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Probabilistic treatment of pipe girth weld residual stress in fracture assessment

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ABSTRACT

This study examines the influence of probabilistic treatment of transverse residual stress in a structural integrity assessment. Pipe girth weld measurement data gathered from numerous studies was statistically interpreted to provide realistic through-thickness stress distributions for use in fracture assessments. The database measurements are shown to follow a normal distribution which is capable of evaluating a probabilistic interpretation of weld residual stress within a fracture assessment. A comparison between deterministic upper bounds, provided by various standards, and probabilistic interpretation was undertaken. The presented results propose a 42% reduction in the estimated probability of failure of the case study using a probabilistic assumption of residual stress. Direct implications include a more realistic model for treatment in fracture assessments which can in turn improve acceptance criteria and avoid unnecessary weld repairs.

1. Introduction

Residual stresses are a common and unavoidable consequence of almost all welding processes. Their effects on flaws and defects within the weld region are critical from the standpoint of maintaining structural and operational safety as they can promote failure mechanisms including fracture, fatigue, and stress corrosion.

Pipe girth welds are commonly used in a range of industries, including nuclear energy, offshore engineering, and construction of land pipelines. This encompasses a wide range of pipe parameters including material, size, and welding technique. This work will focus specifically on axial (i.e. weld-transverse) residual stresses in pipes, as they have a direct influence on fracture development and are often significant for integrity and safety assessments. However, mapping residual stress profiles within industrial girth weld components is notoriously difficult and costly to perform using direct measurements and available finite element modelling techniques. Therefore, generalised upper bound assumptions can be implemented into safety and fracture assessments following the advice of associated standards.

R6 [1], BS 7910 [2] and API 579 [3] provide recommendations of transverse residual stress profiles for use in fracture assessment. These procedures offer two different residual stress upper bounds for low heat input pipe girth welds, the first of these is a uniform membrane stress upper bound (known as Level 1 in BS 7910 and R6) which considers the level of residual stress equal to the yield strength of the parent material.

The second presents, a less conservative, non-linear upper bound (Level 2 in BS 7910 and R6) which assumes a lower level of residual stress towards the inner surface of the pipe wall. The upper bound distributions were first published in BS 7910:1999 [4] based on experimental and theoretical information gathered in the years prior. Since publication however, the profiles have not been substantially revised despite technological advancements in the last two decades that would make this possible.

ND has seen improvements in instrumentation and resolution of through thickness stress measurements, increasing the overall engagement from the engineering community [5]. DHD has also seen continuous development since 1999 and presents an extremely effective method of measuring through-thickness weld residual stress profiles [6, 7]. FEA has, in addition, advanced in weld simulation through more powerful computing capability and scientific understanding of processes which cause residual stress. (e.g. effect of solid-state phase change) [8, 9].

Today, more data of higher quality is available for analysis compared with what was available at the time of BS 7910:1999 [4]. However, attempts to propose an updated upper bound using more up-to-date information has resulted in no significant changes [10]. The two primary factors which are responsible are (1), a lack of traceability

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Nomenclature

σ_R^T	residual stress in transverse direction
B	pipe wall thickness
z	distance from inner pipe wall
σ_Y^P	parent material yield strength
Q	net arc power unit
η	weld process efficiency factor
v	welding velocity
σ_Y^W	weld material yield strength
r_m	pipe mean radius
r_o	pipe outer radius
w_f	weighting factor
N_o	number of observations
K_r	fracture ratio
K_I	(Mode I) stress intensity factor
K_{mat}	fracture toughness
L_r	load ratio
σ_{ref}	reference stress
K_I^{total}	combined stress intensity factor
K_I^P	primary stress intensity factor
V	plasticity adjustment factor
K_I^S	secondary stress intensity factor
a	flaw height
P_f	probability of failure
$N_{failure}$	number of failures
N_{total}	total number of failures
$\bar{x}$	weighted residual stress mean, see Eq. (7)
SD_w	weighted standard deviation, see Eq. (8)
sy	yield strength
su	ultimate tensile strength
GMAW	gas metal arc welding
MMA	mixed manual arc welding
TIG	tungsten inert gas welding
SAW	submerged arc welding
BRSL	block removal slitting and layering
ND	neutron diffraction
DHD	deep hole drilling
CHD	centre hole drilling
iCHD	incremental centre hole drilling
CM	contour method
FEA	finite element analysis
FAD	failure assessment diagram

regarding the upper bound profiles and (2) a large presence of residual stress variability when combining measurement results.

The references given in BS 7910:1999 [4] provide the experimental and theoretical data used to determine the upper bound profiles. Although some small correlations are present between the referenced data and the current profile assumptions, it is clear statistically that additional information was considered when proposing the profile shapes, magnitudes, and associated parameters. This additional information is untraceable and as a result, has created uncertainty regarding profile assumptions and subsequent treatment in assessments.

Variability of residual stress measurements is another crucial source of uncertainty regarding treatment advice [11,12]. Welding is an inherently variable process, even when components and specifications are seemingly identical. Small fluctuations in the materials properties, weld preparation or welding process can ultimately influence the resultant residual stress profile. An upper bound assumption of residual stress, therefore, is safe to assume in a given fracture assessment considering a component's potential variability. Although this justifies the use of upper bound assumptions for residual stress, it is vital that empirical methods are used to acquire them. This can be achieved through statistical analysis of a large database of measurements which can be further utilized for less conservative assumptions which consider variability and general trends seen in data.

Zhang et al. [10] gathered a database of destructive measurements containing a combination of ferritic and austenitic girth welds. One of the primary objectives of this report was to revise the current low heat input upper bound profile using an updated statistical interpretation of the database measurements. The presented results showed a significant presence of unforeseen measurement variability within the proposed database. However, due to the scope of the report it was unable to explore the potential causes of this variability. The authors proposed an updated upper bound profile based on the measurement data however this was not adopted by the associated standards in subsequent editions.

An additional publication by Mirzaee-Sisan & Wu [13] explored the potential of incorporating residual stress variability into fracture assessments using probabilistic methods. This consisted of statistical interpretation of a database of experimental results, focussing specifically on the distribution of data from low heat input welds. The researchers suggested that the variability of measurements can be described using a normal distribution function and proceeded to determine the influence of probabilistic treatment of residual stress using a realistic case study. The results showed that probabilistic interpretation reduced the probability of failure by a factor of six compared with the current upper bound profile assumptions. The conclusions also stated that the results could be improved further using a larger set of data and potentially give updated recommendations of upper bound profiles for generalised use or specific welding techniques such as narrow gap girth welds.

This study builds on previous work regarding low heat input girth weld residual stress by implementing an expanded database of experimental measurements. It has been shown by Zhang et al. [10] and Mirzaee-Sisan & Wu [13] that variability of residual stress measurements is a problematic issue for prediction and thus accurate treatment within fracture assessments. This work proposes an extensive database of measurements to provide an up-to-date statistical model of variability. Defining the variability through empirical methods can provide less overly conservative treatment advice for residual stress in fracture assessments.

2. Treatment of residual stress in pipe girth welds in BS 7910 Annex Q

2.1. Overview

Guidance given for treatment of weld residual stress of pipe girth welds can be found in the R6 [1], API 579 [3] and BS 7910 [2] assessment procedures. This consists of upper bound assumptions which include a uniform membrane stress upper bound (Level 1 in BS 7910 and R6) typically equal to the parent material yield strength and a less conservative, non-uniform distribution (Level 2 in BS 7910 and R6) shown in Fig. 1(b). These assumptions are consistent across each of the assessment procedures, and therefore, for simplicity, the following nomenclature and references will be considered from the standpoint of BS 7910 [2] only. The distributions shown in Fig. 1 were first introduced in BS 7910:1999 [4] and have since remained essentially the same. These upper bounds represent conservative estimates which residual stresses in girth butt welds are unlikely to exceed. Since this first publication in 1999 however, the growing quantity of experimental data

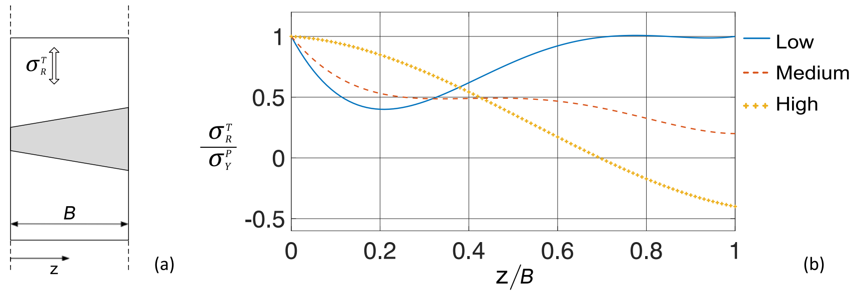

Fig. 1. Components of transverse stress distribution for pipe butt welds adopted from BS 7910 Annex Q [2]. Weld heat input is defined as $(Q\eta/v)/B$, (a) Weld schematic (b) Transverse residual stress profiles for low, medium, and high heat input. Both axes are in normalised units .[11]

have been unable to statistically inform more up-to-date profile revisions. This is not only due to experimental scatter seen in results, but also the traceability of these profiles to their original sources [14–19].

This review of the original sources has found that the largest contributions are given in a study by Scaramangas [14] which was then further developed by Leggatt [19] before being published in BS 7910:1999 [4]. The purpose of this review is to analyse these reports and outline similarities between their results and the current upper bound profiles. Clarifying these sources will indicate the underlying methods used and potentially facilitate future upper bound profile revisions.

2.2. Literature review

The study by Scaramangas [14] published in 1985, measured residual stresses in girth butt welds in addition to model verification using measurement data. The profiles of this study were then combined with results from previous reports by Rybicki [20,21], Shadley [22] and Leggatt [23] to identify trends using a much larger set of pipe data with varying parameters. This consisted of measurements collected using destructive techniques, namely CHD, BRSL alongside FEA. The results from each experiment model were collected and combined together as shown in Fig. 2 (a). The residual stresses are normalised with respect to weld material yield strength and in addition, the through-thickness distance of each pipe are normalised with respect to thickness. This was the first attempt to investigate potential trends qualitatively using a range of realistic cases for illustration.

Scaramangas organised the set of data based on influential parameters which were considered to have an effect on the resultant distribution size and shape. This included the heat input per pass per unit thickness, $(Q/v)/B$, specified on the y-axis in Fig. 2 (a). The x-axis represents the pipe aspect ratio (r_m/B) which considers the cylinder wall flexibility and susceptibility to tourniquet bending. Scaramangas regarded the heat input as the primary parameter influencing weld residual stress while the pipe aspect ratio was considered to have secondary importance.

The conclusions of the report by Scaramangas [14] describe some of the trends seen in the datasets. It states that for higher values of $(Q/v)/B$, girth welds exhibit pure bending stresses due to the later passes heating up the weld uniformly. In addition, at higher heat inputs, a plastic moment was tending to develop at lower values of r_m/B concluding that the "tourniquet effect … is the dominant feature of these cases". At low $(Q/v)/B$, the distributions give a characteristic "S-shape", with tension on the inner pipe wall and compression on the outer surface. This gives evidence that the earlier passes are thermally indifferent to the later passes near the outer surface. With respect to "medium" $(Q/v)/B$ values, no specific conclusions were made, implying that no trends could be seen in the distributions. In overview, the conclusions of this analysis are qualitative, describing observed general trends while confirming the weld heat input and pipe aspect ratio as influential parameters regarding the residual stress distribution.

A year before BS 7910:1999 [4] was published, The Welding Institute (TWI) issued a report by Leggatt [19] reviewing residual stress profiles. This review consisted of a range of different weld geometries including profiles for pipe girth welds. In this report [19], Leggatt adopted the information provided by Scaramangas [14] to analyse generalised trends in data for potential use in BS 7910:1999 [4] (Fig. 2 (b)). Here it can be seen that the heat input parameter was redefined by Leggatt as $Q/(v \times B^2 \times \sigma_Y^W)$. This resulted a smaller scale on the y-axis and a vertical shift of some the distributions which can be seen between Fig. 2 (a) and (b). The conclusions which Leggatt gathered from this analysis (Fig. 2 (b)) were similar to the qualitative results given by Scaramangas regarding high and low heat input shapes. However, Leggatt's report also states that the profile shapes show no visible dependence on pipe aspect ratio but a clear dependence on heat input. This suggests that Leggatt agreed that heat input was the primary driving factor of profile shape and that the pipe aspect ratio could potentially be disregarded entirely.

After review of the studies by Scaramangas and Leggatt there are clear similarities between their inferences of profile shape and those published in BS 7910:1999 [4] (Fig. 1 (b)). This is primarily regarding the qualitative conclusions for the low and high heat inputs; however some differences are noticeably present. (1) The profiles in BS 7910 are normalised using yield strength of parent material (σ_Y^P) rather than the weld metal (σ_Y^W). In most cases the weld material yield strength overmatches the parent material yield strength which can influence the profile magnitude when normalising and comparing profiles simultaneously. (2) BS 7910 defines weld heat input as $(Q/v)/B$ (the same as Scaramangas but different to Leggatt). (3) BS 7910 does not define the pipe aspect ratio as an influential parameter (the same as Leggatt but different to Scaramangas). It is apparent that aspects from both studies are present in BS 7910:1999 [4], however, why certain features were used over others remains unclear. These reports are only referenced in BS 7910:1999 [4] without detailed explanation regarding their relationship to the upper bound profiles. It is therefore likely that a combination of these experimental results alongside additional theoretical information was used to produce the profiles.

2.3. Conclusions

It is clear from this review that much of the basis of BS 7910 upper bound profiles can be found in the studies by Scaramangas and Leggatt. Many of the core elements including parameter information and distribution shape profiles indicate its application in BS 7910:1999 [4]. However, a gap of understanding regarding the rationale taken to produce the upper bound distributions is unmistakably present. It is therefore possible to assume that the profiles may not be completely supported by evidence from experimental or theoretical methods. This lack of traceability is presently the primary difficulty in producing more up-to-date profile revisions. However, there is sufficient scope to provide a revision based on empirical methods similar to those used by Zhang et al. [10]. Currently, there exists a much larger range of residual stress data which are representative of realistic pipes where traceable,

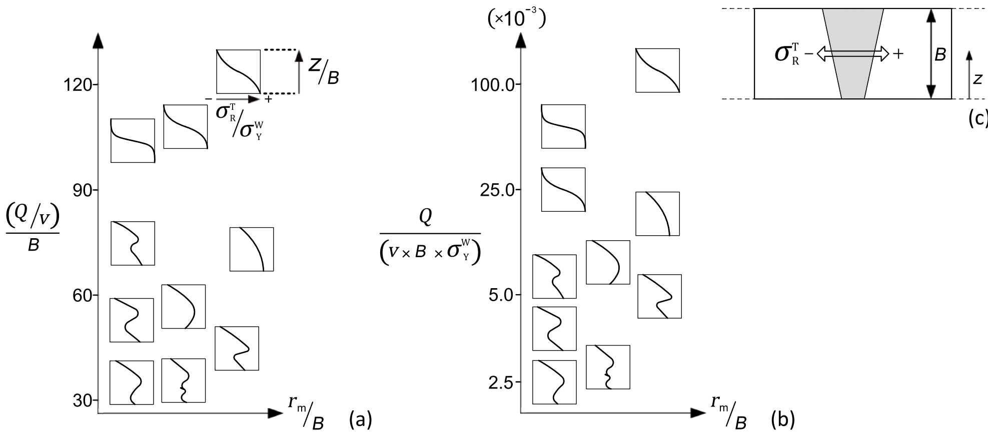

Fig. 2. Measured through-thickness profiles of transverse residual stress in pipe girth welds as a function of heat input and pipe aspect ratio (r_m/B). All data are gathered from sources in Refs. [11–16], both graphs contain the same information; however, possess unique heat input definitions. (a) Adapted from Scaramangas [14], (b) Adapted from Leggatt [16] with updated definition of heat input. This heat input adjustment hinted at a relationship between heat input and distribution shape (low medium and high) although is not currently used by the associated standards. (c) Weld Schematic.

statistical methods can be applied to inform updated profile revisions.

3. Database of low heat input pipe girth welds

The following database is presented to give context of the available experimental data regarding pipe girth weld residual stress. The sources can be found in Tables A1 and A2 in the appendix alongside a list of available parameter information associated with each measurement. However, only low heat input temperature welds will be considered for statistical analysis (Table A1). Fig. 3 shows that the majority of measurements available are of low heat input welds, thus presenting a suitable dataset for statistical interpretation.

The data was collected from a variety of individual reports and collaborative projects. The most prominent include the manufacturing of mock-ups of industrial pipes found in the STYLE [24] and VORSAC [25] projects. STYLE was aimed at improving structural integrity assessment methods of aged reactor coolant pressure boundary components while VORSAC was initiated to improve the understanding of the evolution of residual stresses in nuclear components during manufacturing and service life. Various smaller groups of studies were also carried out by TWI and the University of Manchester, among others.

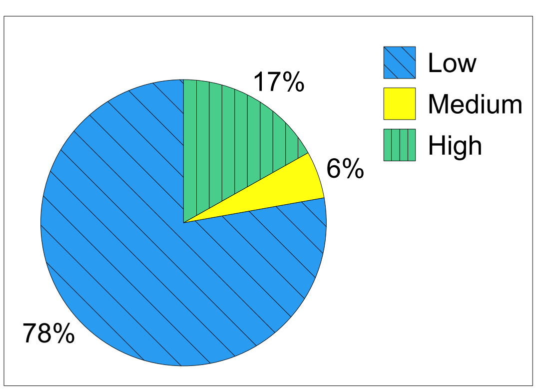

Fig. 3. Pie chart of database measurements showing the amount of data in each heat input band (low, medium, and high) following advice from BS 7910. Low heat input, $\leq 50J/mm^2$ for ferritic and $\leq 120J/mm^2$ for austenitic steel welds. Medium heat input, between $50J/mm^2$ and $120J/mm^2$ for ferritic steel welds only. High heat input, $\geq 120J/mm^2$ for ferritic and austenitic steel welds.

[1] The weld process efficiency factor was not considered in sources [14–19].

3.1. Summary of database parameters

Figs. 4 and 5 give an overview of the low heat input database including some additional parameters such as pipe wall thickness, pipe aspect ratio (defined as r_o/B), welding technique, and measurement technique. This gives an indication of the representativeness of the database and how the data is spread across different parameter subsets. Note that undefined parameter information is labelled accordingly in Fig. 5.

The pipe wall thicknesses range from 5.6 mm to 110 mm (shown in Fig. 4(a)) with most studies focussing on thinner walled piping. However, it can be seen that series of measurements were performed on roughly 60 mm thickness pipes. This is likely due to industry interest and common use of this dimension of pipe. The range of pipe aspect ratios (Fig. 4(b)) give a similar result to wall thickness as the majority of measurements were recorded as having smaller values, a small spike at

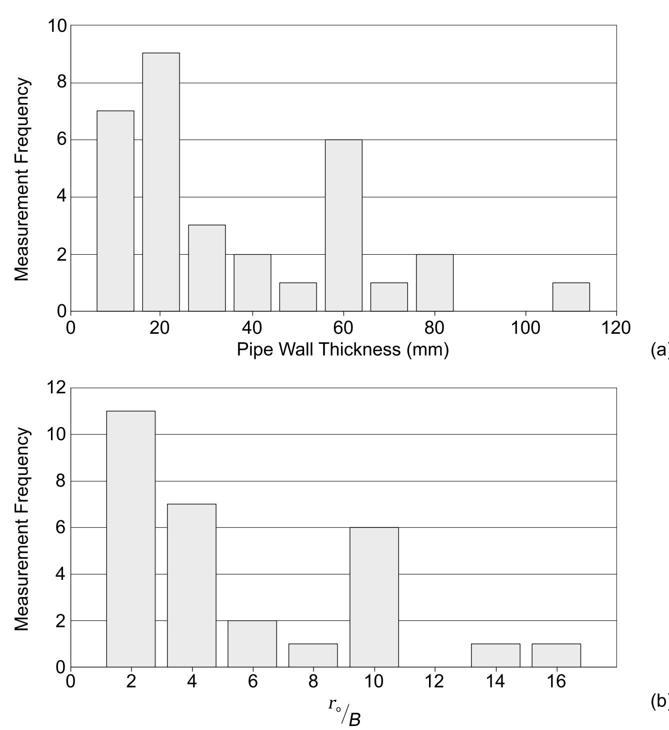

Fig. 4. (a). Histogram of pipe wall thicknesses present in the database, illustrating a large spread of different thickness values. (b) Histogram of the ratio of pipe outer radius to wall thickness. Pipes with smaller r_o/B ratios possess greater restraint which can potentially increase the measured residual stress values [26,27].

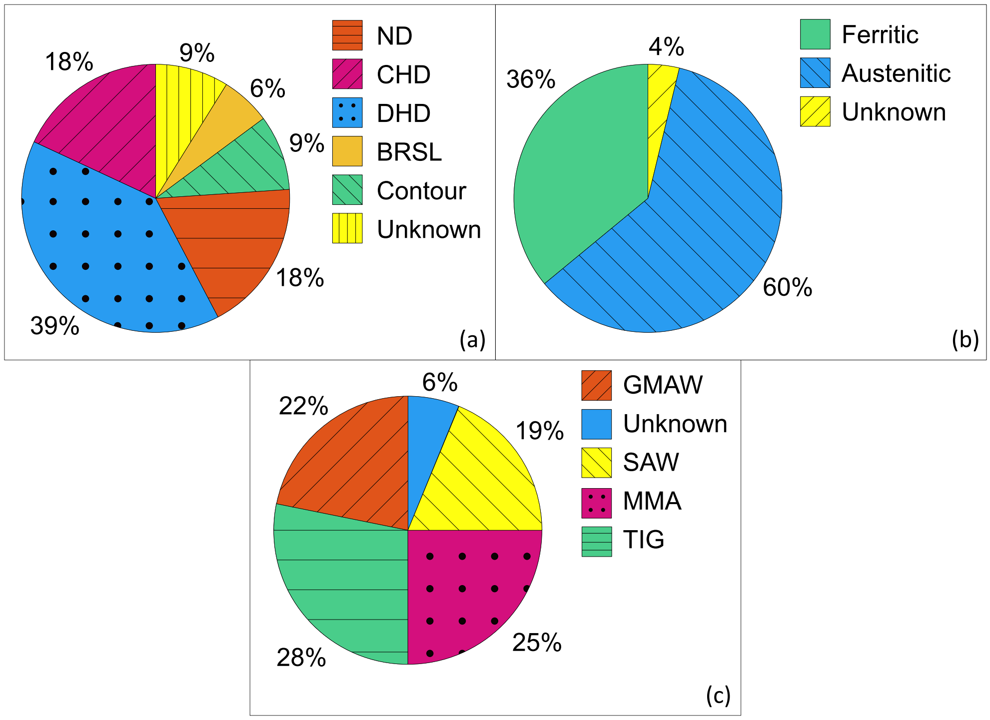

Fig. 5. Pie charts illustrating the population of nonnumerical information which may influence weld residual stress and inclination of measurements at low heat input. Total number of samples in each chart is 33. (a) Residual stress measurement techniques (b) Metallurgical property . (c) Welding processes.

r_o/B of 10 is also present.

The measurement techniques recorded from the database include DHD, iCHD, BRSL, CM and ND, shown in Fig. 5 (a). The majority of measurements were performed using the DHD method (39%) followed by CHD (18%) and ND (18%). CHD is used to measure stresses at the surface of the material and while this technique is frequent, it does not significantly contribute to the through thickness measurements used in the subsequent analysis. “Unknown” measurement techniques represent studies where they were not specifically recorded or outlined in the analysis which was encountered more commonly within older sources. Further information regarding residual stress measurement methods and potential sources of experimental error can be found in Ref. [28].

The parent material was also recorded in Fig. 5(b), presented as either austenitic or ferritic. The type of steel used determines its thermal and mechanical properties and influences the residual stresses which occur. As mentioned in Fig. 3, the heat input band for austenitic steel is much larger than for ferritic and therefore it is reasonable that most measurements (60%) were performed on this material type.

The welding techniques (Fig. 5(c)), recorded from the database include MMA, TIG, GMAW and SAW. It is noted that the indicated welding technique represents the majority of the weld as fill/cap passes may be carried out using a different technique from the one used for root/hot passes. The majority of welding techniques presented in the database are shown to be reasonably well distributed.

Overall, the presented low heat input database covers a large variety of pipe studies involving through thickness residual stress measurements and is currently the largest known open source database of its kind. . However, from Figs. 4 and 5 it is clear that the database is weighted towards certain parameters such as thin-walled pipes. This can potentially influence the appropriateness of the database when considering pipe parameters which are poorly represented. In addition, the amount of data available at low heat input makes this database a viable candidate for further statistical analyses. This can be achieved using similar methods outlined within the literature regarding axial pipe weld residual stresses [10,29,30].

3.2. Normalised database measurements

The presented database (Table A1) covers a variety of low heat input pipe butt welds which differ across many parameters. To help interpret the data statistically, each measurement can be normalised and combined onto a single graph. This is similar to the approach used by Scaramangas [14], and is achieved by normalising the y and x-axes by their respective units of measurements (MPa for y-axis and mm for x-axis). Following BS 7910, the transverse residual stresses are normalised using the parent material yield strength (σ_Y^P), and the depth measurements are normalised by the pipe wall thickness (B).

The different spatial resolutions of the measurement techniques is also considered in the comparison. ND can produce a through thickness dataset of fewer than 10 data points whereas DHD is capable of producing hundreds. Therefore, a weighting factor w_f (Equation (1)) was introduced to eliminate skewness towards higher resolution measurement techniques. Precise values of uncertainty regarding individual measurements were largely unattainable from the sources and because of this have been temporarily disregarded within the current analysis.

$$w_f = \frac{1}{N_0} \tag{1}$$

The combined through-thickness measurements and weighted mean are shown in Fig. 6 alongside the BS 7910 low heat input upper bound. The database measurements tend to be highly variable, especially towards the pipe outer surface. Although this is the case, a general trend can be seen within the data surrounding the weighted mean. As the residual stress magnitudes vary according to the position within the pipe, statistical tests were performed at incremental locations throughout the wall thickness to determine a potential probability distribution type. It was found that the majority of the data was normally distributed around the mean, verified using Kolmogorov-Smirnov [31] and Anderson-Darling tests [32]. This also agrees with the normality analysis performed by Mirzaee-Sisan and Wu [29] using a smaller dataset.

This work allows the database to be used in further statistical

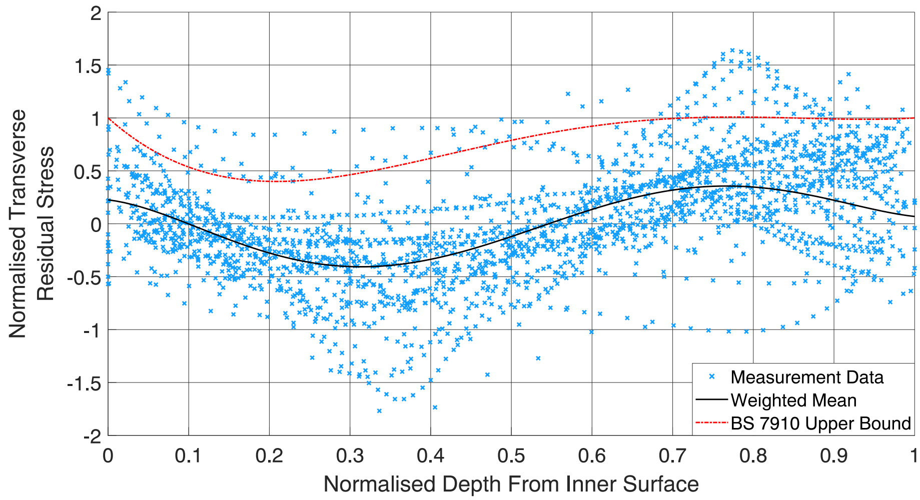

Fig. 6. Pipe girth weld database measurements at low heat input from database (Table A1). Solid line represents the weighted mean while dashed line represents the BS 7910 upper bound given in Annex Q.

analyses involving residual stress. One method can include providing an updated upper bound profile using the database similar to the current BS 7910 level 2 approach. However, due to the size of the database it is reasonable to suggest more robust methods such as probabilistic interpretation. This alternative approach can consider the variability surrounding the weighted mean and provide a less conservative assumption of residual stress compared with deterministic upper bounds while maintaining an appropriate level of safety.

4. Residual stress treatment in fracture assessments

4.1. Deterministic fracture assessments

Weld residual stresses contribute to the crack driving force within flaws and defects. R6, BS 7910 and API 579 advise the use of the FAD method (Fig. 7) to represent the crack driving force and determine the likelihood of failure for a given structure or component [33]. The fracture ratio (K_r) and plastic collapse (L_r) parameters are calculated to determine the potential susceptibility to failure. Points outside the curve are deemed as potentially unsafe while those inside the Failure Assessment Line (FAL) are considered safe.Where K_r is defined (under primary loading only) as:

$$K_r = \frac{K_I}{K_{mat}} \tag{2}$$

And L_r is defined as:

$$L_r = \frac{\sigma_{ref}}{\sigma_Y^P} \tag{3}$$

Residual stresses, treated as secondary stresses, directly influence the combined stress intensity factor solution given in Equation (4) [34].

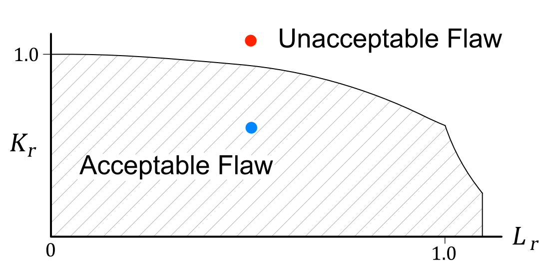

Fig. 7. Typical Failure Assessment Diagram assessment result presenting an unacceptable flaw outside the FAL and an acceptable flaw within the FAL.

$$K_I^{total} = K_I^P + V \cdot K_I^S \tag{4}$$

The V factor is used in the procedures of R6 and BS 7910 among others, specifically for the calculation of combined stress intensity factor solutions. It applies for all secondary stress factors and is typically based on geometry-specific analysis and finite element calculations.

For the polynomial representation of residual stress (Level 2 BS 7910 and R6) where a crack is loaded by a non-uniform stress distribution the weight function method [35] can be applied using Equation (5).

$$K_I = \int_0^a h(x,a)\sigma(x)dx \tag{5}$$

where $h(x,a)$ is the weight function (typically represented as a polynomial of order >4) and $\sigma(x)$ is the distribution of stress perpendicular to the flaw. Equations (2)–(5) are used to assess semi-elliptical flaws via CrackWISE® (TWI's structural integrity assessment software [36]) deterministically.

4.2. Probabilistic fracture assessments

Probabilistic assessment methods involve application of statistical knowledge of individual or multiple input parameters to provide a more realistic representation of a structure's potential behaviour. This can be useful in cases of safety management as a probabilistic approach can demonstrate quantitative probability of failure of a given structure or component. In the case of fracture assessment, this corresponds to the probability of failure through uncertainty of input parameters. More detail of potential sources of uncertainty can be found in Annex K.3-K.5 of BS 7910. In the following probabilistic analysis this will be strictly limited to statistical uncertainty determined using the database measurements. A probability distribution is used to describe the parameter variability, determined through appropriate statistical tests. The parameters associated with the probability distribution are generated from random inputs and implemented into probabilistic assessments. In CrackWISE®, random inputs are generated using a Monte Carlo analysis. To increase the reliability of the results, a large number of generated points should be used so that the distribution function is captured adequately in the analysis.

4.3. Probabilistic interpretation of residual stress

In fracture assessments, the generated random inputs are used to determine values of K_r and L_r respectively. Similar to the deterministic calculation, the results are plotted on a FAD, resulting in a "safe", or "unsafe" verdict. The ratio between the number of failures (i.e. "unsafe" outcomes) and the total number of generated points is denoted as the probability of failure (POF), given by Equation (6).

$$P_f = \frac{N_{failure}}{N_{total}} \tag{6}$$

The application of probabilistic treatment of residual stress involves calculation of the weight function (Equation (5)) in conjunction with a description of its potential variability using the database measurements (Fig. 6). The variability in this analysis is defined by a normal distribution function, requiring further calculation of its respective mean and standard deviation.

Applying the weighting factor (Equation (1)) into the database calculations subsequently introduces further weighted parameters regarding the probability distribution function. This is to eliminate skewness of the database with varying measurement spatial resolution. The weighted mean parameter ($\bar{x}$) is determined using Equation (7). This averages the entire database of weighted measurements as a single value which is further used to determine a generalised weighted standard deviation (SD_w) of the database.

$$\bar{x} = \frac{\sum_{i=1}^{N} w_{f\,i} x_i}{\sum_{i=1}^{N} w_{f\,i}} \tag{7}$$

where x_i is the measurement value, w_{f_i} is the corresponding weight factor of the measurement (determined using Equation (1)). From this, the weighted standard deviation SD_w can be calculated using Equation (8) below.

$$SD_w = \sqrt{\frac{\sum_{i=1}^{N} w_{fi}(x_i - \bar{x})^2}{\frac{(M-1)}{M}\sum_{i=1}^{N} w_{fi}}} \tag{8}$$

The variability of the presented database measurements is represented using a normal distribution function. The associated parameters comprise of the weighted mean and weighted standard deviation. These values encompass an overall depiction of the database which does not consider a varying profile shape as shown in Fig. 6. Incorporating the profile shape into the probabilistic analysis will improve its accuracy and representativeness according to the experimental measurements. In reality, the standard deviation of measured stresses will also vary through-thickness however for simplicity SD_w is assumed to be invariant through the wall thickness.

The polynomial profile is incorporated into the probabilistic assessment following the weight function method (Equation (5)) which is varied according to the weighted standard deviation (Equation (8)). The constant term of the polynomial weight function operates as the mean parameter of the normal distribution for probabilistic interpretation. This generalised approach can be applied to any given fracture case without recalculation of the polynomial and probabilistic parameters involved.

This overview provides the probabilistic framework to determine the influence of residual stress on fracture assessment and probability of failure results. The following analysis aims to compare assessment results of different interpretations of residual stress using a industrially representative pipe case study.

5. Pipe case study

The pipe case study follows an industrial research report by Hadley [37]. The report outlines diverse methods of structural reliability determination for pressure equipment, with specific reference to the oil and gas industry. Part of this report focusses on probabilistic fracture mechanics (PFM) methods using BS 7910 (Annex K) and R6 (Section III.13). The following analysis will adopt the parameters associated with Case Study 2 in the report considering a pressure piping component.

The case study consists of an X60 ferritic pipeline steel welded at low heat input with an internal semi-elliptical flaw. Further parameters of the pressure piping component can be found in Table A3 in the Appendix. The fracture toughness and tensile properties of the pipe are also assumed as probabilistic parameters outlined in Tables A4 and A5 following respective procedures provided in BS 7910 and R6.

The research report [37] provides a practical case study which can be incorporated into the proposed analysis. Due to the difference between the uniform and non-uniform upper bound assumptions at the inner surface (Fig. 8), the proposed probabilistic analysis can be easily applied for direct comparison between each deterministic interpretation of residual stress.

6. Method

This section will consider the case study pipe parameters and provide a probabilistic interpretation of the weld residual stress. The probabilistic fracture assessment results will be compared with the Level 1 and Level 2 interpretations using the calculated probability of failure (Equation (6)). The analysis will consist of deterministic assumptions of weld residual stress before applying the proposed probabilistic interpretation. As the analysis involves consideration of the residual stress in a pipe component, the "normalised" stress values are multiplied by 110% of the specified minimum yield strength of the X60 parent material (415 MPa) to give the appropriate input values for the fracture assessment.

The deterministic assumptions consist of the uniform and non-uniform upper bounds given in Fig. 8. The uniform distribution represents a single value (456.5 MPa) throughout the component thickness while the non-uniform upper bound applied using the weight function method (Equation (5)). The crack height region is also highlighted in Fig. 8 to illustrate the difference between the upper bound assumptions and subsequent influence this has on the following assessment results.

The probabilistic interpretation of residual stress involves combining various aspects of this study. First, the statistical analysis of the database given in Fig. 6 indicated that the data was normally distributed through the wall thickness. Due to the weighting factor w_f (Equation (1)) applied to the database measurements, the weighted mean and weighted standard deviation can be determined using Equations (7) and (8). The mean parameter used in the probabilistic analysis will consist of the weighted mean distribution (Fig. 6) applied using the weight function method (Equation (5)) and distributed according to the weighted standard deviation (Equation (8)). A Monte Carlo set consisting of one million random samples will be used in each analysis to adequately sample the probability density function.

7. Results

The results of the probabilistic parameters calculated using the

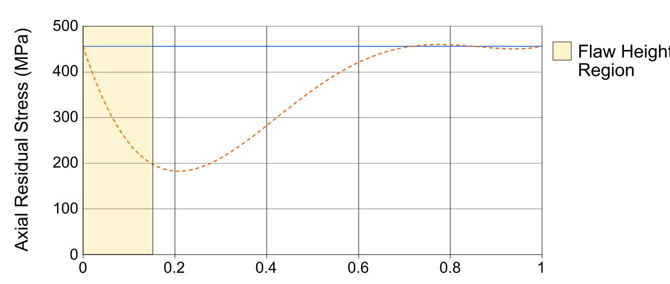

Fig. 8. Deterministic assumptions of residual stress used in analysis. Solid line represents Level 1 uniform distribution, while the dashed line represents the Level 2 non-uniform distribution. Shaded region represents defect flaw height considered in the case study illustrating the section of polynomial considered in the fracture assessment.

database are shown in Table 1 and Equation (9). This consists of the weighted standard deviation and through-thickness residual stress polynomial used to evaluate the normal probability distribution function.

Fig. 9 illustrates the unnormalized database used for the case study analysis alongside the respective mean polynomial and upper and lower bounds of two standard deviations. The upper bounds provide a good indication of the minimum and maximum residual stress magnitudes generated during the probabilistic fracture assessment.

$$y = 17120x^5 - 44680x^4 + 37330x^3 - 9412x^2 - 427.9x + 103.2 \quad (9)$$

The results consist of three different interpretations of residual stress evaluated using the prescribed probabilistic case study parameters given in Table A5 in the Appendix. The influence of each interpretation on the probability of failure is presented in Table 2 and Fig. 10.

The results show a reduction of probability of failure with each interpretation of residual stress. This result is expected as we are starting with the most conservative deterministic assumption before introducing the non-uniform upper bound and probabilistic interpretation using the database. Although the probabilities of failure are exaggerated due to the use of deterministic variables (such as applied stress and flaw size), the result does clearly illustrate the influence and potential benefit of less conservative assumptions of residual stress on a pipe component.

8. Discussion

8.1. BS 7910 upper bound profiles

The information gathered within the referenced sources have been critically reviewed in this work to give context of their origins. This critique has highlighted the studies by Scaramangas [14] and Leggatt [19] as the most significant contributors due to their gathering and analysis of through thickness girth weld measurements to find general trends. The results of these studies are predominantly qualitative although provide approximate upper bounds of the data, which are unfortunately untraceable. It seems that elements of both studies were considered in BS 7910:1999 [4], however, the underlying justification remains unclear. There is limited statistical evidence to imply that empirical methods were used in the final decision, suggesting that most likely, the upper bound profiles are the result of sensible observation of available data and reasonable engineering judgement.

Although these conservative assumptions are capable of providing useful estimates for use in fracture assessments, there is a lack of traceability behind these highly reasonable claims. It is therefore necessary to suggest that a complete statistical revaluation of the upper bounds is to be implemented using the presented approach. This would allow for more realistic assessments in the future, which are traceable and readily updated as new residual stress measurements are reported.

8.2. Measurement database and statistical interpretation

The database results presented in Table A1 consist of a collection of measured residual stress data of pipe girth welds found predominantly in published literature. This was to provide a reliable statistical interpretation of pipe girth welds, with specific focus on the most frequently measured heat input range (low temperature). The presented database is currently the largest known in published literature and a beneficial resource of residual stress knowledge. This is due to the combining of different measurement techniques which have been, in previous studies, kept separate.

Table 1
Results of Equation (8) evaluation of the weighted standard deviation using database measurements relating to the case study analysis.

	Weighted Standard deviation (SD_w)
Normalised	0.51
Unnormalized	233 MPa

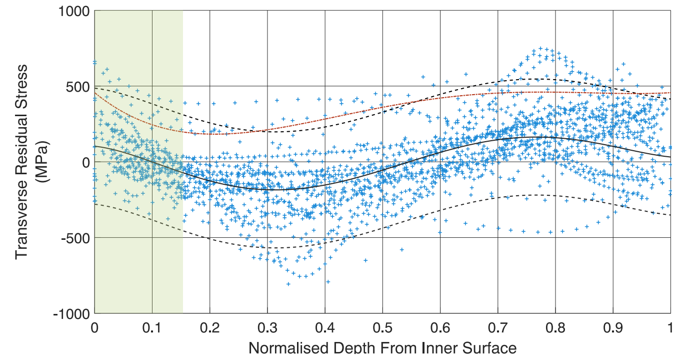

Fig. 9. Through-thickness residual stress measurement data from database in unnormalized units. Solid line represents the residual stress distribution as a function of through-thickness position (stated in Equation (9)). Upper and lower bounds consist of two standard deviations above and below the mean (see Table 1). BS 7910 Level 2 upper bound is also plotted for comparison. Shaded reigon represents flaw height of case study.

Table 2
Weld residual stress treatment conditions and respective probabilities of failure.

Condition	POF
As-welded, Level 1 treatment of residual stress	0.169
As-welded, Level 2 treatment of residual stress	0.0326
As-welded, probabilistic treatment of residual stress	0.019

The statistical interpretation of the low heat input database agrees with a self-equilibrating definition of residual stress in the transverse direction. It is possible to further use the database information to propose an updated upper bound assumption of residual stress although this would be similar to the current upper bound profiles, which are highly conservative. Therefore, an alternative approach is considered using probabilistic methods to represent a more realistic assumption considering the large amount of variability within girth weld residual stress measurements. The proposed method can be applied to any given fracture assessment and can also be applied for specific cases.

8.3. Case study results

The result of probabilistic interpretation of residual stress given in Fig. 10 indicates a clear reduction in the estimated POF using the proposed probabilistic method. Due to the flaw location on the inner pipe wall surface, a significant difference between the Level 1 and Level 2 deterministic assumptions of residual stress can be seen. This encapsulates the portion of the Level 2 distribution which has a significantly lower bending stress, for which the results of the proposed study are of particular interest. The estimated POF of the case study was reduced by 42% between the Level 2 and proposed probabilistic assumption.

The proposed approach offers a less conservative assumption of residual stress while maintaining an appropriate level of uncertainty. This is encapsulated by consideration of the potential levels of residual stress which have been recorded in measurements found in literature. From this, it is reasonable to propose this approach as a less conservative assumption of residual stress, compared to the Level 1 and Level 2 upper bounds.

9. Conclusions

We have presented a novel technique to aid the structural integrity assessment of girth-welded steel pipes containing unknown residual

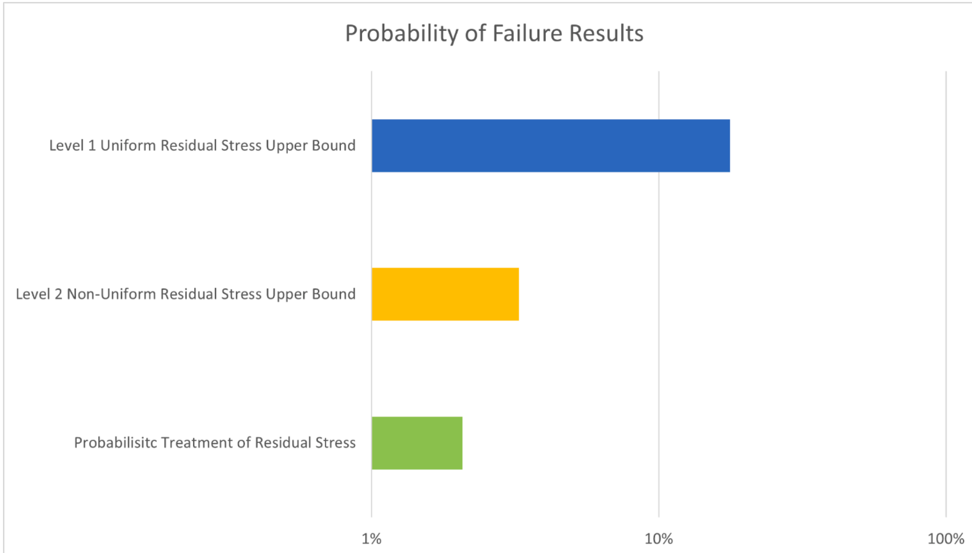

Fig. 10. Pipe girth weld case study probability of failure using different interpretations of weld residual stress.

stresses. Using a database of residual stress measurements from similar pipe girth welds, we take a probabilistic approach to estimating the weld residual stress distribution. This approach is straightforward to use with current FAD-based integrity assessment methodology via Monte Carlo analysis and provides a means to more realistically assess the contribution of residual stress to the pipe's POF under given loading conditions. In the case study presented, the use of this probabilistic approach on residual stress estimation reduced the predicted POF by 42% in comparison with deterministic upper-bound estimates of residual stress (Level 2). This statistical method could also be extended to other weld and component geometries where sufficient residual stress characterisation data exists.

Credit author statement

Matthew Weltevreden: Investigation, Data curation, Writing – original draft; **Isabel Hadley**: Conceptualization, Writing – review & editing; **Harry Coules**: Project administration, Writing – review & editing

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table A1
Transverse residual stress measurements of pipe girth welds at low heat input.

Ref No.	Weld Reference	Outer diameter *mm*	Wall thickness *mm*	Welding process	Base metal	Parent Material Yield Strength *MPa*	Heat Energy input J/mm^2	Measurement technique
[38]		396	84	MMAW	0.5Cr0.5Mo0.25 V Steel	–	–	Trepanning
[39]		400	50	TIG	ASME CF8M	251–274	24	BRSL
[14]	A, B, C	500	9.1, 15, 19.5	MIG & MAG	Grade 50D	–	77, 47, 36	BRSL
[40]		910	32	MIG & SAW	X52	335	–	CHD & DHD
[41]		369	40	TIG	Type 316 F	–	–	DHD
[10]		406	19.1	GMAW	X70	519	32	DHD
[10]		508	22.9	GMAW	X65	539.2	24	BRSL
[42]		323.9	24.3	GMAW	X60	449–451	70	CHD & DHD
[43]	A, B, C	453.6, 468, 462	84, 65, 35	SAW	–	–	–	DHD
[44]		355.6	19.05	GMAW	X65	510	37	ND
[45]		420	70	EBW	0.5Cr0.5Mo0.25 V Steel	–	–	BRSL
[46]		290	55	–	P91	489	27	
[47]	A, B	60.48, 69.36	5.6, 10.2	GTAW	Type 304	–	–	XRD, ND
[48]	MU-1, MU4-3, 2xHalf-inch thick (low, med), Esshete pipe	250, 250, 264.16, 182	25, 25, 12.7, 35	GTAW (x2), TIG, TIG & MMAW	Type 316L (x3), Esshete 1250	290 (x3), 370	–	Contour
[49]	SP19	411.6	19.6	MMAW	316H	272	71	DHD, ND, Contour
[50]	OU20	152	20	MMAW	316L	308	90	ND, CHD, DHD

(continued on next page)

Table A1 (*continued*)

Ref No.	Weld Reference	Outer diameter mm	Wall thickness mm	Welding process	Base metal	Parent Material Yield Strength MPa	Heat Energy input J/mm^2	Measurement technique
[30]	SP 37, S5VOR A & B, S5 Old, S5 New, S5 NG, RR	392.2, 364 (x2), 364, 364, 372, 396	37, 65 (x2), 65, 65, 62, 110	MMAW (x5), TIG, SAW	316H (x7)	328 (x6), 274	59, 37(x2), 22, 15, 35, 16,	ND, CHD, BRSL
N/A		970.2	27.8	GMAW	X65	–	–	DHD, DHD, CHD & DHD (x2), DHD, DHD, DHD & CHD
[52]		508	25.4	GMAW	X65	478	30	ND

Table A2
Transverse residual stress measurements of pipe girth welds at medium and high heat input.

Ref No.	Weld Reference	Outer diameter, mm	Wall thickness, mm	Welding process	Base metal	Parent Material Yield Strength MPa	Heat Energy input J/mm^2	Measurement technique
[51]	A, B	100.5, 100.5	7.75, 7.5	MAG	S355J2H + N, X6CrNiTil8-10	355, 223	142, 147	ND
[53]	A, B	429, 429	65, 65	MMAW	316H (Aged)	–	–	CHD & DHD
[48]	Esshete 1250, 1/2 Half-in thick (high)	182, 264	35, 12.7	TIG/MMA, TIG	Esshete 1250, Type 316L	370, 305	51,110	Contour & iDHD, ND
[54]	Weld C	795	15.9	SAW	316L	338	138	ND, CHD, BRSL
[55]	A, B	1067,1067	24, 30	MAG	X70	483	88, 70	ND

Table A3
Assessment parameters of case study analysis

Parameter	Value	Unit
Thickness	19	mm
Outer Radius	127	mm
Flaw Height	3	mm
Flaw Length	15	mm
Yield Strength	456.5	MPa
Tensile Strength	615	MPa
Young's Modulus	208,000	MPa
Poisson's Ratio	0.3	-
Toughness	63.9	$MPa.\sqrt{m}$
Membrane Stress	277	MPa
Bending Stress	0	MPa
Stress Concentration Factors	1	-

Table A4
Probabilistic guidance for fracture toughness and tensile properties outlined in BS 7910 and R6.

Probabilistic Guidance		
Parameter	BS 7910	R6
Fracture Toughness	Annex K (K.7.2), Weibull Distribution COV of 0.25	Section III.13.5.2, normal, log-normal or Weibull distribution
Tensile Properties	Annex K (Table 7.2), COV for tensile properties for ferritic steels	Section III.13.5.3, normal, log-normal or Weibull distribution

Table A5
Probabilistic parameters used in case study analysis.

Parameter	Units	Distribution Type	Distribution Parameter	Value	Distribution Parameter	Value
Toughness	MPa	Weibull	Shape	4.99	Scale	112.26
sy	MPa	Normal	Mean	540	Standard Deviation	54
su	MPa	Normal	Mean	693.5	Standard Deviation	69.35

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