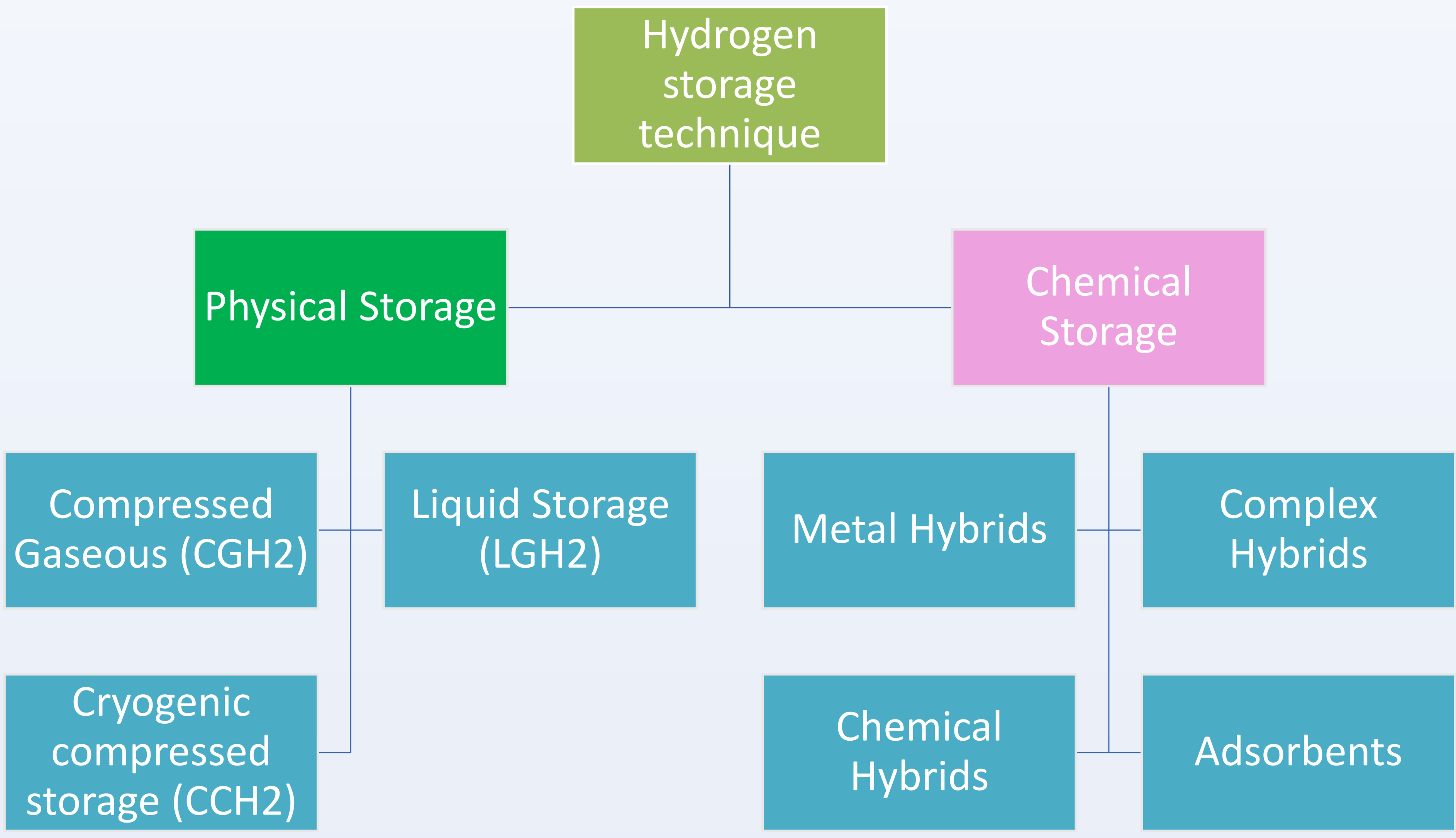
Data Analysis

- Sensitivity analysis for each failure model
- Data analysis of each model
- Comparison of model results with experimental

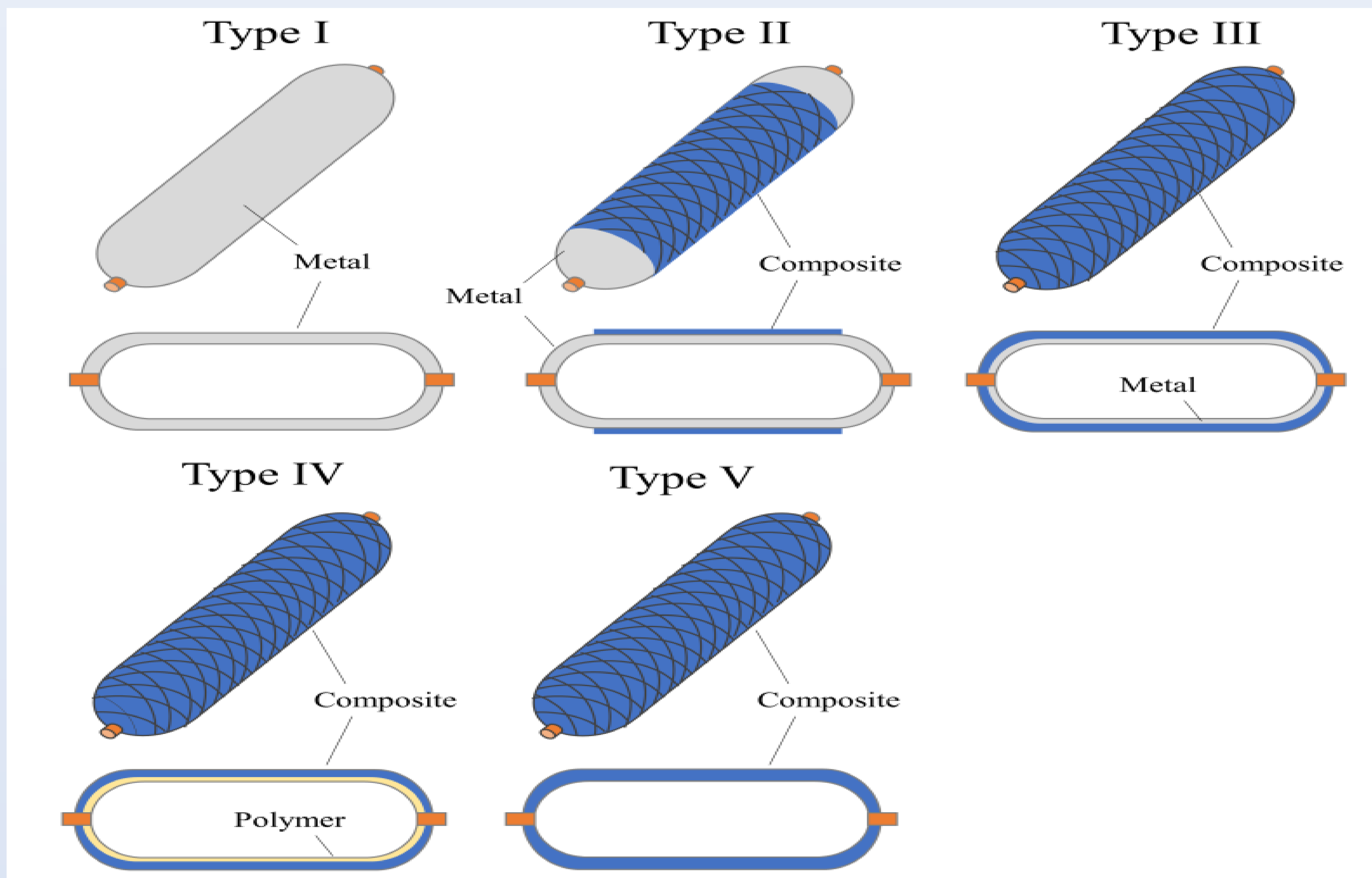
Why Hydrogen? [1],[2]

- It can be produced from and converted to electricity at high efficiency
- Available raw materials for harvesting hydrogen
- A renewable form of fuel
- Unlike other sources of renewable energy, it can be stored and transported
- It does not produce any pollution when obtained from sustainable energy sources
- High energy storage compared to other fuels.

Hydrogen Storage [1],[2]:



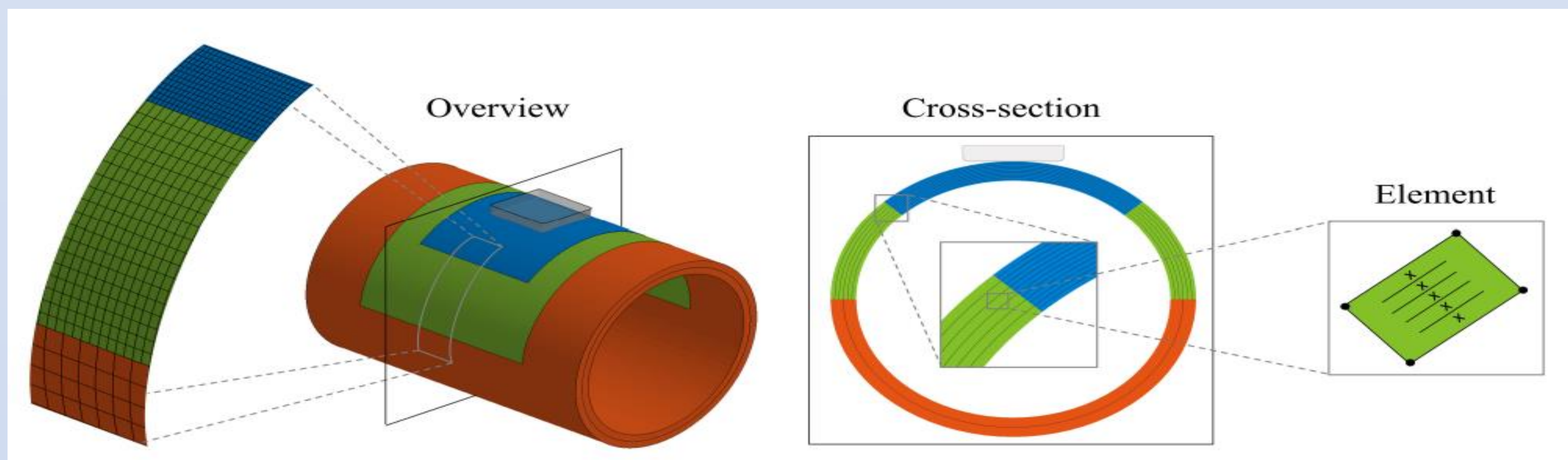
Compressed Gaseous (CGH2) pressure vessel types [2]:



Type IV advantages:

- To withstand 70MPa pressure, it is lighter than the metallic tube due to the high strength-to-weight ratio of composites
- The hydrogen can enter the metals in form of corrosion
- Type V is primarily manufactured from composite material which increases the cost compared to type IV where a high-density polymer liner is used

Modelling the cylindrical vessel:



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EFFECT OF CHLORIDE CONTAMINATION PRIOR TO SPRAYING ON THE CORROSION PERFORMANCE OF THERMAL SPRAY ALUMINIUM (TSA) COATINGS

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Problem / Motivation

- TSA on low carbon steels using electrochemical and surface characterisation techniques have shown that TSA method will effectively minimise corrosion losses in marine environments, especially when this method is ideally applied in compliance with surface cleanliness requirements of available international standards.
- Control of the surface profile (roughness) and the level of contaminants; such as rust, mill scale, dust, oil, grease, and salts is an essential stage before the application of any coating system [1] Various methods and grades of cleanliness are presented in ISO 8501.
- This ideal surface conditions are difficult to achieve on existing offshore platforms in the marine environment where water-soluble salts contamination prior TSA spraying is highly likely .

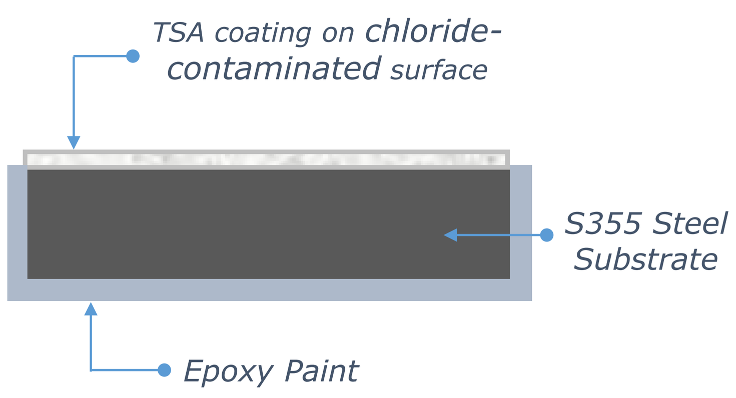

Figure 1. Schematic of substrate with TSA coating

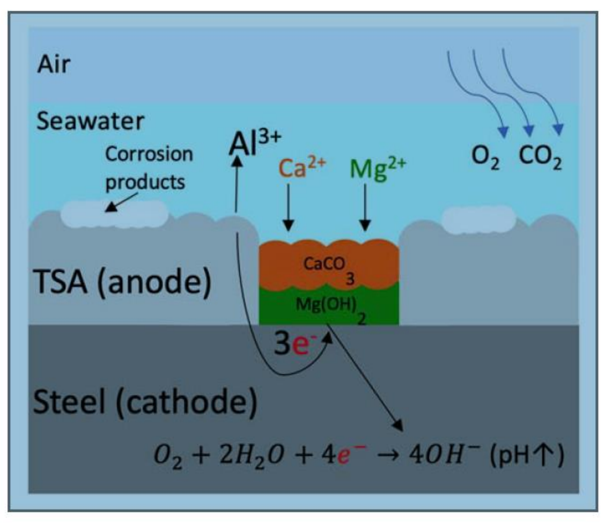

Figure 2. Cathodic protection mechanism of steel substrate by TSA (anodic) coating ***[2]***

Aims and Objectives

OBJECTIVES

Literature Review on surface cleanliness requirement of TSA coating and TSA corrosion performance

Preparation of S355 steel substrates to Sa-3 standard.

Discussion of results with reference to existing literatures

AIM

Study the effect of water-soluble salts contamination prior to spraying on the corrosion performance of TSA coatings on steel substrate

Experimental validation of salt concentration as a factor of immersion time in synthetic sea water

Evaluation of the corrosion performance of TSA coating by Linear Polarization Resistance method.

Validation/calibration of methods with experimental data results

Sample identification and Instrumentation

Sample	Contamination/time	TSA Coating	Experiment Method	Number of samples
S1 – S3	No Contamination	No ☒	Contamination (salt kit)	3
S4 – S6	Contamination C_1 at t_1	No ☒	Contamination (salt kit)	3
S7 - S9	Contamination C_2 at t_2	No ☒	Contamination (salt kit)	3
S10 - 12	Contamination C_3 at t_3	No ☒	Contamination (salt kit)	3
S13 – S17	No Contamination	Yes ☑	LPR[1]	5
S18 – S22	Contamination C_1 at t_1	Yes ☑	LPR[1]	5
S23 – S27	Contamination C_2 at t_2	Yes ☑	LPR[1]	5
S28 – S32	Contamination C_3 at t_3	Yes ☑	LPR[1]	5

[1] Linear polarization resistance (LPR) test is a technique in laboratory evaluations of the level of corrosion activity. This technique requires only within 30 minutes to a few hours to complete.

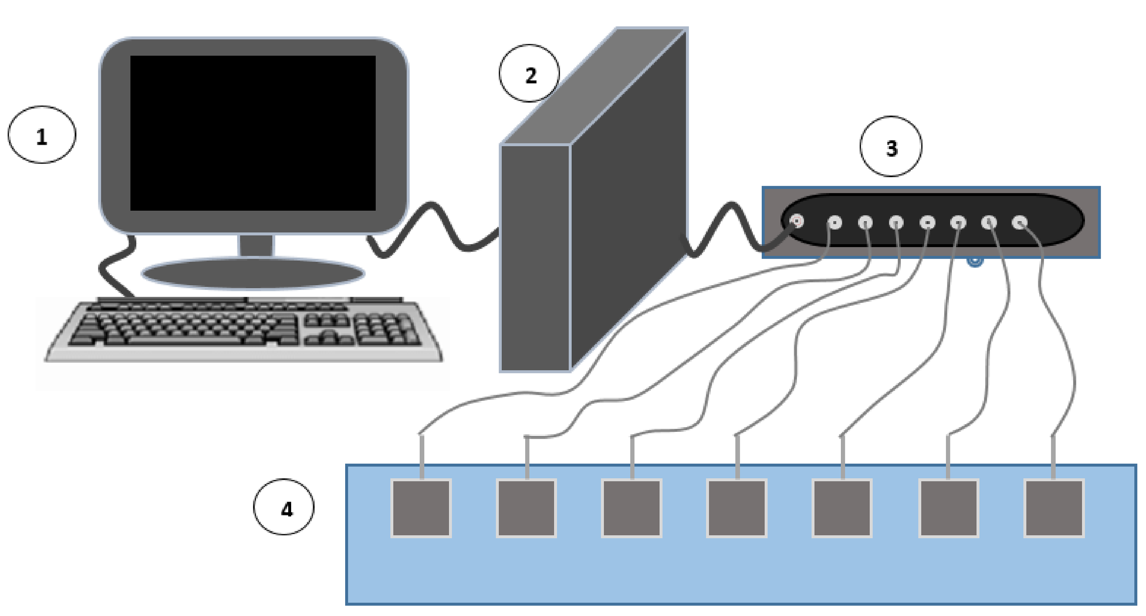

Figure 3. Test Set-up

1. Computer system
2. Potentiostat and controller board
3. Eight-channel multiplexer
4. Corrosion cell with test samples

Experiment Method

Preparation of S355 steel substrate to Sa-3. (ISO 8501-1, BS 7079)

⇨

Evaluate the relationship between immersion time and concentration of soluble salt on substrate surface – (Salt Kit)

⇩

Contaminate substrate by immersion in synthetic sea water at varying immersion time.

⇩

Coating deposition on S355 steel by arc-spray (Arc140) TSA (Al99.5 in accordance with ISO 14919, code number 3)

⇦

Submerge TSA-coated substrate in SSW up to 30 Days and perform LPR to study the corrosion performance of TSA

⇧

Results and Discussion

References

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2. B. Syrek-Gerstenkorn, S. Paul, and A. J. Davenport, "Sacrificial thermally sprayed aluminium coatings for marine environments: A review," Coatings, vol. 10, no. 3, pp. 1–19, 2020, doi: 10.3390/coatings10030267.

SIMULATION OF HYDROGEN DIFFUSION IN DUPLEX STAINLESS STEELS

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Problem/Motivation

- Hydrogen assisted cracking has been recognised as a primary cause of failure in offshore applications of duplex stainless steels coupled with cathodic protection systems.
- Due to the high expense of performing near-accurate experiments, the mechanism of hydrogen ingress from these protective systems into the microstructure of duplex stainless steels is not thoroughly documented.
- An alternative approach is to develop 2D FE models of a flat plate duplex stainless steel to:
  - i. Save the cost of experiments.
  - ii. To determine the hydrogen transport path within the dual-phase microstructure.
  - iii. To determine the effect of strain on hydrogen diffusion.

Aims/Objectives

- To **evaluate existing literature** on hydrogen diffusion in duplex stainless steels, FE simulations of hydrogen diffusion mechanisms in steel microstructure, and the effect of strain on hydrogen diffusion.
- To **develop a 2D model of a flat plate duplex stainless steel** with distinct ferrite-austenite zones.
- To **simulate the steady-state hydrogen diffusion** within the individual phases in DSS by applying Fick's law in ABAQUS.
- To **investigate the hydrogen diffusion behaviour** with respect to internal strain under applied tensile load.
- To **compare the numerical output of hydrogen flux** in the individual phases to existing literature of experimental results.

Previous work

- Hydrogen diffusion analysis of duplex stainless steel sample utilising micrograph-based FE models.
- The influence of hydrogen diffusion around the crack tip in austenitic stainless steel (Homogeneous case).
- Plastic strain impact on hydrogen diffusion was studied using 3D models of U-bend specimens.

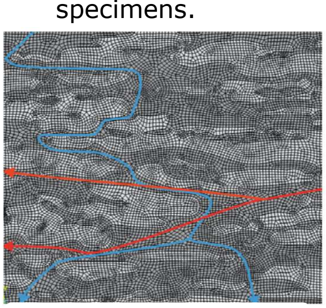

Figure 1. Micrograph–based FE model.

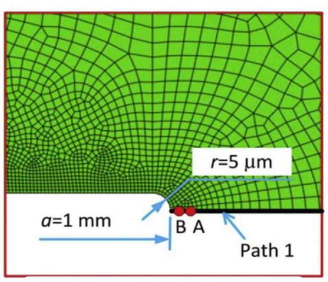

Figure 2. Crack tip analysis of hydrogen using FE.

Ongoing work

- A 2D FE model of a flat plate with ferrite-austenite grains has been created.
- Austenite phases are depicted by "green circular islands," whereas ferrite is represented by red zone.
- Hydrogen charge will be simulated from the top horizontal surface.
- Hydrogen flux and concentration in the pseudo microstructure shown in figure 3 will be analysed.
- Plastic strain influence on hydrogen diffusion will be simulated under tensile load.

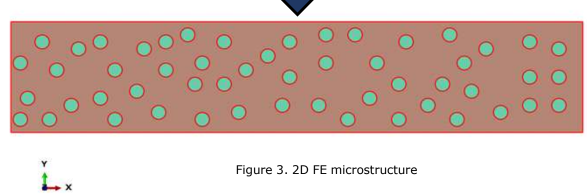

Figure 3. 2D FE microstructure

References

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P. Tao, J. Gong, Y. Wang, W. Cen, and J. Zhao, "Modeling of hydrogen diffusion in duplex stainless steel based on microstructure using finite element method," *International Journal of Pressure Vessels and Piping*, vol. 180, Jan. 2020, doi: 10.1016/j.ijpvp.2019.104031.

FRACTURE SIMILARITIES BETWEEN ASHBY SAMPLES AND PRESSURE VESSELS

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Problem / Motivation

Brittle failure and ductile failure are the two most common failure mechanisms seen in materials. Ductile fracture of material happens with large plastic deformation before fracture (Ref 6). On the other hand, brittle materials, is said to have no significant post – cracking ductility. when subjected to stress, break with little elastic deformation

Pressure vessels are mostly used in industries from oil and gas, to chemical, petrochemical, food industries and so on. These are enclosed containers that retain or hold all form of gases, liquids, vapours at a pressure that is much greater or lower than atmospheric pressure. They must therefore operate within their design parameters such as temperature and pressure and adhere to their safety limits. The accidental release and leakage of their contents is a danger to its surrounding environment. Most vessel pressures fracture undergo brittle failures. Figure 1 and 2 show examples of a brittle fracture of a pressure vessels that were sudden and catastrophic.

Once brittle fracture is initiated, it is a fast and unstable type of fracture. There is no forewarning, and the results can be catastrophic. In view of this, Ashby proposed a unique sample geometry for fracture characterisation of brittle materials. This sample allows for stable mode I crack propagation in brittle materials (Ref 1, 3).

In a facility with pressure vessels, brittle failure is often a high-consequence danger (Ref 2) and to improve on the fracture characterisation of materials for pressure vessels; this current paper assesses the constraint effects and variation on the fracture toughness for a range of Ashby samples geometries and their stress state similarity with the pressure vessels.

Aim

The aim of this work is to assess the constraint effects and variation on fracture toughness for a range of Ashby sample geometries and their stress state similarity with pressure vessels.

Objectives

The objective of this work are as follows;

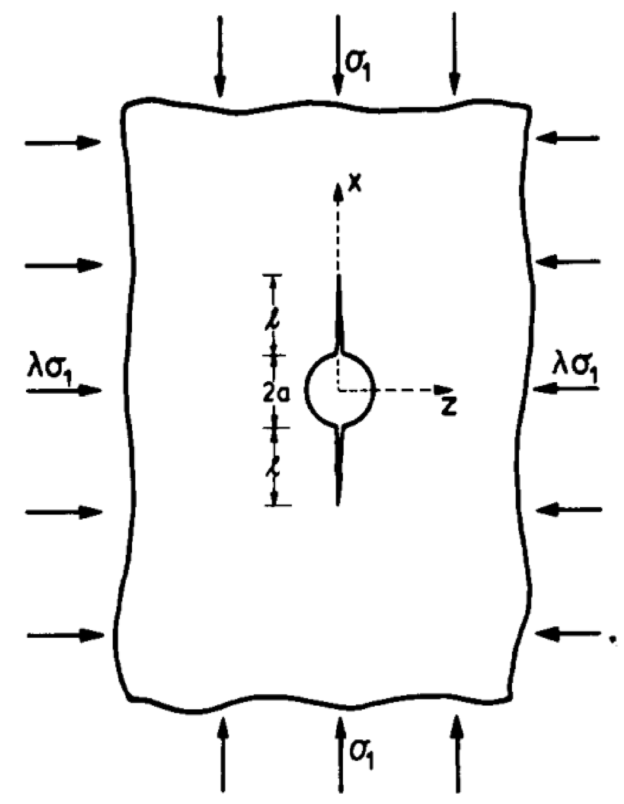
- Conduct a comprehensive literature review in relevant topics required for an understanding of the aim of this work.
- To investigate crack propagation under compression using Ashby sample
- To determine the correlation between Ashby analytical model and finite element crack modelling in Ashby sample and cracked pressure vessels
- To assess the Ashby sample and pressure vessel using J – integral in the vicinity of the crack to estimate the effective crack driving force for the crack initiation
- To characterise the near-tip behaviour of the cracked geometries (elastic-plastic crack tip field) using J-T or J-Q parameter framework.
- To assess the behaviour of fracture toughness using the key characterisation parameters (K, J and Q) of Ashby samples in relation to pressure vessels.

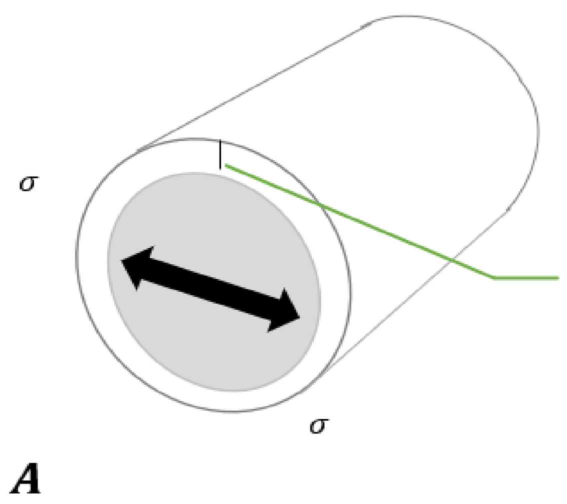
Figure 1 - Brittle fracture of a steel pressure vessel during proof test. (The vessel walls were 149 mm thick, and a 2-tonne fragment was thrown 46 m).

Source: J. Knott (2015), D. J Benac et al (2016)

Figure 2 shows a brittle fracture that occurred suddenly in an NH3 plant

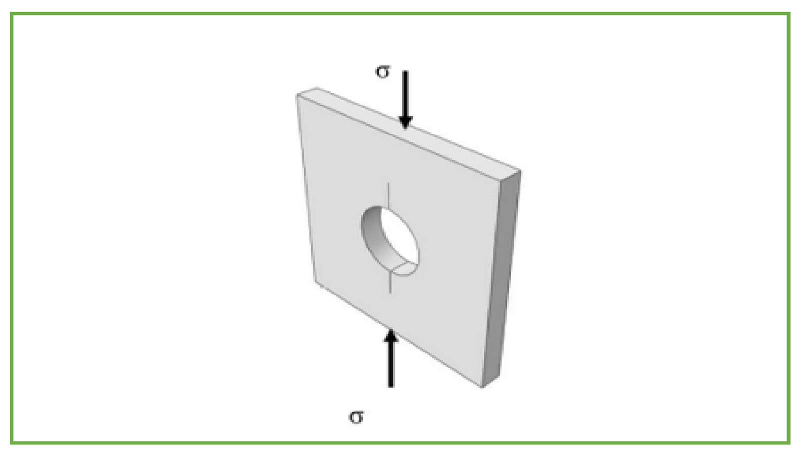
Figure 3 - Crack geometry and co-ordinate system for Ashby 2-Dimensional Calculations





A

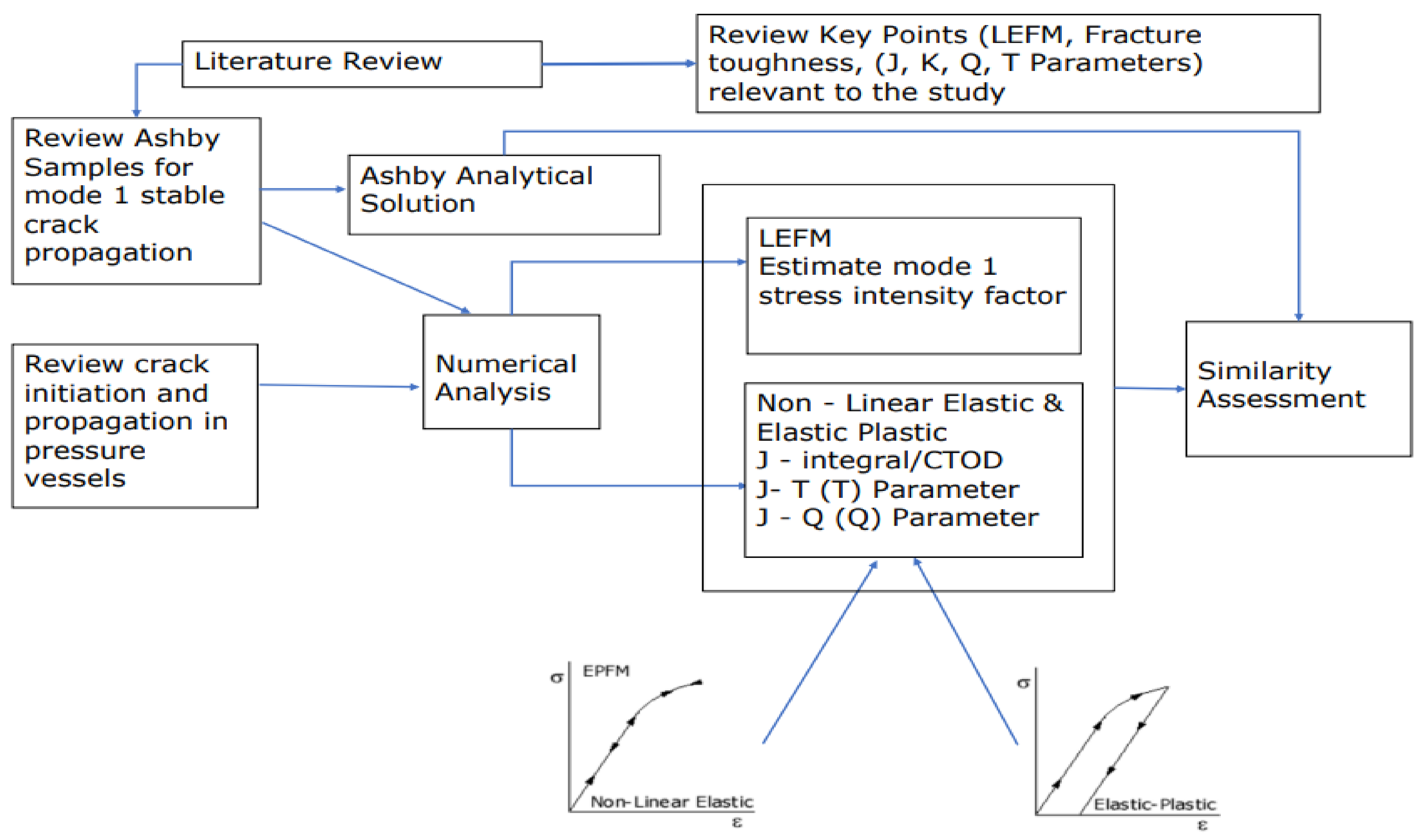
Figure 4 - A and B represents cylindrical pipe (pressure vessel) subjected to internal pressure with cracks under compression



B

Source: N. Bourne et al (2018), C. G. Sammis and M. F. Ashby (1986)

Methodology



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Application of Machine Learning in Estimation of Fracture Toughness of Elastic-Plastic Specimens

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Problem / Motivation

1. Different Specimens are used to determine fracture parameters:

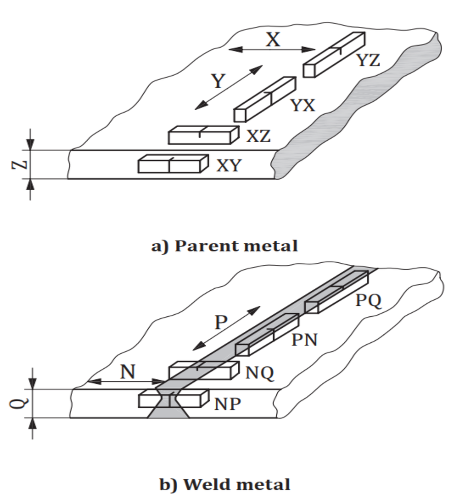
   .Compact Tension (CT)
   .Middle Tension (MT)
   .Single-Edge Notched Tension (SENT)
   .Single-Edge Notched Bend (SENB or three-point bend)
   .Extended Compact Tension (ECT)
   .Centre Cracked Tension (CCT)
   .Surface Cracked Tension (SCT)
   .Composite Materials under modes I, II, and III loading

2. Specimens consist of a vast range of specific geometries to map their driven fracture parameter to the actual part used in the project.

3. Analysis of specimens either by a lab test or FE analysis requires a high cost, in terms of material or analysis time.

4. Machine learning methods have been established in numerous scientific fields to predict the future performance of a phenomenon by using available previous data.

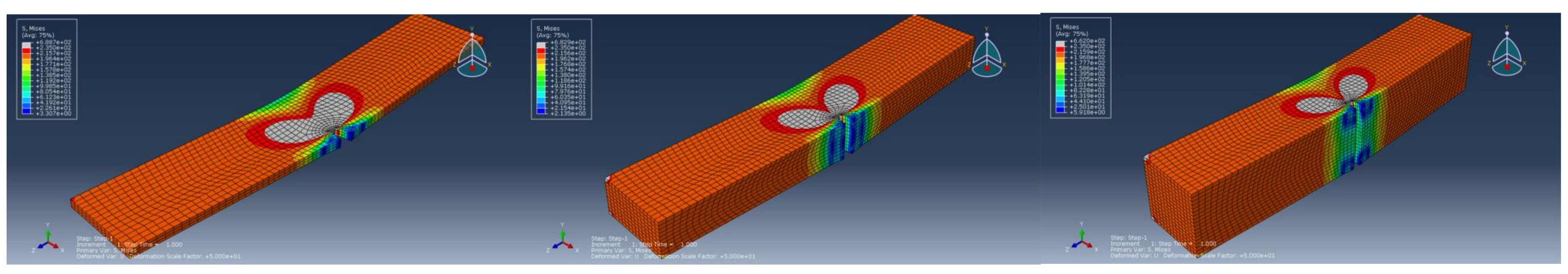
5. The main aim of this project is to assess the effectiveness of the ML methods to predict the solution of elastic-plastic fracture analysis of the test specimens.



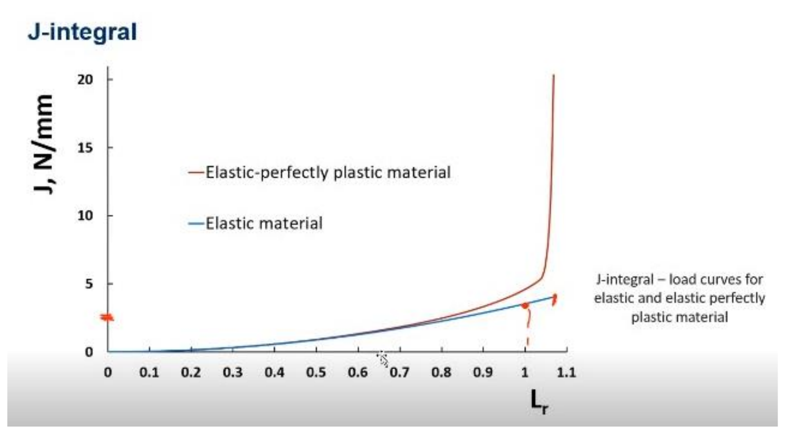
Methodology

1. For using Machine learning algorithms, an initial set of reliable data is needed. These data were extracted by Finite Element analysis of the stationary crack model using the contour method in Abaqus.

2. Total 40 FE models were developed for four different ligaments of 20, 30, 40, and 50 mm and ten different thicknesses from 10 mm to 100 mm.



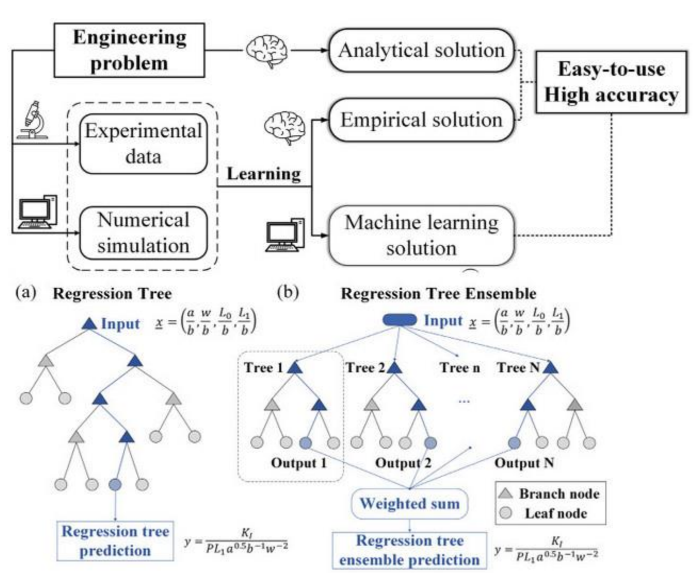
3. In order to perform fracture analysis to estimate 'J' values, the specimens were loaded with their associated limit load.



$$P_L = W \cdot t \cdot \sigma_y \cdot f_L$$

$$f_L = \begin{cases} (\gamma/1.702)\cdot\left(1-\alpha-1.232\alpha^2+\alpha^3\right) & 0 \le \alpha \le 0.545 \\ \gamma\cdot\left[\sqrt{\left(0.794-(1-\alpha)\right)^2+0.5876\cdot(1-\alpha)}-\left(0.794-(1-\alpha)\right)\right] & 0.545 < \alpha < 1 \end{cases}$$

4. Then the extracted 'J' values will be used to train ML Model in order to predict 'J' values for broader range of specimen geometries.



Regression-tree-based solutions [1]

Review of the Scientific Background and Literature

1. The crack behaviour is formulated in two significant regimes.

2. In material with linear behaviour, the main parameter which defines stress and strain values around the crack tip is the stress intensity factor [2].

$$\sigma_{ij} = \frac{K}{\sqrt{2\pi r}}\tilde{\sigma}_{ij}(\theta)$$

$$\varepsilon_{ij} = \frac{K}{\sqrt{2\pi r}}\tilde{\varepsilon}_{ij}(\theta)$$

3. In material with nonlinear behaviour, the stress intensity factor no longer is applicable around the crack tip. In this situation, another parameter is used to describe the mentioned item which is called the 'J' integral proposed by J. R. Rice [3].

$$\sigma_{ij} = \sigma_0\left[\frac{E \cdot J}{\sigma_0^2 \cdot I_n \cdot r}\right]^{1/n+1}\tilde{\sigma}_{ij}(\theta, n)$$

$$\varepsilon_{ij} = \varepsilon_0\left[\frac{E \cdot J}{\sigma_0^2 \cdot I_n \cdot r}\right]^{n/n+1}\tilde{\varepsilon}_{ij}(\theta, n)$$

4. .Jin has investigated the effect of different loading conditions on elastic pined SECP (Single edge crack plate) specimens consisting of various geometrical parameters. He derives the solution of stress intensity factors by using stress components parallel to the edge of the crack front face; this component is known as T stress. He publishes his results in terms of numerous tables which consist of complete solutions of stress intensity factors for specimens with various geometries [4].

z/t	Uniform			Linear			Parabolic			Cubic		
	F	V	W	F	V	W	F	V	W	F	V	W
$t/W = 0.1$												
0	1.4535	0.5144	−0.6499	0.6307	0.3297	−0.4241	0.4022	0.2298	−0.2906	0.2816	0.1664	−0.2076
0.0346	1.4534	0.5144	−0.6533	0.6305	0.3295	−0.4258	0.4021	0.2297	−0.2916	0.2816	0.1663	−0.2083
0.1001	1.4524	0.5165	−0.6783	0.6296	0.3298	−0.4384	0.4015	0.2298	−0.2993	0.2811	0.1664	−0.2135
0.161	1.4505	0.5203	−0.7269	0.6279	0.3303	−0.4624	0.4002	0.2299	−0.3139	0.2802	0.1665	−0.2235
0.2176	1.4475	0.5256	−0.8006	0.6253	0.3311	−0.4984	0.3984	0.2303	−0.3359	0.2789	0.1668	−0.2385
0.2702	1.4431	0.5324	−0.9047	0.6217	0.332	−0.5484	0.3959	0.2308	−0.3664	0.2771	0.1672	−0.2595
0.3191	1.4368	0.5403	−1.0502	0.6169	0.3331	−0.6167	0.3926	0.2316	−0.4083	0.2747	0.168	−0.2884
0.3646	1.4276	0.5492	−1.2599	0.6103	0.3343	−0.7128	0.3881	0.2328	−0.4675	0.2716	0.1691	−0.3293
0.4069	1.4136	0.5585	−1.5888	0.6009	0.3355	−0.8594	0.3819	0.2344	−0.5583	0.2673	0.1707	−0.3924
0.4462	1.3899	0.5653	−2.2089	0.5864	0.3356	−1.1279	0.3726	0.2362	−0.7261	0.2608	0.1724	−0.5094
0.4827	1.3423	0.2544	−3.2018	0.56	0.2055	−1.553	0.3559	0.1564	−0.9924	0.2492	0.1172	−0.6955
0.5000	1.1833	0.1095	−11.4792	0.4881	0.1594	−4.9707	0.3105	0.1292	−3.1642	0.2175	0.0982	−2.2165
$t/W = 0.2$												
0	1.4493	0.4804	−0.3115	0.6334	0.3213	−0.2257	0.4053	0.2284	−0.1626	0.2842	0.1668	−0.119
0.049	1.449	0.4808	−0.3165	0.6331	0.3213	−0.2287	0.4051	0.2283	−0.1646	0.284	0.1667	−0.1204
0.1361	1.4472	0.4832	−0.3485	0.6312	0.321	−0.2479	0.4036	0.2275	−0.177	0.2829	0.1659	−0.129
0.2098	1.4438	0.4875	−0.4064	0.6278	0.3203	−0.2816	0.401	0.226	−0.1986	0.2809	0.1645	−0.1438
0.2722	1.4388	0.4931	−0.4896	0.623	0.3193	−0.328	0.3973	0.2241	−0.2278	0.2782	0.1628	−0.1638
0.325	1.432	0.4998	−0.6021	0.6167	0.3178	−0.3875	0.3925	0.2219	−0.2647	0.2746	0.161	−0.1891
0.3698	1.4228	0.5071	−0.7536	0.6086	0.316	−0.4635	0.3866	0.2198	−0.3113	0.2703	0.1593	−0.2209
0.4076	1.4102	0.5145	−0.9649	0.5984	0.3137	−0.5639	0.3793	0.2178	−0.3725	0.265	0.1581	−0.2629
0.4397	1.3922	0.5211	−1.2846	0.585	0.3108	−0.708	0.3701	0.2164	−0.4606	0.2585	0.1574	−0.3235
0.4668	1.3636	0.5249	−1.8624	0.5662	0.3072	−0.9562	0.3575	0.2157	−0.6134	0.2496	0.1576	−0.4294
0.4898	1.2968	0.5015	−3.5112	0.5295	0.2955	−1.6352	0.334	0.2121	−1.0368	0.2331	0.156	−0.7243
0.5000	1.1315	−0.0833	−11.7734	0.4547	0.0779	−4.9612	0.2869	0.0781	−3.1319	0.2003	0.0629	−2.1866

Stress intensity factor K and T-stresses (T11 and T33) results [4]

5. Liu et al. have used the machine learning method to demonstrate advantages over analytical methods in the estimation of fracture toughness values of the microfabricated brittle ceramic microcantilevers [1].

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