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OPTIMISING THE SAFE DESIGN OF PRESSURISED COMPONENTS

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ABSTRACT

The structural integrity of pressure vessels (PVs) is controlled by the application of various design and fabrication codes and standards. Within the European single market (ESM) design codes exist at both a European and a national level which can lead to variability in design procedures. The European standard EN 13445 has been updated several times to modify the design curves based on analytical modelling of high strength materials. The design curves in EN 13445 now differ significantly from those presented in the British national code that preceded it, namely PD 5500. As a result higher minimum Charpy test temperatures (T_{27J}) are found using the EN 13445 procedure in comparison to those derived using the PD 5500 procedure. While the PD 5500 design curves have been validated experimentally it is generally accepted that they are overly conservative. This inherent conservatism in PD 5500 may account for some of the differences in the minimum Charpy test temperature, the analytical model used to generate the EN 13445 design curves however was validated with data from high strength steels only ($\sigma_y \geq 420$ MPa). It is not clear that the results can be applied directly to low/medium strength materials. This work identifies some of the disparities between the EN 13445 and PD 5500 procedures, for low temperature applications. A programme of work, at Imperial College London, is described. This programme of work, currently underway, is aimed at addressing concerns about the robustness of the updated EN 13445 design curves, especially for lower-strength steels in the as-welded condition.

NOMENCLATURE

α''	Geometrical parameter with contributions from a, B, W
σ	Stress
σ_{ref}	Reference stress ($=L_r\sigma_y$)
σ_y	Yield stress
σ_p	Primary stress
σ_{nsy}	Yield stress of the net section
a	Geometrical parameter: crack length
B	Geometrical parameter: specimen thickness
B_{eff}	Geometrical parameter: total crack front length

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C_V Charpy impact toughness
K_C Critical stress intensity factor
K_r Stress intensity ratio (=K_1/K_{mat})
K_{mat} Fracture toughness
K_I Mode 1 stress intensity factor
K_I^P Stress intensity factor from primary stress
K_I^S Stress intensity factor from secondary stress
L_r Stress ratio (=σ_{ref}/σ_y)
P Applied load
P_b Bending load
P_m Membrane load
P_f Probability of fracture toughness being less than 100 MPa$\sqrt{\text{m}}$
T Temperature at which K_{mat} is to be determined
T_0 Master curve transition temperature. Temperature at which mean $K_{mat} = 100$ MPa$\sqrt{\text{m}}$ for 25 mm thick specimen
T_{27J} Impact transition temperature at 27J
T_{40J} Impact transition temperature at 40J
T_D Temperature at which K_{mat} is to be determined (EN 13445)
T_K Temperature describing scatter in Charpy versus fracture toughness correlation
V Plasticity correction factor
W Geometrical parameter: specimen height
ESM European single market
FAD Failure assessment diagram
HAZ Heat affected zone
MVC Microvoid coalescence
NDT Non-destructive testing
PED Pressure Equipment Directive
POD Probability of detection
PV Pressure vessel
SIF Stress intensity factor
TT Transition temperature

INTRODUCTION

Failure of safety critical components such as pressure vessels must be avoided for both societal and economical reasons. One of the major contributing factors to the continuing safe design and operation of these complex components has been the use of codes and standards. For pressure vessels (PVs) sold in the European single market (ESM), the legal requirement is for adherence to the Pressure Equipment Directive (PED), rather than to a particular design standard; codes and standards exist at both a European and national level, which can lead to some variability in the design and manufacturing processes. This work is specifically related to the low temperature toughness requirements. The current European code for design and manufacture of unfired pressure vessels is BS EN 13445 [1], the corresponding British national level code is PD 5500 [2]. The relevant sections of each code dealing with low temperature operations are EN 13445 Part 2 and PD 5500 Annex D, respectively. Both codes are considered acceptable design codes for PVs sold in the ESM.

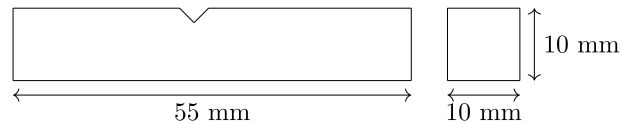

FIGURE 1: STANDARD CHARPY IMPACT TOUGHNESS SPECIMEN

The toughness of a material can be determined using a variety of methods. The simplest and most often adopted method is the Charpy impact toughness test. This method involves impacting a standard size Charpy specimen (Figure 1) with a weighted pendulum. The Charpy impact energy is estimated from the energy remaining in the pendulum after it has impacted the specimen. Testing is typically conducted for multiple specimens over a range of temperatures, generally three specimens per temperature [1, 2], to derive the 'transition temperature' (TT). The TT defines a temperature, above which, failure is more likely to occur in a ductile manner. This test method is qualitative rather than quantitative but is useful in comparing materials performance and provides some indication of fracture toughness. Further work [3] has shown that the TT can be used to infer a value of fracture toughness from Charpy impact toughness based on statistical analysis.

For PV design the toughness of a material at the operating temperature is of paramount importance in ensuring structural integrity and protection against brittle fracture. Both EN 13445 and PD 5500 provide 'design curves' for various materials and multiple thicknesses. The materials performance is quantified by achieving a minimum Charpy impact toughness at a specific impact test temperature. The impact test temperature is inferred from the relationship between the design reference temperature (a function of the operating temperature) and the design curve associated with the material under examination. Assuming that the measured impact toughness, at the derived impact test temperature, is at least equal to the minimum Charpy impact toughness then the material is considered 'acceptable'.

The latest revision of the European code [1] has been subject to significant changes with respect to the impact toughness test temperature requirements, in comparison to earlier revisions [4, 5]. Figure 2 plots the design curves for a 30 mm thick material for yield strengths between 265 MPa and 360 MPa. If a design reference temperature of -20°C is assumed, the current EN 13445 guidance requires a minimum Charpy energy of 27 J at a test temperature of approximately $+8$°C for yield strength of ≤ 265 MPa, and, approximately -10°C for yield strength ≤ 355 MPa. The same conditions in the earlier revision of the code [5] required impact test temperatures of approximately -25°C and -35°C, respectively.

Hadley and Garwood [6] conducted a case study that compared two case histories of brittle pressure vessel failures, using

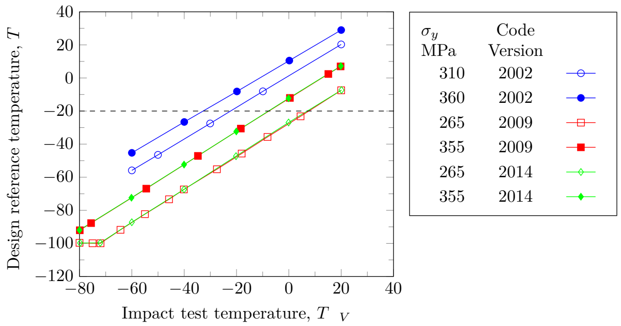

FIGURE 2: COMPARISON OF TOUGHNESS REQUIREMENTS IN AS-WELDED MATERIALS

the EN 13445 and PD 5500 design curves. They found that the failures could have been avoided should the PD 5500 method been applied at the time of PV manufacture. However, failure may not have been avoided if the current EN 13445 guidance was applied. It should be noted that there is some ambiguity about the validity of the comparisons owing to unknown information relating to the vessels and questions regarding the conversion of the EN 13445 design curves to a format directly comparable with those given in PD 5500. Nevertheless, it is clear that further investigation of changes to the current version of EN 13445 design curves is warranted.

The changes to the EN 13445 design curves were based on research data that were generated relatively recently [7, 8] using an analytical model and a fracture mechanics type approach. This differs considerably from the method used to derive the PD 5500 design curves. It is generally accepted that the PD 5500 design curves are conservative [6, 9] but discerning the level of conservatism in PD 5500 is not simple. A programme of work is underway at Imperial College London to investigate methods of utilising data, from PD 5500 and historical literature associated with the code, in conjunction with modern fracture assessments (conducted to BS 7910 [10]) to assess the level of conservatism in the PD 5500 design curves. It is hoped that similarities between the EN 13445 analytical model and the BS 7910 fracture assessment will provide correlations on the impact of various operating parameters on assessments and furthermore provide some indication on the level of conservatism in the design curves of each code and standard. The following sections provide some insight into the background of each method, highlighting area's of similarity and disparity between the relevant codes.

PD 5500

The design curves included in the British national code PD 5500 were derived from a mixture of engineering experience and validation using experimental testing [11]. The tests were conducted, on welded panels of varying thicknesses, prompted by a number of brittle PV failures during hydrotest. Each panel was notched with a 10 mm long through thickness defect located in either the weld, HAZ or plate material and loaded in tension until approximately 0.5% plastic strain was achieved [12]. A later review by Dawes and Denys [9] concluded that these design curves were generally safe and, in some cases, were overly conservative. Dawes and Denys did express some concern about the validty of the design curves for thin materials. Resulting from this concern further work [13, 14] focussed on thin plates and the curves were modified so that materials in the thickness range of $2 \geq t \leq 10$ mm utilised the design curve for 10 mm thick plates.

The design curves in the most current revision of PD 5500 [2] have not changed in recent years [15, 16]. Rather than stipulating separate curves for multiple yield strength materials PD 5500 increases the minimum required Charpy impact energy from 27 J to 40 J for materials with ultimate tensile strengths ≥ 450 MPa. Testing is required on weld metal and base material only under the assumption that the design curves are conservative enough to ensure that the Heat Affect Zone (HAZ) will not fracture in a brittle manner. Charpy impact specimens are orientated longitudinal to the rolling direction (in the case of base metals) or transverse to the weld (weldment specimens).

In cases where the minimum required impact energy can not be met PD 5500 allows the use of 'alternative methods' such as those outlined in PD 5500 Annex U. Annex U allows two types of fracture procedure, a direct application of BS 7910 which requires specific information related to material properties, stresses, defect size and location etc. or a 'comparable' procedure that provides a similar level of tolerance to fracture as that provided by PD 5500 Annex D. The comparable procedure is predominately meant to cover materials that are not explicitly covered by Annex D. This method requires the reference defect size used in the fracture procedure to be either a through wall defect of length 10 mm ($a = t$, $2c = 10$) or a surface defect with a quarter wall depth ($a = t/4$) and a length six times the depth ($2c = 6a$). Specific requirements for the applied stress and residual stresses are also included.

The following section of this work discusses the specific requirements of BS 7910 for a fracture mechanics assessment.

BS 7910

BS 7910 [10] is a British national level standard that assesses whether an existing defect is 'safe' or 'unsafe'. It is not within the scope of this work to outline the entire process but a brief overview of the major points is included for the purpose of comparison with the EN 13445 analytical model.

The size and location of any postulated defect is of significance in this type of assessment. The defect may be idealised to some 'worst case' scenario (such as those outlined in the last paragraph of the previous section), or where applicable, may be based on estimated defect sizes from some NDT method. The likelihood of failure due to the presence of a defect is visualised

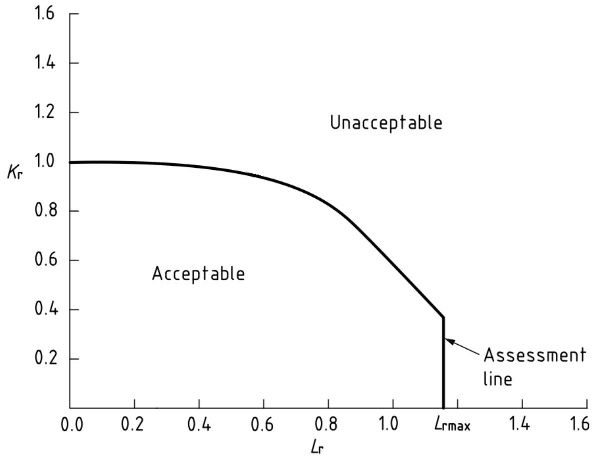

FIGURE 3: FAILURE ASSESSMENT DIAGRAM MODIFIED FROM [10]

using a failure assessment diagram (FAD). The FAD plots the ratio of applied load to plastic collapse load, L_r (Equation 1), against the ratio of stress intensity to fracture toughness, K_r, taking due account of residual stresses (Equation 2, where K_I is calculated as per Equation 5). The L_r and K_r point/(s) for a specific defect with known loading condition/(s) is bounded by a curve (generally based on material properties). The position of the L_r and K_r points relative to the bounding curve stipulate the level of risk to the overall structural integrity. Points of (L_r, K_r) that lie within the bounding curve are 'safe', points that lie on, or outside, the bounding curve are considered to be 'unsafe' (see Figure 3).

$$L_r = \frac{\sigma_{ref}}{\sigma_y} \tag{1}$$

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

The reference stress σ_{ref} (Equation 1) is a function of the geometry, loading and defect size. For a through thickness defect under combined tension and bending loads the reference stress is calculated in accordance with Equation 3. In the case of a surface defect under combined tension and bending loads the reference stress is calculated as per Equation 4, where α'' is dependent on geometrical parameters (See Annex P6.1 [10]).

$$\sigma_{ref} = \frac{P_b + \sqrt{P_b^2 + 9P_m^2}}{3\left[1 - (2a/W)\right]} \tag{3}$$

$$\sigma_{ref} = \frac{P_b + \sqrt{P_b^2 + 9P_m^2\left(1-\alpha''\right)^2}}{3\left(1-\alpha''\right)^2} \tag{4}$$

The stress intensity parameter, K_I (Equation 2), is dependent on contributions from both primary and secondary loads as shown in Equation 5. The parameter V 'combines the mechanical relief of residual stress and plasticity correction, ρ, into a single factor' [17]. This plasticity correct factor, V, should be calculated as per Equation 6 for $L_r < 1.05$ and assumed to be 1 for $L_r > 1.05$.

$$K_I = K_I^P + VK_I^S \tag{5}$$

$$V = \min \begin{cases} 1 + 0.5L_r + 0.02K_I^s\left(\frac{L_r}{K_I^P}\right)(1 + 2L_r) \\ 3.1 - 2L_r \end{cases} \tag{6}$$

The fracture toughness, K_{mat}, can be calculated in a variety of ways. The preferred method is from fracture toughness testing, conducted to a relevant test method, on full thickness specimens. However, BS 7910 allows for the use of other test data should full thickness test information be unavailable. If, for example, Charpy impact energy data is available at the service temperature then the fracture toughness can be estimated as per Equation 7, where B represents the thickness of the material for which a K_{mat} is required. In cases where the Charpy data do not exist at the required temperature the Master Curve approach can be used to shift data (see Equation 8) by assuming that the probability that fracture toughness is less than estimated is low ($P_f = 0.05$) and applying a suitable correlation to T_0 (Equations 9 and 10). The minimum value of three valid test values should be used which gives a high confidence (87.5%, [10]) of the median value of fracture toughness. Additionally the lowest value of three must be shown not be $\leq 70\%$ of K_{mat}.

$$K_{mat} = \left[\left(12\sqrt{C_v} - 20\right)\left(\frac{25}{B}\right)^{0.25}\right] + 20 \tag{7}$$

$$K_{mat} = 20 + \left\{11 + 77e\left[0.019\left(T - T_0 - T_K\right)\right]\right\} \left(\frac{25}{B}\right)^{\frac{1}{4}}\left[ln\left(\frac{1}{1-P_f}\right)\right]^{\frac{1}{4}} \tag{8}$$

$$T_0 = T_{27J} - 18°C \tag{9}$$

$$T_0 = T_{40J} - 24°C \tag{10}$$

EN 13445

Wiesner [18] stated that early revisions of EN 13445 were developed as a 'combination of relevant existing national codes'. Hadley and Garwood [6] showed that, whilst the design curves in earlier version of EN 13445 and PD 5500 were comparable, those contained in the current revision of EN 13445 deviate significantly when comparing to PD 5500. For example they showed that when comparing lower strength steels in the ranges 265 MPa $\leq \sigma_y \leq$ 275 MPa in the as-welded condition, the impact test temperature required by EN 13445 differed from that required by PD 5500 by up to 58°C. The result being that effectively EN 13445 requires a much lower toughness in comparison to PD 5500. There are however distinct differences in the methods behind each code. This section discusses the main differences between older version of the EN 13445 [5] and the current revision [1], as well as a discussion on how the current design curves evolved.

Unlike PD 5500 where HAZ testing is only required if welding heat input exceeds 5 kJ/mm, the EN 13445 method requires the minimum impact energy to be met for each section of material such as base, heat affected zone (HAZ) and weld metal. The required minimum impact energy, for carbon steels, is specified to be 27 J for materials with yield strengths $\leq$ 355 MPa [1, 4]. Further it is specified that Charpy impact specimens should be machined transverse to the weld, at a maximum distance of 2 mm from the surface of the plate. Similar to PD 5500 a minimum of three samples per set must be tested and the mean impact energy of the three specimens should be $\geq$ 27 J. The lowest value of impact energy must not be less than 70% of the required impact energy.

Older revisions of EN 13445 provided design curves for materials with yield strengths in the ranges $\leq$ 310 MPa and 310 MPa $< \sigma_y \leq$ 360 MPa and 360 MPa $< \sigma_y \leq$ 460 MPa for an impact energy of 27 J. The current standard [1] provides separate design curves for materials with a yield strength $\leq$ 275 MPa and materials in the range 275 MPa $> \sigma_y \leq$ 355 MPa. For yield strengths $>$ 355 MPa the impact energy requirement increases to 40 J. Comparatively PD 5500 increases the required impact energy to 40 J for materials with tensile strengths $\geq$ 450 MPa.

This work is predominately focussed on materials with yield strengths $\leq$ 360 MPa. Figure 4 plots the design curves from an older revision of EN 13445 [5]. As can be seen increasing the

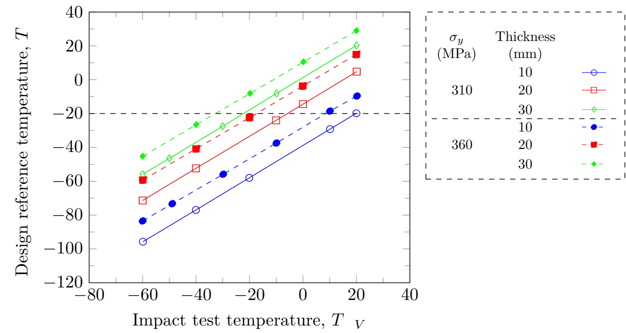

FIGURE 4: DESIGN CURVES FROM OLDER REVISION EN 13445 [5] FOR YIELD STRENGTHS $\leq$ 360 MPa VARYING THICKNESS

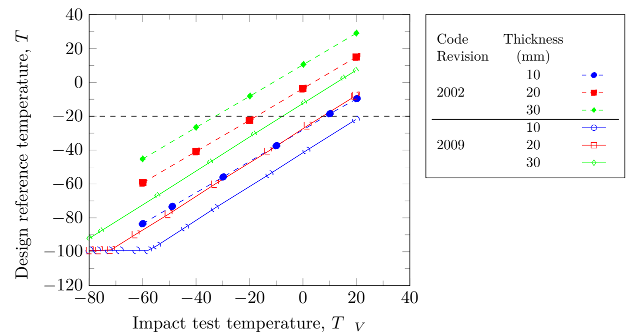

FIGURE 5: DESIGN CURVES FROM OLDER REVISION EN 13445 [5] AND UPDATED EN 13445 [1] FOR YIELD STRENGTHS $\leq$ 360 MPa VARYING THICKNESS

yield strength of the material reduces the required Charpy impact test temperature for materials of comparable thickness. Hence to achieve the required impact energy, higher strength materials should be tested at lower temperatures in comparison to lesser yield strength materials. Figure 5 compares historical design curves [5] to the current design curves [1] for materials with yield strengths in the range 310 MPa $\leq \sigma_y \leq$ 360 MPa. As shown, for each thickness, the curve has shifted to the right, the result being that a higher impact test temperature is allowed, for specimens of comparable yield strengths, using the updated code.

The following paragraphs discuss the analytical model [7, 8, 19] used to validate changes to the design curves in the EN 13445 standard. The authors assumed that any existing defect greater than 50% of the plate thickness would have a high probability of detection (POD) using modern non-destructive testing (NDT) techniques such as ultrasonics. A function describing the relationship of the plate to defect size was generated. The maximum and minimum values of the function were specified to be unity (representing a through wall defect) and 0.25 (a quarter wall thickness defect), respectively. The crack ratio was set at $a/c = 0.4$ and a smooth transition between the maximum and minimum function was assumed.

The primary stress (σ_p) was assumed to be equal to be approximately $\frac{2}{3}\sigma_y$, the secondary stress, in the as-welded condition was assumed $\frac{1}{3}\sigma_p$. The fracture toughness was estimated from Charpy V-notch test data using the Master curve approach (see Equation 11) with an additional shift to account for the high strain rates seen during impact testing. It was specified that the B_{eff} was assumed to be equal to the total crack front length. This differs from the definition of B given in BS 7910 (Equation 8) where B was specified to be the thickness of the material for which a K_c is being sought but, presumably, is related to crack length via the function used to describe the plate to crack depth thickness.

$$K_c = 20 + \left[11 + 77exp\left(\frac{T_D - T_{27} + 18}{52}\right)\right] \left(\frac{25}{B_{eff}}\right)^{\frac{1}{4}} \left(ln\frac{1}{1-p_f}\right)^{\frac{1}{4}} \tag{11}$$

The FAD was generated similar to the R6 Option 2 approach using Equation 12 [20]. The R6 document specifies that this method is only relevant for values in the range of $L_r < 1$. It is unknown whether L_r was limited in the case of the EN 13445 method. It should however be noted that the calculation of the L_r parameter used in the EN 13445 method (Equation 13) differs from that in the R6 or BS 7910 documents (see Equation 1). This variation in the calculation of L_r may allow values to be extended beyond the limiting value stated in R6. This is currently under investigation. The fracture parameter, a ratio of stress intensity due to the presence of the defect and the critical stress intensity factor, K_r, was specified to be that shown in Equation 14. This parameter is identical to that provided in BS 7910 and R6.

$$K_r = \left(1 + 0.5L_r^2\right)^{\frac{1}{2}} \tag{12}$$

$$L_r = \frac{\sigma}{\sigma_{nsy}} \tag{13}$$

$$K_r = \frac{K_I}{K_{IC}} \tag{14}$$

The stress intensity factor K (Equation 15) was calculated, similarly to BS 7910 and R6, with both primary and secondary stress contributions, with a plasticity correction applied to the stress intensity associated with secondary stresses (Equation 5). The stress intensity factor was calculated from Equation 15 with an assumed geometrical factor Y of unity. This differs from the BS 7910 method where the geometrical factor Y is calculated for specific defect aspect ratios. The plasticity correction factors are shown in Table 1. These values are a simplification of finite element analysis conducted for the SINTAP project [17]. The original work investigated plasticity correction using J-integral results from elastic and elastic plastic analyses for a butt welded plate. The material properties were taken from a C-Mn steel girth weld with a yield strength of 300 MPa. For the evenly matched analysis (where σ_y is identical when comparing base and weld materials) the weld properties were assumed to be identical to the parent properties. Over-matching and under-matching properties were assumed to be $\pm 30\%$ of the parent material properties, respectively. The EN 13445 approach uses the data generated in [17] to fit a curve to, predominately, the evenly matched data set. This method of calculating plasticity due to secondary stresses differs again from the method provided in BS 7910 (see Equation 6).

TABLE 1: PLASTICITY CORRECTION FACTORS

$\frac{V}{V_0} = 1$	$L_r \leq 0.7$
$\frac{V}{V_0} = 2.17 - 1.67L_r$	$0.7 \leq L_r \leq 1.0$
$\frac{V}{V_0} = 5.5 - 5L_r$	$1.0 \leq L_r \leq 1.1$

$$K = Y\sigma\sqrt{\pi a} \tag{15}$$

The analytical model results were plotted for minimum design temperature versus plate thickness; the historical design code data is included as a reference. The plot shows that, for a postulated 7 mm defect in a 15 mm plate a significantly higher minimum design temperature was found using the analytical model (approximately -50°C) compared to the historical code data (approximately -70°C). Additionally the authors [7] investigated the relationship between impact test temperature, design temperature and fracture toughness, including the analytical model results and incorporating test data. A relatively good agreement was found between test data and the analytical model. Test data however was limited to materials with $\sigma_y \geq 450$ MPa, other material properties are not addressed.

DISCUSSION

The design curves in PD 5500 were derived from experience and were validated using wide plate test data. The validation tests were loaded to extreme values of strains to ensure against brittle fracture. It is considered unlikely that PVs in service would ever be loaded in such a way and hence it is generally accepted that the design curves published in PD 5500 are overly-conservative [6, 9, 11, 15]. The level of conservatism in the PD 5500 curves is not clear, nor is it immediately obvious how the level of conservatism can be assessed.

The European code EN 13445 has increased the required Charpy impact test temperature by using fracture mechanics techniques in comparison to earlier editions of EN 13445. The validation of the model was, however, limited and the performance of lower strength steels in the as-welded condition was not assessed. Additionally, where prior versions of EN 13445 design curves were comparative to those in PD 5500, that is no longer the case. Hadley and Garwood [6] showed that, for comparable materials, the required impact energy could be achieved much more readily employing the EN 13445 compared to the PD 5500 method. Given that the curves in PD 5500 are known to be overly-conservative some differences in energy requirements is not unexpected however, the largest reduction in required test temperature coincides with design curves for lower strength materials which were not validated with test data.

The PD 5500 design curves, or more specifically the validation tests associated with these design curves, can be investigated using fracture mechanics techniques (BS 7910). The fracture mechanics method outlined in BS 7910 is similar to the analytical model used to justify the current EN 13445 design curves. Hadley and Garwood [6] have already assessed the two methods (PD 5500 and EN 13445) against historical PV failures. They showed that, had the designers been following the current PD 5500 method (which had not been published at the time), these failures could have been avoided. Should the EN 13445 method have been employed, it was less clear whether or not these failures could have been avoided. The ambiguity was, according to the authors, related to the differences in the methods. It is hoped that, by reassessing data using a standardised fitness for service code (BS 7910), the performance of the EN 13445 design curves can be clarified.

With that in mind a programme of work will be conducted at Imperial College London on a lower strength steel ($\sigma_y \leq$ 350 MPa). The work will include both Charpy impact testing and fracture toughness testing at lower temperatures. Results will be assessed using BS 7910 and the EN 13445 analytical model.

CONCLUSIONS

PD 5500 design curves were originally derived based on experience and validation tests. The validation tests were conducted under extreme loading conditions and hence it is likely that the curves are overly-conservative.

BS 7910 can be used to assess defects similar to those used in the PD 5500 design curve validation tests. Using this fracture mechanics approach the influence of various test conditions, such as loading and defect size, can be reassessed. By correlating the PD 5500 Charpy impact toughness to fracture toughness the level of conservatism in PD 5500 can be estimated. These data can also be more readily compared to the EN 13445 design curves.

The EN 13445 design curves have been modified using an analytical fracture mechanics based approach. The updated curves are, compared with previous EN 13445 design curves, significantly less onerous in terms of required Charpy test temperature. There is some ambiguity surrounding whether the EN 13445 design curves are robust enough to prevent brittle failures in lower strength materials due to limited validation tests.

A programme of work is underway at Imperial College London aimed at addressing concerns about the robustness of the EN 13445 design curves. The work will focus specifically on a lower strength material. The materials performance, in terms of both Charpy impact energy and fracture toughness, at low temperatures will be investigated and, where possible, literature test data for comparable materials will be incorporated to increase the statistical power of the data. These data will be assessed using the fracture mechanics assessments in BS 7910 and EN 13445 analytical model for a variety of loading conditions. Deviations in the methods and the impact of these deviations on structural integrity will be investigated.

ACKNOWLEDGMENT

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