Computational Fracture Mechanics: Evaluation of The Structural Integrity in a Penstock Applying the BS7910 Standard and Finite Element Analysis

G O Barrionuevo¹, B A Guerrero² and M Walczak¹

¹ Department of Mechanical and Metallurgical Engineering, School of Engineering, Pontificia Universidad Católica de Chile, Av. Vicuña Mackenna, 4860, Macul, Santiago, Chile.
² School of Mechanical Engineering, University of Adelaide, Adelaide, SA 5005, Australia.
¹gobarrionuevo@uc.cl

Abstract. The present work aims to determine the structural integrity of penstocks, applying the BS7910 standard and finite element analysis (FEA). For the study of fracture mechanics in thin-walled cylinders that have defects inside, the structural integrity of the element is determined through a failure assessment diagram (FAD) where the fracture failure index (Kr) is graphed versus plastic collapse index (Lr). Based on the locus of the initial point of failure, the safety factor is calculated, and it is defined if the element is fit for service or if corrective action must be taken to continue operating; later, crack growth is analyzed, where the critical point of rupture of the penstock and therefore its useful life is determined. To contrast results, a simulation of fracture mechanics is performed in ANSYS, where the stress intensity factor (KI) is determined using the fracture tool, and the useful life of the element is also calculated through a fatigue analysis. The use of tetrahedral elements is recommended for the overall meshing and a cobweb configuration for meshing at crack-tip. Finally, the results obtained are compared, where the mean average percentage error of 3.24% was obtained, denoting the usefulness of the two methods as well as the simplicity of the Paris’ law.

1. Introduction
Traditionally, the design of a structural element is carried out under the assumption that the material is continuous, homogeneous, and without defects. Besides that, the supported stress will be less than its yield strength. However, defects in materials are a reality, so when designing, the presence of these defects must be considered to guarantee the safety of people in the first place and ensure the structural integrity of the element. Different failure theories are used in traditional design (Rankine, Saint Venanat, Von Mises, Tresca, Mohr-Coulomb, and so on), depending on if the material is ductile or brittle. However, fracture mechanics improve product design, as well as manufacturing and inspection processes to control the spread of defects that could lead to failure of its components, without the need to use arbitrary safety factors [1].

For the design of pressure vessels, penstocks, storage tanks, and boilers, it is necessary to comply with internationally established standards and codes. The ASME B31.1 [2] code for pressure piping, the API
The 579/ASME FFS [3] standard that determines the suitability for service of structural elements or the BS7910 [4] standard, which provides methods to evaluate the acceptability of flaws in metallic structures.

Failure of a mechanical element in service occurs due to plastic deformation, fracture, or fatigue. Classical failure theory assumes that a plate subjected to a load will have a uniform distribution of forces along with the plate; however, it is known that at the time of manufacturing or during service, small imperfections are generated in it, which generate stress concentrators [5]. Fracture mechanics is a discipline that links, through analytical expressions, the geometry of the cracked component and the loads to which it is subjected [6]; it is based on the study of displacements, deformations, and stresses in the vicinity of the crack head. Erdogan [7] explored some of the tools that are used today as the stress intensity factor \( (K_I) \), where \( \sigma \): is the applied stress, and \( a \): flaw extension.

\[
K_I = \sigma \sqrt{\pi a}
\]  

(1)

It is known that all materials, even the most fragile ones, can develop a certain degree of plasticity at the crack-tip; this improves the strength of brittle fracture [8]. The developed plastic region is known as the crack-tip plastic zone, and according to its extension, it can be approached by three different sub-disciplines [7]:

1. Linear elastic fracture mechanics (LEFM): discipline used when the extension of the plastic deformation is confined to a small area above the head of the flaw, and the deformation of the rest of the body has an elastic behavior.
2. Elastic-plastic fracture mechanics (EPFM): applied when the plastic area on the head of the fissure has a considerable extension, similar to crack length.
3. Plastic fracture mechanics (PFM), used when the fracture is preceded by generalized plastic deformation.

According to Behal & Solodyankin [9], LEFM is enough to characterize the fracture mechanics in 3D objects. LEFM theory assumes that the end of the crack ends in a point, which means infinite stress in that area [10]. In reality, the end has a radius, and the stresses tend to relax due to yielding (figure 1), this radius is known as plasticity radius \( (r_p) \) [11], which is given by the following expression, where \( \sigma_y \) is the yield strength.

\[
r_p = \frac{1}{6\pi} \left( \frac{K_I}{\sigma_y} \right)^2
\]  

(2)

The elastic zone is controlled by the evolution of the \( K_I \) and must be large enough so that the plastic zone is within it, between 2 to 5\% of the length of the crack [5].

Figure 1. Plastic zone extension in LEFM
In recent years, the term *structural integrity* has emerged, which consists of analyzing an element and determining its suitability for service [12]. Structural integrity analysis contributes to decision-making and maintenance-scheduling, creating an economic and safety culture for mechanical component service [13]. The Welding Institute established a failure assessment diagram (FAD) to evaluate the structural integrity defining the fracture failure index ($K_r$) and plastic collapse index ($L_r$), a complete description of the road map could be found in [14].

**Computational Fracture Mechanics**

The fundamental objective of computational mechanics is the development and implementation of computational models for the characterization and prediction of the behavior of structural and mechanical components. Computational mechanics is based on the use of numerical methods such as finite differences, finite elements, or boundary elements [15]. The basis of the finite element analysis (FEA) is established in the decomposition of the domain into a finite number of subdomains (elements), these elements are interconnected by a series of points called nodes, which guarantee the continuity of the displacement field, the equations that govern the behavior of the domain also govern the behavior of each element. In this way, it is possible to go from a continuous system with infinite degrees of freedom, to a discrete system with a finite number of degrees of freedom [16]. The displacement ($x$) is calculated applying Hooke’s law, where $K$ is the stiffness matrix and $F$ the global load vector.

$$[K][x] = [F] \quad (3)$$

According to Chu & Liu [17], the FEA is effective for predicting the behavior of crack growth due to fatigue. Sun & Zhang [18] developed a method for the evaluation of crack growth using Ansys Mechanical APDL with its software language (UIDL). In addition, Jensen [19] improved this method using the interaction between Matlab and Ansys APDL. Behal & Solodyankin [9], simulated the crack growth and estimated the life of structural elements in 3D, to determine the growth rate of the crack they used a modified Forman’s experimental equation and also used FEA in Ansys, where it was determined that a linear elastic analysis is sufficient to characterize fracture mechanics in ductile materials.

In the analysis of crack propagation, quadrilateral and hexahedral elements are used for problems in two and three dimensions, respectively. Zakavi et al. [20] recommend 8 and 9 node Lagrangian quadratic elements for two-dimensional problems, and 20 and 27 node Langrangian three-dimensional problems. The most efficient mesh design for the region around the crack-tip is the cobweb configuration, which consists of concentric rings of elements arranged concentrically around the head of the flaw, the first ring of which consists of singular elements. The design of the cobweb configuration allows a smooth transition from a fine mesh in the vicinity of the crack to a thick mesh in the rest of the component [21].

Regarding the current work, first, BS7910 standard is applied to determine the fracture locus and determine the suitability of the element, this assessment is based on the determination of the fracture and plastic collapse index. Stress intensity factor is compared to fracture toughness for fracture assessment, and the reference stress is compared to yield stress to determine if the element fails by plasticity; then, an FEA is employed to assess $K_I$, parametrizing the flaw depth ($a$), and flaw length ($c$). Through a fatigue assessment, the fatigue crack growth is evaluated following the Paris law, and the two methodologies are compared.

2. **Methodology**

2.1. **Case study**

For the design of a penstock (figure 2), it is regularly considered as thin-walled cylindrical bodies, if there is a significant difference between the wall thickness ($t$) and pipe diameter ($D$) [22].

$$\frac{D}{t} > 10 \quad (4)$$

For thin-walled vessels, the stress state is considered as plane-stress; as a result of internal pressure, mechanical stress called hoop stress ($\sigma_\theta$) is generated, given by the following expression:
\[
\sigma_0 = \frac{P r}{t}
\]  
(5)

Where, \( P \) is the internal pressure, and \( r \) pipe inner radius, and \( t \) wall thickness.

Due to water hammer, cyclic loads must be considered, and therefore the penstock should be designed to avoid fatigue failure. Furthermore, residual stresses remain in a component in the absence of external loads and originate in manufacturing processes such as welding. In a multi-pass weld heat-affected zone (HAZ) is subjected to straining and aging, reducing toughness [23]. BS7910 recommends a magnitude of around 20 \% of the yield stress (\( \sigma_y \)). The maximum stress concentration factor is the sum of the hoop stress and residual stress around the weld (figure 3).

Fracture toughness (\( K_{IC} \)) is the maximum value that \( K_I \) can reach, and it is related to energy absorption and could be calculated through [4]:

\[
K_{IC} = \left[ (12\sqrt{Cv} - 20) \left( \frac{25}{t} \right)^{0.25} \right] + 20
\]  
(6)

Where \( Cv \) is the energy during the impact test.

Nominal parameters for the case study are presented in table 1:

| Parameter                  | Magnitude | Unit    |
|----------------------------|-----------|---------|
| Pipe inner diameter        | 2.2       | m       |
| Wall thickness             | 30        | mm      |
| Static head of water       | 4.9       | MPa     |
| Water pressure at hammer   | 6.86      | MPa     |
| Crack size                 | 4         | mm      |
| Internal pressure change   | 10000     | Times/year |

The nominal chemical composition of the material employed for the construction of pressure vessel is ASTM 537 class I, (table 2). The mechanical properties are listed in table 3.
Table 2. Chemical composition of A537 steel alloy [24].

| Elements (wt %) | C   | Si  | Mn  | P   | S   | Cr  | Cu  | Mo  | Ni  |
|----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|                | 0.24| 0.15-0.50 | 0.7-1.35 | 0.035 | 0.035 | 0.25 | 0.35 | 0.08 | 0.25 |

Table 3. Mechanical properties of A537 steel alloy [24].

| Plate thickness | Yield strength | Tensile strength | Modulus of elasticity | Elongation |
|-----------------|----------------|-----------------|-----------------------|------------|
| mm              | MPa            | MPa             | GPa                   | %          |
| 16 – 40         | 345            | 550             | 200                   | >18        |

2.2. Structural integrity: BS7910 procedure

For the evaluation of structural integrity, the British standard BS7910 (Guidance on Methods for Assessing the Acceptability of flaws in metallic structures) has been employed. Which is carried out through a failure evaluation diagram (FAD), where the vertical axis represents the fracture index (Kr), which shows the relationship between KI and KIC. In contrast, the horizontal axis represents the relationship between the supported stress (σref) and σY or plastic collapse index, denoted by (Lr). The location of Kr and Lr index provides the coordinates of the evaluation point or the geometric location of the failure. The positions of the points are compared with the FAD limit curve to determine the acceptability of the structure (figure 4).

Figure 4. Procedure for flaw locus location in the FAD [3].
BS7910 has three levels of evaluation; at each level, the acceptability of the defect can be evaluated, and the calculation can be iterated to determine the limit value of a parameter such as the crack size, the maximum stress supported, or the fracture toughness. The limit values can be obtained through analytical calculations, or through the location in the FAD to determine which point contacts the FAD limit curve [4].

- **Level 1**: it is a very conservative evaluation process, requires a simple analysis of failure evaluation diagrams and fracture mechanics.
- **Level 2**: determines the specific failure of a material, estimates the interaction between fracture and plasticity.
- **Level 3**: consider the effects of ductile tear and plasticity through the calculation of the integral-J, which implies a direct calculation of the effects of plasticity.

British Standard BS7910, recommends the use of the following equation for the evaluation of materials where welding processes were employed [4]:

$$K_r = (1 - 0.14 Lr^2) [0.3 + 0.7 \exp(-0.65 Lr^6)]$$

One of the critical aspects to take into account is the stress intensity correction factor ($Y$) [20], which modifies the magnitude of $K_i$. $Y$ depends on the geometry of the flaw (figure 5).

$$K_i = Y \sigma \sqrt{2a}$$

**Figure 5. Stress intensity correction factor Y for surface flaws in tension [4].**

For the characterization of plastic collapse, it is necessary to determine the referential stress ($\sigma_{ref}$), which is a measure of the plasticity at the crack-tip [25].

$$\sigma_{ref} = \frac{3\sigma + [(3\sigma\alpha)^2 + 9\sigma^2 (1 - \alpha)^2]^{0.5}}{3(1 - \alpha)^2}$$

Where $\sigma$ is the hoop stress, and $\alpha$: a geometric constant given by:
\[ \alpha = \frac{a}{1 + \frac{B}{c}} \]  \hspace{1cm} (10)

2.3. Computational fracture mechanics: Ansys procedure

A classical finite element analysis (FEA) consists of three steps: pre-processing, solution, and post-process [26][27]. When working with a 3-D element, it is convenient to distinguish between some areas for meshing process (figure 6). In general, two areas of importance are distinguished, the first represents the meshing of the entire element or the global mesh, and the second represents the meshing in the fracture zone, the refined mesh. It is important to distinguish a third zone (transition mesh), where there is a smooth transition between global mesh and refined mesh [28].

In figure 6, seven zones could be distinguished: 1) the solid, 2) global mesh, 3) buffer zone, 4) fracture limit, 5) fracture zone, 6) front of the flaw, and 7) discontinuity planes. For global meshing (zones 1, 2, 3) tetrahedral elements are recommended to ensure the precision of the results, for zones 4 and 5 a smooth transition mesh is recommended, and in zone 6 and 7 a spider-type mesh is used to represent the singularity of the elements at the crack-tip.

The main objective of the simulation is to determine the $K_I$, in a penstock that has an axially oriented flaw inside, figure 7 shows the geometry evaluated at the left side and in the right, the flaw location.
2.4. Crack propagation
Fatigue is a process of accumulating damage, cracking, and fracturing of components subjected to fluctuating, variable, or cyclic loads [29]. In order to estimate the useful life of a structural element subjected to cyclic stresses, research has shown a correlation between crack propagation and the number of fatigue load cycles called crack growth rate. For a constant amplitude load, the crack growth rate can be described by the Paris’ law:

$$\frac{da}{dN} = C \Delta K_i^m$$  \hspace{1cm} (11)

Where \( C \) and \( m \) are constants that depend on the material [30]. From equation 11, a mathematical model is obtained to determine the number of cycles (\( N \)) that an element withstands before the fracture, given by the following expression:

$$N = \int_{a_i}^{a_f} \frac{da}{C \left( Y \Delta \sigma \sqrt{\pi a} \right)^m}$$  \hspace{1cm} (12)

Where \( a_i \) and \( a_f \) represent the initial and final crack length, respectively. Finally, the useful life of the penstock could be calculated using the following equation:

$$\text{life (years)} = \frac{N}{\text{cycles per year}}$$  \hspace{1cm} (13)

3. Results and Discussions
3.1 BS7910 results
Table 4 summarizes the results obtained by applying the BS7910 standard; the values used to locate in the FAD are fracture index (\( Kr \)) and the index for plastic collapse (\( Lr \)).

| Parameter                          | Symbol | Magnitude | Unit   |
|------------------------------------|--------|-----------|--------|
| Minimum stress                     | \( \sigma_{\text{min}} \) | 179.78    | MPa    |
| Maximum stress                     | \( \sigma_{\text{max}} \) | 251.74    | MPa    |
| Alternating stress                 | \( \sigma_a \)        | 35.96     | MPa    |
| Mean stress                        | \( \sigma_m \)        | 217.74    | MPa    |
| Residual stress                    | \( \sigma_{\text{res}} \) | 69        | MPa    |
| Stress intensity correction factor | \( Y \)            | 0.75      | -      |
| Primary stress intensity factor    | \( K_{ip} \)         | 478.14    | MPa/\( \sqrt{\text{mm}} \) |
| Secondary stress intensity factor  | \( K_{is} \)         | 183.41    | MPa/\( \sqrt{\text{mm}} \) |
| Fracture toughness                 | \( K_{ic} \)         | 2717.03   | MPa/\( \sqrt{\text{mm}} \) |
| Fracture index                     | \( Kr \)             | 0.24      | -      |
| Reference stress                   | \( \sigma_{\text{ref}} \) | 186.87    | MPa    |
| Plastic collapse index             | \( Lr \)             | 0.54      | -      |

Figure 8 shows the assessment point at no load (A), due to the residual stresses originated in the welding process and the flaw locus (B), which is in the safety zone, and therefore, the structural integrity of the element, is guaranteed. To determine the safety factor, under the penstock is operating, a line is plotted,
starts from the assessment point at no load (A), goes through the point (B) and intersects with the FAD limit curve (C), using the AC/AB ratio the safety factor is obtained.

Through the BS7910 application, two values of $K_I$ were obtained, the first one ($K_{IP}$) product of the applied stress, and the second one ($K_{IS}$) product of the residual stresses. The global $K_I$ is the sum of both, with a value of 661.46 MPa$\sqrt{\text{mm}}$; this value is well below the $K_{IC}$ (2717.03 MPa$\sqrt{\text{mm}}$). Once know $K_{IC}$, it is possible to determine the maximum stress supported by the penstock, through equation 8 is determined $\sigma_x = 468.9$ MPa.

Finally, knowing $K_I$ to validate the LEFM applicability, the plasticity radius is calculated with equation 2, where $r_p = 0.195$ mm; equivalent to 4.875 % of the flaw depth, these results are in accordance with [21].

3.2 FEA results
The parameter that characterizes fracture mechanics is the stress intensity factor, which reaches its maximum value at the crack-tip (figure 9).

The FEA was developed as a linear elastic problem, due to the characteristics of the material employed, with elongation percentage is superior to 18 %, which imply a ductile material. This approach was validated analytically, through the characterization of the plasticity radius, which demonstrates that FEA is appropriate to be applied to fracture mechanics assessment practice of penstocks based on LEFM.
3.3 Crack propagation

To determine $K_I$ in each iteration, a constant relationship is maintained between the extension and the depth of the crack $c = a + l$ (Fig. 10), with which a constant value is obtained for the geometric correction factor $Y = 0.75$ (figure 5).

Table 5 shows the evaluation of fatigue life applying Paris’ law, with $C=1 \times 10^{-11}$, and $m=3$.

| Parameter                | Magnitude | Unit   |
|--------------------------|-----------|--------|
| Initial size of detected crack | 4         | mm     |
| Critical flaw size       | 19        | mm     |
| Stress variation         | 35.96     | MPa    |
| Cycles number            | 495486.8  | -      |
| Total life               | 49.5      | years  |

From figure 11, the critical flaw size is obtained, tending to a failure by a ductile fracture due to the elastic characteristics of the material. When the crack depth exceeds 19 mm, dynamic crack growth begins and its subsequent failure.
ANSYS allows the parameterization of several factors from the model geometry, in this case, the depth \((a)\) and extent \((c)\) of the crack were parameterized to simulate the crack growth, with which the value of the \(K_I\) is obtained in each iteration (figure 12).

Through the ANSYS fatigue tool (Fig. 13), and applying the Goodman criterion, with a fluctuating distribution of stresses between a minimum value given by the static head of water and a maximum value given by the effect of water pressure hammer, it is obtained that for the area of interest life fluctuates between 34750 and 535110 cycles.

![Figure 11. Fatigue crack growth.](image1)

![Figure 12. \(K_I\) evaluation and parametrization in ANSYS.](image2)
3.4 Results comparison
Since the parameter chosen for the characterization of fracture mechanics in the present study was the stress intensity factor ($K_I$), a comparison of each value is shown in figure 14 as the crack size grows. The FEA of fracture mechanics has generated satisfactory results since a mean average percentage error of 3.24% was obtained concerning the BS7910 standard, with a minimum value of 0.054 and a maximum of 9.726%. Besides, the life calculated by BS7910 applying the Paris’ law gave a result of 49.5 years, and by FEA, an average value of 44 years was obtained, demonstrating the effectiveness of the FEA in the assessment of LEFM problems [31].

4. Conclusions
This paper aims to evaluate the structural integrity in a penstock with a detected flaw inside the pipe. Two methods were applied to determine if the component is suitable to work or if corrective action should be taken to prolong the useful life of the pipe. The following conclusions can be drawn:

(1) BS7910 presents a robust methodology to assess different flaws and taking into account the effect of residual stress around the welded zone; in that sense, the determination of the stress intensity correction factor is vital to determine the fracture ratio and determine the locus of the flaw. Through the FAD, the security factor has been established with a value of around 2.05, which determines the aptitude for service.
Fracture toughness is determined with data provided by the manufacturer on the Charpy test, it relates the impact energy and the thickness of the sheet, obtaining a value of 85.92 MPa√m, these data are supported by Welding Research Supplement, where results for fracture toughness of A537-1 steel with a range between 84.6 and 92.3 MPa√m were published.

The fatigue assessment shows that the critical point before the brake is at 19 mm, knowing the fracture toughness was possible to determine the maximum stress that the penstock could hold up, around 470 MPa.

The characterization of the $K_I$ employing FEA has generated satisfactory results. The radius of the plasticity of less than 5% of the crack size has been determined, which ensures that it is a linear elastic problem.

Acknowledgments
This study has been completed under the financial support of the State Secretariat for higher education, science, technology and innovation (SENESCYT) grant number ARSEQ-BEC-000329-2017 and the Research Centre for Nanotechnology and Advanced Materials (CIEN-UC).

References
[1] Pisarski H 2013 Assessment of flaws in pipeline girth welds - A critical review *Weld. World* **57** 933-945
[2] The American Society of Mechanical Engineers 2012 ASME B31.1-2012 Power Piping ANSI Stand B31.1
[3] American Petroleum Institute 2009 API 579-2/ASME FFS-2 2009- - Fitness-For-Service Example Problem Manual Society
[4] BS-7910 2005 Guide to methods for assessing the acceptability of flaws in metallic structures,” *BSI Stand. Publ.* 3 306
[5] Christensen RM 2013 The Theory of Materials Failure *Theory Mater. Fail.*
[6] Anderson TL 2017 Fracture Mechanics, Fundamentals and Applications *CRC press*
[7] Erdogan F 2000 Fracture mechanics *Int. J. Solids Struct.* **37** 171–183
[8] Arnoult XC, Růžičková M, Kunzová K and Materna A 2016 Short review: Potential impact of delamination cracks on fracture toughness of structural materials *Frat. ed Integrita Strutt.* **10** 509–522
[9] Běhal J and Solodyankin K 2012 Crack growth simulation in the course of industrial equipment life extension 20th SYSFEM ANSYS Users’ Gr. Meet. Conf. 1-9
[10] Nowell D and Nowell SC 2019 A comparison of recent models for fatigue crack tip deformation,” *Theor. Appl. Fract. Mech.* **103** 102299
[11] Andrade L 2013 Design of penstock pipe for a hydroelectric pumped storage station *J. Chem. Inf. Model.* **53** 1689–1699
[12] Xin W, Yan P, Du J and Cai F 2017 Safety assessment of Cracked K-joint Structure Based on Fracture Mechanics *J. Phys. Conf. Ser.* **843** 012011
[13] Simpson CA, Tonge S, Connolley T, Reinhard C, Marrow TJ and Mostafav M 2019 Validating 3D two-parameter fracture mechanics models for structural integrity assessments *Theor. Appl. Fract. Mech.* **103** 102281
[14] Wintle JB 2003 Which procedures for fitness-for-service assessment: API 579 or BS 7910? *Int. Conf. Press. Vessel Technol.* 1–7
[15] Brighenti R and Carpinteri A 2013 Surface cracks in fatigued structural components: A review *Fatigue Fract. Eng. Mater. Struct.* **36** 1209–1222
[16] Kim JM and Huh NS 2010 On crack interaction effects of in-plane surface cracks using elastic and elastic plastic finite element analyses *Nucl. Eng. Technol.* **42** 680–689
[17] Chu SJ and Liu C 2012 Finite element simulation of fatigue crack growth: Determination of exponent m in paris law *Trans. Korean Soc. Mech. Eng. A* **36** 713–721
[18] Sun Y and Zhang Q 2010 Mix-mode crack growth intelligence analysis and simulation module development based on UIDL and APDL Proc. Int. Conf. Electr. Control Eng. ICECE 2010 1276–1279

[19] Jensen BE 2015 Numerical Analysis of Crack Propagation and Lifetime Estimation

[20] Zakavi B, Kotousov A, Khanna A and Branco R 2019 A new method for analysis of part-elliptical surface cracks in structures subjected to fatigue loading Theor. Appl. Fract. Mech. 103 102258

[21] Cordeiro SGF and Leonel ED 2018 Mechanical modelling of three-dimensional cracked structural components using the isogeometric dual boundary element method Appl. Math. Model. 63 415–444

[22] Kim Y, Hwang IS and Oh YJ 2018 Unified formulae for evaluating load reduction by change in stiffness of circumferential crack considering general piping systems Int. J. Press. Vessel. Pip. 165 68–80

[23] Dong P 2020 Quantitative weld quality acceptance criteria: An enabler for structural lightweighting and additive manufacturing Weld. J. 99 39S-51S

[24] McFarlane B 2016 Boiler & Pressure Vessel Steel Plate

[25] Li Y, Gong B, Lacidogna G, Carpinteri A and Wang D 2019 An improved crack driving force estimation approach for stress-based engineering critical assessment of reeled pipes Theor. Appl. Fract. Mech. 103 102312

[26] Norrie DH 2007 A first course in the finite element method

[27] Khennane A 2013 Introduction to FEA using Matlab and ABAQUS

[28] ANSYS Inc. 2015 ANSYS Meshing User’s Guide 15317 724–746

[29] Long XY, Liu K, Jiang C, Xiao Y and Wu SC 2019 Uncertainty propagation method for probabilistic fatigue crack growth life prediction Theor. Appl. Fract. Mech. 103 102268

[30] Jacob A, Mehmanparast A, D’Urzo R and Kelleher J 2019 Experimental and numerical investigation of residual stress effects on fatigue crack growth behaviour of S355 steel weldments International Journal of Fatigue 128 105196

[31] Zong L, Shi G and Wang Y 2015 Experimental investigation and numerical simulation on fatigue crack behavior of bridge steel WNQ570 base metal and butt weld Constr. Build. Mater. 77 419–429