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COMPARISON OF BS 7910 AND API 579-1/ASME FFS-1 SOLUTIONS WITH REGARDS TO LEAK-BEFORE-BREAK

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ABSTRACT

One of the ways to aid the decision whether or not to live with defects in pressurised component is through the demonstration of Leak-Before-Break (LBB). In this paper, three of the main solutions to carry out the LBB assessment, namely Stress Intensity Factor (SIF), Reference Stress (RS) and Crack Opening Area (COA) have been evaluated and compared for both BS 7910 and API 579/ASME FFS-1 standards. Differences with respect to the choice of solutions and boundary conditions are illustrated and discussed. Same applied loads and material properties have been used when applying each procedure. Different geometries for potential pressurised components which are of interest with regards to LBB have been considered for each solution. Focus is made on cylinders where axially and circumferentially oriented through-wall and surface cracks were analysed. While SIF solutions produce similar results for both standard, reference stress solutions show higher differences in results. However, in LBB assessments it is the reference stress solution which is more relevant, since most LBB assessments pre-suppose the material to be ductile. Here there are significant differences between the different assumptions. In terms of COA, solutions are not given at the same location however they seems to agree well within the common range of applicability. Differences in the assessment route between the standards is also discussed. Experimental data from literature has been also been compared to the different standard predictions, to illustrate the accuracy of the solutions for axially oriented surface cracks. Aptitude of solutions to predict the boundary between leak and break is discussed, in relation to how this shows the level of conservatism.

INTRODUCTION

A LBB assessment demonstrates that leakage of fluid through a crack in the component's wall would be detected prior to conditions of instability at which rapid extension occurs. Although generally applied in the nuclear industry, widely established structural integrity assessment procedures such as BS 7910 [1] and API 579-1/ASME FFS-1 [2] offer this route to assess crack-like defects. Both are recognised as representing best practice and safe, although they may not always give the same results. While the structure of the assessment is similar, solutions provided differs and some differences in the assumptions may be observed.

LBB assessment procedures consider two independent aspects to the potential failure, namely fracture mechanics and leakage assessment [3]. Fracture mechanics calculations are used to determine the criticality of defects with respect to both brittle fracture and also plastic collapse. The inter-relation of these two failure modes is done using a Failure Assessment Diagram (FAD) approach to compare the assessment point to the FAD line showing the boundary between safe and potentially unsafe conditions. Assessment of plastic collapse is carried out via the collapse ratio parameter known as L_r (defined as the ratio between reference stress and the material's yield stress), along with assessment of the material's resistance to fracture via the fracture ratio parameter, K_r (the ratio of the stress intensity factor to the material's fracture toughness). The conservative calculation of the fracture side of LBB is to assume a larger flaw size than might be present. However, this would over-estimate the leak rate, where a smaller flaw size than anticipated will give a conservative prediction of leakage. On the other side of the

LBB assessment, the leakage rate calculations are centred on the evaluation of the resulting crack opening area. The LBB consideration of fitness-for-service requires that the amount of fluid that is leaking can be detected and monitored sufficiently before any risk of fracture to enable repairs to be safely carried out. To carry out the assessment, both standards follow the same structure, including the calculation of stress intensity factor, reference stress and crack opening area. These three parameters will be investigated below.

NOMENCLATURE

a	Half defect length for through-thickness defect, defect height for surface defect
c	Half defect length for surface defect
K_r	Fracture ratio
L_r	Plastic collapse ratio
P_b	Primary through-wall bending stress
$P_{b,l}$	Primary through-wall bending stress due to locally applied bending loads
P_m	Primary membrane stress
$P_{m,a}$	Primary membrane stress due to global axial loads
$P_{m,p}$	Primary membrane stress due to internal pressure
$P_{m,b}$	Primary membrane stress due to global bending moments
R_{el}	Lower yield strength of discontinuously yielding material
R_i	Inner radius of pipe/cylinder
R_m	Mean radius of a pipe/cylinder
R_o	Outer radius of pipe/cylinder
σ_{ref}	Reference stress
t	Wall thickness of pipe/cylinder
W	Width of pipe/cylinder

CRACK-LIKE DEFECT AND LBB ASSESSMENTS IN BS 7910 AND API 579-1/ASME FFS-1

For pressurised equipment in a non-nuclear context, BS 7910 and API 579-1/ASME FFS-1 are the most commonly used procedures for FFS assessment. They both offer different generic routes to cover a wide range of components, each being dependent on the quality and detail of the material's property data available. The higher the level of analysis, the higher is the required input data and the more complex are the analysis. On the other hand, the lower the level of analysis the more conservative the result.

Common features of fracture assessment to BS 7910 and API 579-1/ASME FFS-1 include assessment of plastic collapse (L_r), material's resistance to fracture (K_r) and representation of those results on an FAD. With 2013 update BS 7910 differs somewhat from that of current API 579-1/ASME FFS-1 FAD. Prior to BS 7910, a similar study has been conducted between BS 7910 and R6/FITNET [4]. The current work follow the framework of this paper. After the introduction of general assessment strategy of each procedure, the equations used to determine L_r and COA in the two documents and their validity ranges will be presented and compared in detail. SIF required to determine K_r will not be detailed here as a similar work can be found in [5].

BS 7910:2013 offers now three alternative routes, called "options", to carry out fracture assessments following the harmonization with R6 [6] procedure. Option 1 require basic information and is divided into continuous yielding material or not whereas Option 2 requires full stress-strain data for the material under consideration. Option 3 which is recommended to use for specific cases as an alternative to the two previous, requires both elastic and elastic-plastic analysis with the help of numerical analysis of crack driving forces.

The current edition of API 579-1/ASME FFS-1 offers three "levels" depending on available material properties and assessor skills. Level 1 is a quick screening method for the assessment, whereas Level 2 is a more sophisticated analysis using generic FAD. A Level 2 analysis requires stresses to be expressed in terms of membrane and bending components and partial safety factors are applied to the independent variables to account for uncertainty. Level 3 offer five methods to provide the best estimate of structural integrity including a method using material's specific FAD similar to BS 7910's Option 2 or elastic plastic analysis similar to Option 3.

The different routes to calculate FADs are presented in Annex A. To be noted that the equation of API's FAD for a level 2 assessment was used in previous BS 7910's edition (2005). As BS 7910's option 1 (A.1) and API 579-1/ASME FFS-1's level 2 (A.5) can be regarded as equivalent in terms of required data, they are compared in Annex A. It can be observed that BS 7910's equation depends on material properties (i.e. E, N,…) while API's one is only defined via L_r. Parametric studies shows the influence of Young modulus (Figure 5), ratio yield stress to ultimate tensile stress (Figure 6) and yield stress (Figure 7) and FAD's shape. In most cases, BS 7910's FAD curve tends to be slightly lower for $0 < L_r < 0.8$, higher for $0.8 < L_r < 1$ and lower for $1 < L_r$. This allows potential larger flaws in the region just before plasticity while more conservatism is applied once $L_r > 1$.

In terms of LBB, both standards are using principles described earlier to carry out the fracture resistance side of the assessment. BS 7910 provides the same procedure as R6, with a simplified procedure to study hypothetical through wall defect and a more rigorous procedure considering growth of initially part-penetrating defect. API 579-1/ASME FFS-1 provides a procedure to assess through-wall defects already leaking, with re-characterization of the existing defect. While the structure of the assessment is similar between API 579-1/ASME FFS-1 and BS 7910's simplified procedure, solutions provided for the calculation of the different parameters differs.

The analytical procedure of calculating the different parameter in accordance with both standards for a given defect was performed using Matlab. Details of each analysis can be found in the following sections.

ASSESSMENT OF PIPE/CYLINDER WITH AXIAL DEFECT

Pipe/cylinder containing axial defect is the first part of assessment. Two different type of defect were considered as the most common in LBB assessment, namely surface and through-thickness defect. See Figure 1 and Figure 2 for geometrical definition. Since the structure of solutions requires applied loads to be expressed as membrane stress and bending stress, the following conversion formulae were used for pressure loading:

$$P_m = \frac{P \cdot R_i}{t} \tag{1}$$

$$P_b = \frac{P \cdot R_o^2}{R_o^2 - R_i^2}\left[\frac{t}{R_i} - \frac{3}{2}\left(\frac{t}{R_i}\right)^2 + \frac{9}{5}\left(\frac{t}{R_i}\right)^3\right] \tag{2}$$

Where P is the internal pressure, R_i the inner radius, R_o the outer radius and t the wall thickness. Within this part of the study, pipes/cylinders with a width of 1000 mm, inner radius of 400 mm and thickness of 20 mm were analysed. The material was assumed to have a Young modulus of 210 GPa, a yield strength of 450 MPa and ultimate tensile stress of 530 MPa. The loading conditions considered were membrane and bending stress of 150 MPa. Pressure induced through-wall bending can be ignored as it is not considered to contribute to collapse load [7].

- Through-thickness defect

As mentioned earlier, calculation of K_r, via the stress intensity factors will not be detailed for all cases in this paper. However, some remarks will be made through this case. In both case the general SIF equation is provided, divided into primary and secondary stresses, adapted to all geometry with tabulated values:

$$K_I = ((Y\sigma)_p + (Y\sigma)_s)\sqrt{\pi a} \tag{3}$$

API 579-1/ASME FFS-1 allows the users to take crack face pressure into account and also provide an equation for internal pressure loading only:

$$K_I = \frac{PR_o}{t} G_p \sqrt{\pi a} \tag{4}$$

where G_p is calculated using tabulated values.

Results of the SIF calculation for pipes/cylinders containing through-thickness defect can be seen on Figure 8. All solutions provide similar results with a maximum difference under 4%. Comparison of SIF solutions for other geometry can be found in [5].

To assess reference stress for through-thickness defects, both code references Willoughby and Davey [8] which is a solution for derived for plates and corrected with a correction factor to fit to pipes/cylinders geometries. In BS 7910 (Equation B.1), a factor of 1.2 applied to the membrane stress is intended to produce a similar level of conservatism as that inherent in the flat plate solutions. A unique surface correction factor, M_T, is provided (B.2) whereas three different factors are available in API 579-1/ASME FFS-1 (B.4),(B.5) and (B.6). Note that equation (B.4) is recommended for use in all assessment being a best fit to data from different references ((B.5) is an approximate expression and (B.6) an upper bound expression). The latter, equation (B.6), is the same surface correction factor than in BS 7910 (B.2):

From (B.7): $\lambda^2 = 3.305\frac{a^2}{R_i.t}$

Inserting in (B.6):

$$M_{t(API579)} = \sqrt{1 + 0.4845\lambda^2} \cong \sqrt{1 + 1.6\left(\frac{a^2}{R_i.B}\right)} = M_{T(BS7910)}$$

Results of the reference stress calculation for pipes/cylinders containing through-thickness defect can be seen on Figure 9 to Figure 11. The length of defect, 2a, was normalized to the length of the pipe/cylinder, W. Plastic collapse is presented via the parameter L_r, defined as:

$$L_r = \frac{\sigma_{ref}}{\sigma_{ys}} \tag{5}$$

BS 7910 solution gives higher value of reference stress than all API 579-1/ASME FFS-1 solutions. Removing the 1.2 factor, the modified solution matches with API 579-1/ASME FFS-1 solution using the third surface correction factor (B.6) and API 579-1/ASME FFS-1 equation. Using API's two first surface correction factors ((B.4), (B.5)) give similar result. Taking the recommended correction factor (B.4) a difference of around 20% is shown for small crack length between BS 7910 and API 579-1/ASME FFS-1. This difference due to the factor 1.2 on the membrane stress part in (B.1). As the crack length increase, this difference increase due to the different surface correction factors used. In the example presented here with membrane stress loading only, the difference between reaches 40% at $L_r = L_{r,max}$. Assuming bending stress only, it has to be noted that API 579-1/ASME FFS-1 equation results in a constant value equal to $0.66P_b$ while BS 7910 is varying with the defect length.

In terms of crack opening area, solutions provided are different. BS 7910's equation (C.1) is a solution for plate corrected for cylindrical shape (C.2) and small-scale plasticity (C.3) [9]. The solution is strictly valid only when flaw lengths do not exceed the least radius of curvature of the shell. For axial cracks, $\lambda \leq 8$. As many solution, COA is given at mid-thickness. API's recommended solution is based on a wide range of FEA validation based on linear elastic fracture mechanics. However, this solution can be corrected for elastic-plastic conditions (C.8) with the help of a plasticity correction factor (C.9). It also account for the crack taper resulting from through-wall bending loads. It is evaluated using tabulated values and allows to evaluate COA for both inside and outside surface.

Results of the COA calculation for pipes/cylinders containing axial through-thickness defect can be seen on Figure 12. Solution provided in BS 7910 at mid-thickness assumes a higher COA than in API's one when reaching its limit of applicability. However it can be observed that both solution give coherent results.

- Surface defect

Limit load solutions can be complicated for surface defect problems as it can be defined as the load corresponding to local yielding ('local' limit load), or net section yielding, ('global' limit load). For the case of surface defect, in contrast to API 579-1/ASME FFS-1 (B.18), BS 7910 distinguishes internal and external case even if the same solution is provided (B.15). None of the above allow consideration of defect face pressure in case of an internal defect in a pressurized component. As per through-thickness solution, BS 7910 provides a unique surface correction factor (B.16), M_s, while API 579-1/ASME FFS-1 provides different solutions (B.21), (B.22).

Results of the reference stress calculation for pipes/cylinders containing surface defect can be seen on Figure 13 to Figure 16. The length of internal surface defect, 2c, is normalized to the width, W, of the pipe/cylinder and the defect depth, a, is normalized to the wall-thickness, t.

Figure 13 shows the effect of the surface correction factors available in API 579-1/ASME FFS-1 on L_r. Calculations presented with equation (B.21) have been calculated using C=0.85. One can see that recommended equations tend to lower reference stress results. Note that Eq. (B.4) and (B.22) are recommended to use for all assessment. Comparison with BS 7910's solution will be made using this couple of surface correction factors only.

In Figure 14 to Figure 16, the L_r vs a/t results of membrane only, membrane and bending and bending only cases were drawn for increasing 2c/W values. As long as membrane stress is involved, BS 7910 gives higher reference stress values. This is partly due to the 1.2 factor applied on membrane stress (B.15) as per through-thickness case. Moreover as the crack length increase, BS 7910's solution tends to increase more rapidly for defects with a depth superior to the half thickness (Figure 14). Another observation can be made on the effect of bending stress (Figure 15 - Figure 16). API 579-1/ASME FFS-1's solutions are reduced due to the parameter g (B.19). Without this parameter applied on bending stress, solutions give similar results.

Experimental data from [10] have been used to check the validity of the above reference stress solutions. Tests have been conducted tests on cylinders fabricated with the material 4134V steel and data can be found in Table 1. Cases have been plotted in a plane of hoop stress versus a/2c. A failure boundary has been developed using reference stress solutions, assuming a constant thickness, t, of 7.5 mm, inner radius, R_i, of 110.94 mm and crack depth, a, of 5.75 mm. Results can be found on Figure 17. The boundary created using reference stress solutions separates leak and break cases almost distinctly for API's recommended solutions while BS 7910's is more conservative assuming leakage as failure. Removing the 1.2 factor applied on membrane stress in BS 7910's solution (B.15) is presented as well as 'BS 7910 – Mod' and leads to a less conservative assumption. However, the failure boundary still exclude leaks. The reference stress solution provided in API 579-1/ASME FFS-1 is found to successfully distinguish leak and break cases of the literature test data considered. On the other hand, BS 7910's solution does not allow leaks.

ASSESSMENT OF PIPE/CYLINDER WITH CIRCUMFERENTIAL DEFECT

Pipe/cylinder containing circumferential defect is the second part of assessment. As previously, two different type of defect were considered, namely surface and through-thickness defect. See Figure 3 and Figure 4 for geometrical definition.

Since the structure of solutions requires applied loads to be expressed as membrane stress and bending stress, the following conversion formulae were used for pressure loading accounting for internal pressure and axial loading:

$$P_m = \frac{P \cdot R_i^2}{R_o^2 - R_i^2} + \frac{F}{\pi(R_o^2 - R_i^2)} \tag{6}$$

Where P is the internal pressure, R_i the inner radius, R_i the outer radius and F the axial force. Within this part of the study, pipes/cylinders with a width of 1000 mm, inner radius of 400 mm and thickness of 20 mm were analysed. The material was assumed to have a yield strength of 450 MPa and ultimate tensile stress of 530 MPa. The loading conditions considered were membrane and bending stress of 150 MPa.

- Through-thickness defect

Results of the reference stress calculations for pipes/cylinders containing circumferential through-thickness defect can be seen on Figure 18 to Figure 20. For the analysis, BS 7910 (B.8) and API 579-1/ASME FFS-1 formulae (B.9) were employed. The geometrical normalisation for circumferential flaws is made by the division of the half crack angle, θ, by π. The assessment results of the pipe/cylinder containing a through thickness defect subject to pure tension, combined tension and bending, and in addition to combined tension, bending and internal pressure can be found in Figure 18, Figure 19 and Figure 20 respectively.

For the case where through-thickness defects are subject to pure tension (Figure 18), both BS 7910 and API 579-1/ASME FFS-1 deliver nearly the same results. However, the difference in the assessment of combined tension and bending case is important (Figure 19). This is mainly due to the definition of α (B.11) in API 579-1/ASME FFS-1, which is two times lower than in BS 7910 and the presence of the squared denominator. Taking only bending stress into consideration, (B.8) and (B.9) reduce to:

$$\sigma_{ref-BS} = \frac{2P_b}{3(1 - \frac{2a}{\pi R_i})} \neq \sigma_{ref-API} = \frac{2P_b}{3(1 - \frac{a}{\pi R_m})^2}$$

As a result, BS 7910 gives higher reference stress results. However the evolution of solution is similar on the range of applicability for both standards. Same observation can be made when internal pressure is taken into account together with tension and bending (Figure 20).

In terms of crack opening area, BS 7910 provides the same equation than for axial defect with a correction factor, $\alpha(\lambda)$, different (C.12) The solution is strictly valid only for circumferential defects with $\lambda \leq 5$. As per axial defect, API 579-1/ASME FFS-1provides two equations for COA calculation using tabulated values for both inside and outside surface. It can be calculated with internal pressure (C.13) or stress (C.14) loading.

Results of the COA calculation for pipes/cylinders containing circumferential through-thickness defect can be seen on Figure 21. Solution provided in BS 7910 at mid-thickness is coherent with API's pressure equation (C.13) until half of its applicability range and assumes a much lower COA after. Moreover API's stress equation (C.1) give much higher COA results than others. This effect was already seen a little for axial defects. Remembering that COA solution will be used to assess the leak rate which is a critical parameter in a LBB assessment, an over-estimation of the COA can lead to non-conservative result and an under-estimation lead to a very conservative result.

- Surface defect

For the case of circumferential surface defect, both BS 7910 (B.24) and API 579-1/ASME FFS-1 (B.26) [11] distinguish internal and external case. None of the above allow consideration of defect face pressure in case of an internal defect in a pressurized component. Only internal defect will be illustrated here.

Results of the reference stress calculation for pipes/cylinders containing circumferential surface defect can be seen on Figure 22 to Figure 24. The geometrical normalisation for circumferential defect is made by the division of the half defect angle, θ, by π and the defect depth, a, is normalized to the wall-thickness, t. The assessment results of the pipe/cylinder containing a surface defect subject to membrane, combined membrane and bending only can be found in Figure 22, Figure 23 and Figure 24 respectively. Considering membrane stress only, solutions give similar results for small defect depth and diverges significantly as the defect depth increases (Figure 22). Solution in API 579-1/ASME FFS-1 increase much slower than BS 7910's one. For combined membrane and bending stress loading, BS 7910 gives higher results than API 579-1/ASME FFS-1 (Figure 23). When only bending stress is considered, solutions give similar results (Figure 24).

CONCLUSIONS

Based on the comparisons undertaken in this work, it was found that:

- For axial defects, BS 7910 tends to give higher results for both through-thickness and surface defects. The multiplier of 1.2 introduced for the reference stress solutions (B.1), (B.15) to achieve a certain level of conservatism is partially responsible from this result. It should also be noted that in the original papers of Folias, this factor is not present.
- For circumferential defects, when only membrane stress loading is considered, both standards give similar results. However, when bending stress loading is applied, BS 7910's solutions tend to give higher reference stress results. To be noted that reference stress solutions recommended in BS 7910 are mainly from local limit load solutions, as they are more conservative.
- Analyse of the reference stress solutions for axial surface defects versus experimental data available shows that API 579-1/ASME FFS-1 1 is found to successfully distinguish leak and break cases. On the other hand, BS 7910 gives more conservative results, assuming leak as a fail. This is also seen even after the factor 1.2 removed.
- In terms of COA, results are similar for axial defects. However, for circumferential defects, BS 7910 tends to produces a lower COA as the defect size increase. More surprisingly, solutions from API 579-1/ASME FFS-1 with stress parameter gives much higher results. Remembering that COA solution will be used to assess the leak rate which is a critical parameter in a LBB assessment, an over-estimation of the COA can lead to non-conservative result and an under-estimation lead to a very conservative result.

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ANNEX A

FAD DEFINITION

A.1 FAD DEFINITION IN BS 7910

- Option 1 (Without yield discontinuity):

$$K_r = \begin{cases} \dfrac{0.3 + 0.7e^{-\mu L_r^{6}}}{\sqrt{1 + 0.5L_r^2}} \; for \; L_r \le 1 \\ f_1(1) \cdot L_r^{\frac{N-1}{2N}} \; for \; 1 < L_r < L_{r,max} \\ 0 \; for \; L_r \ge L_{r,max} \end{cases} \quad \text{(A.1)}$$

Where $\mu = \min\left(\frac{0.001E}{\sigma_{ys}}, 0.6\right)$ and $N = 0.3\left(1 - \frac{\sigma_{ys}}{\sigma_{uts}}\right)$

- Option 1 (With yield discontinuity):

$$K_r = \begin{cases} \dfrac{1}{\sqrt{1 + 0.5L_r^2}} \; for \; L_r < 1 \\ \dfrac{1}{\sqrt{\lambda + \frac{1}{2\lambda}}} \; for \; L_r = 1 \\ f_1(1) \cdot L_r^{\frac{N-1}{2N}} \; for \; 1 < L_r < L_{r,max} \\ 0 \; for \; L_r \ge L_{r,max} \end{cases} \quad \text{(A.2)}$$

Where $\lambda = 1 + \frac{E\Delta\varepsilon}{R_{el}}$

- Option 2 (Material specific):

$$K_r = \begin{cases} \left(\dfrac{E\varepsilon_{ref}}{L_r\sigma_{ys}} + \dfrac{L_r^3\sigma_{ys}}{2E\varepsilon_{ref}}\right)^{-1/2} \; for \; L_r < L_{r,max} \\ 0 \; for \; L_r \ge L_{r,max} \end{cases} \quad \text{(A.3)}$$

Where ε_{ref} is the true strain at true stress $\sigma_{ref} = L_r\sigma_{ys}$

- Option 3 (Numerical analysis):

$$K_r = \begin{cases} \sqrt{\dfrac{J_e}{J}} \; for \; L_r < L_{r,max} \\ 0 \; for \; L_r \ge L_{r,max} \end{cases} \quad \text{(A.4)}$$

A.2 FAD DEFINITION IN API 579-1 / ASME FFS-1

- Level 1:

Screening criteria

- Level 2:

$$K_r = \begin{cases} [0.3 + 0.7e^{-0.65L_r^{6}}][1 - 0.14L_r^2] \; for \; L_r \le L_{r,max} \\ 0 \; for \; L_r \ge L_{r,max} \end{cases} \quad \text{(A.5)}$$

- Level 3 – Method B:

$$K_r = \begin{cases} \left(\dfrac{E\varepsilon_{ref}}{L_r\sigma_{ys}} + \dfrac{L_r^3\sigma_{ys}}{2E\varepsilon_{ref}}\right)^{-1/2} \; for \; L_r < L_{r,max} \\ 0 \; for \; L_r \ge L_{r,max} \end{cases} \quad \text{(A.6)}$$

ANNEX B

REFERENCE STRESS SOLUTIONS

B.1 Reference stress solutions for pipes/cylinders with axial through-thickness defect

B.1.1 BS 7910:2013

$$\sigma_{ref} = 1.2 M_T P_m + \frac{2P_b}{3\left(1-\frac{2a}{W}\right)} \quad (B.1)$$

Where

$$M_T = \sqrt{1 + 1.6\left(\frac{a^2}{R_i . t}\right)} \quad (B.2)$$

B.1.2 API 579-1 / ASME FFS-1

$$\sigma_{ref} = \frac{P_b + \sqrt{P_b^2 + 9(M_t . P_m)^2}}{3} \quad (B.3)$$

Where three definitions are given for M_t:

$$M_t = \sqrt{\frac{1.02 + 0.4411\lambda^2 + 0.006124\lambda^4}{1 + 0.02642\lambda^2 + 1.533(10^{-6})\lambda^4}} \quad (B.4)$$

$$M_t = \begin{cases} \sqrt{1 + 0.3797\lambda^2 - 0.001236\lambda^4} & \text{for } \lambda \le 9.1 \\ 3.3 + 0.01936\lambda^2 & \text{for } \lambda > 9.1 \end{cases} \quad (B.5)$$

$$M_t = \sqrt{1 + 0.4845\lambda^2} \quad (B.6)$$

And

$$\lambda = \frac{1.818a}{\sqrt{R_i . t}} \quad (B.7)$$

B.2 Reference stress solutions for pipes/cylinders with circumferential through-thickness defect

B.2.1 BS 7910:2013

$$\sigma_{ref} = \frac{\pi(P_{m,a} + P_{m,p})}{\pi - \frac{a}{R_i} - 2arcsin\left(0.5sin\left(\frac{a}{R_i}\right)\right)} + \frac{\pi P_{m,b}(R_o^4 - R_i^4)}{(4R_o {R_m}^2 . t)\left(\pi - \frac{a}{R_i} - 2\frac{sin^2\left(\frac{a}{R_i}\right)}{\pi - \frac{a}{R_i}} - \frac{sin\left(\frac{2a}{R_i}\right)}{2}\right)} + \frac{2P_{b,l}}{3(1-\frac{2a}{\pi R_i})} \quad (B.8)$$

B.2.2 API 579-1 / ASME FFS-1

$$\sigma_{ref} = \frac{P_b + \sqrt{P_b^2 + 9(Z . P_m(1-\alpha)^2)^2}}{3(1-\alpha)^2} \quad (B.9)$$

Where:

$$\theta = \frac{a}{R_m} \quad (B.10)$$

$$\alpha = \frac{a}{\pi . R_m} \quad (B.11)$$

$$\tau = \frac{t}{R_o} \quad (B.12)$$

$$\psi = arcos(\frac{sin\theta}{2}) \quad (B.13)$$

$$Z = \frac{\pi . ({R_o}^2 - {R_i}^2)}{(2-\tau)R_o . t(2\psi - \theta)} \quad (B.14)$$

B.3 Reference stress solutions for pipes/cylinders with axial surface defect

B.3.1 BS 7910:2013

$$\sigma_{ref} = 1.2 M_s P_m + \frac{2P_b}{3(1-\alpha")^2} \quad (B.15)$$

Where:

$$M_s = \frac{1 - \frac{a}{t . M_T}}{1 - \frac{a}{t}} \quad (B.16)$$

$$\alpha" = \frac{\frac{a}{t}}{1+\frac{t}{c}} \quad \text{for } W \ge 2(c+t)$$
$$\alpha" = \frac{a}{t}\frac{2c}{W} \quad \text{for } W < 2(c+t) \quad (B.17)$$

Use R_i for inner defect and R_o for outer defect in the calculation of M_T

B.3.2 API 579-1 / ASME FFS-1

$$\sigma_{ref} = \frac{g . P_b + \sqrt{(g . P_b)^2 + 9(M_s . P_m . (1-\alpha)^2)^2}}{3 . (1-\alpha)^2} \quad (B.18)$$

Where:

$$g = 1 - 20\alpha^3\left(\frac{a}{2c}\right)^{0.75} \quad (B.19)$$

$$\alpha = \frac{\frac{a}{t}}{1 + \frac{t}{c}} \quad (B.20)$$

Two definitions are available for the surface correction factors:

$$M_{s1} = \frac{1 - C\left(\frac{a}{t . M_t}\right)}{1 - C\left(\frac{a}{t}\right)} \quad \text{Where } C = \begin{cases} 1 \text{ for rectangular shape} \\ 0.67 \text{ for parabolic shape} \\ 0.85 \text{ for a best fit to the data} \end{cases} \quad (B.21)$$

$$M_{s2} = \frac{1}{1 - \frac{a}{t} + \frac{a}{t}\left(\frac{1}{M_t(\lambda_a)}\right)} \quad (B.22)$$

Where

$$\lambda_a = \frac{1.818c}{\sqrt{R_i . a}} \quad (B.23)$$

B.4 Reference stress solutions for pipes/cylinders with circumferential surface defect

B.4.1 BS 7910:2013

$$\sigma_{ref} = \frac{P_m\left[\pi\left(1-\frac{a}{B}\right)+2\left(\frac{a}{B}\right)sin\left(\frac{c}{R}\right)\right]}{\left(1-\frac{a}{B}\right)\left[\pi-\left(\frac{a}{B}\right)\left(\frac{c}{R}\right)\right]}+\frac{2P_b}{3(1-\alpha")^2} \tag{B.24}$$

Where

$$\alpha" = \frac{\frac{a}{B}}{1+\frac{B}{c}} \quad \text{for } \pi R \geq c+B$$
$$\alpha" = \frac{a}{B}\frac{c}{\pi R} \quad \text{for } \pi R < c+B \tag{B.25}$$

B.4.2 API 579-1 / ASME FFS-1

$$\sigma_{ref} = \frac{P_b+\sqrt{(P_b)^2+9(Z.P_m.(1-\alpha)^2)^2}}{3.(1-\alpha)^2} \tag{B.26}$$

Where

$$\theta = \frac{\pi c}{4R_o} \text{for external crack}$$
$$\theta = \frac{\pi c}{4R_i} \text{ for internal crack} \tag{B.27}$$

$$x = \frac{a}{t} \tag{B.28}$$

$$\tau = \frac{t}{R_o} \tag{B.29}$$

$$A = x\left[\frac{(1-\tau)(2-2\tau+x\tau)(1-\tau+x\tau)^2}{2\{1+(2-\tau)(1-\tau)\}}\right] \tag{B.30}$$

$$\alpha = \frac{\frac{a}{t}}{1+\frac{t}{c}} \tag{B.31}$$

$$\psi = arcos(Asin\theta) \tag{B.32}$$

$$Z = \left[\frac{2\psi}{\pi}-\frac{x\theta}{\pi}\left(\frac{2-2\tau+x\tau}{2-\tau}\right)\right]^{-1} \tag{B.33}$$

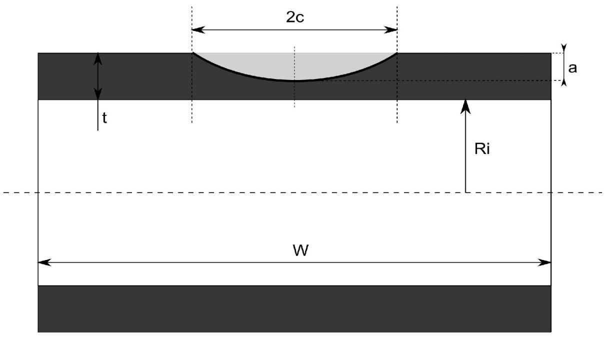

Figure 1: Pipe/cylinder with axial surface defect

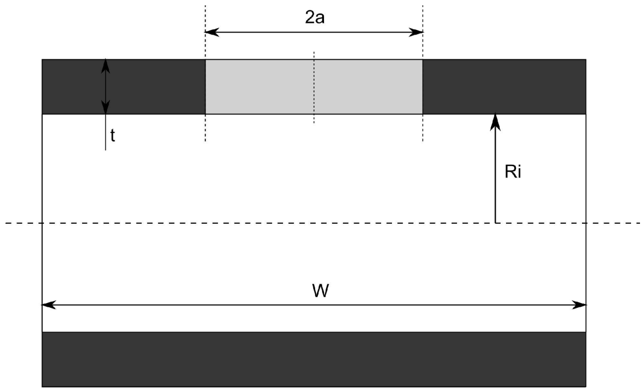

Figure 2: Pipe/cylinder with axial through-thickness defect

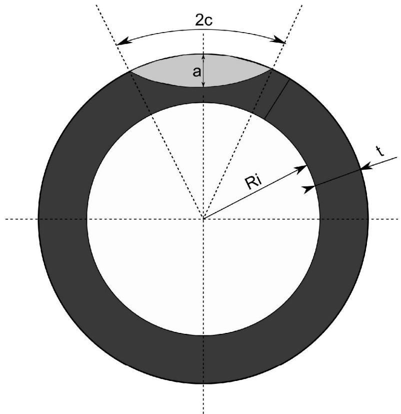

Figure 3: Pipe/cylinder with circumferential surface defect

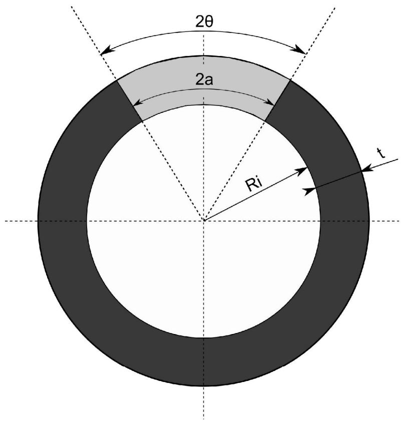

Figure 4: Pipe/cylinder with circumferential through-thickness defect

ANNEX C

CRACK OPENING AREA SOLUTIONS

C.1 CRACK OPENING AREA FOR AXIAL DEFECTS

C.1.1 BS 7910:2013

$$COA = \alpha(\lambda)\frac{2\pi\sigma_m c^2}{E'}\left(\left(1+\frac{S^2}{2}\right)^{\frac{3}{2}} - \left(\frac{S^2}{2}\right)^{\frac{3}{2}}\right) \quad (C.1)$$

$$\lambda = \sqrt[4]{0.75(1-\nu^2)}\frac{2c}{\sqrt{R_m.t}} \quad (C.2)$$

$$\alpha(\lambda) = 1 + 0.1\lambda + 0.16\lambda^2 \quad (C.3)$$

The terms in brackets represents a first-order correction for the effects of crack-tip plasticity increasing with the load level S being the ratio between the membrane stress to the flow stress:

$$S = \frac{\sigma_m}{\sigma_f} \quad (C.4)$$

C.1.2 API 579-1/ASME FFS-1 - PRESSURE

$$COA = H_p\left(\frac{pR_o}{t}\right)\left(\frac{2\pi c^2}{E}\right) \quad (C.5)$$

C.1.3 API 579-1/ASME FFS-1 - STRESS

$$COA = (P_m H_o + P_b(H_0 - 2H_1))\frac{2\pi c^2}{E} \quad (C.5)$$

Where:

$$H_{0,1,p} = \frac{A_0 + A_1\lambda + A_2\lambda^2 + A_3\lambda^3}{1 + A_4\lambda + A_5\lambda^2 + A_6\lambda^3 + A_7\lambda^4} \quad (C.6)$$

$$\lambda = \frac{1.818a}{\sqrt{R_i.t}} \quad (C.7)$$

$$COA_p = \gamma_p.COA \quad (C.8)$$

Where the plasticity modifier γ_p, is determined using the following equation, valid for $0 \leq L_r \leq 1.2$:

$$\gamma_p = 1.008 - 0.33015\,L_r^2 + 5.53696\,L_r^4 - 3.96974\,L_r^6 + 2.00844\,L_r^8 \quad (C.9)$$

C.2 CRACK OPENING AREA FOR CIRCUMFERENTIAL DEFECTS

C.2.1 BS 7910:2013

$$COA = \alpha(\lambda)\frac{2\pi\sigma_m c^2}{E'}\left(\left(1+\frac{S^2}{2}\right)^{\frac{3}{2}} - \left(\frac{S^2}{2}\right)^{\frac{3}{2}}\right) \quad (C.10)$$

$$\lambda = \sqrt[4]{0.75(1-\nu^2)}\frac{2c}{\sqrt{R_m.t}} \quad (C.11)$$

$$\alpha(\lambda) = \sqrt{1 + 0.117\lambda^2} \quad (C.12)$$

C.2.2 API 579-1/ASME FFS-1 - PRESSURE

$$COA = H_0\left(\frac{pR_o{}^2}{R_o{}^2 - R_i{}^2}\right)\left(\frac{2\pi c^2}{E}\right) \quad (C.13)$$

C.2.3 API 579-1/ASME FFS-1 – STRESS

$$COA = (P_m H_o + P_b(H_0 - 2H_1))\frac{2\pi c^2}{E} \quad (C.14)$$

Where:

$$H_0 = \frac{A_0 + A_1\lambda + A_2\lambda^2}{1 + A_3\lambda + A_4\lambda^2 + A_5\lambda^3} \quad (C.15)$$

$$\lambda = \frac{1.818c}{\sqrt{R_i.t}} \quad (C.16)$$

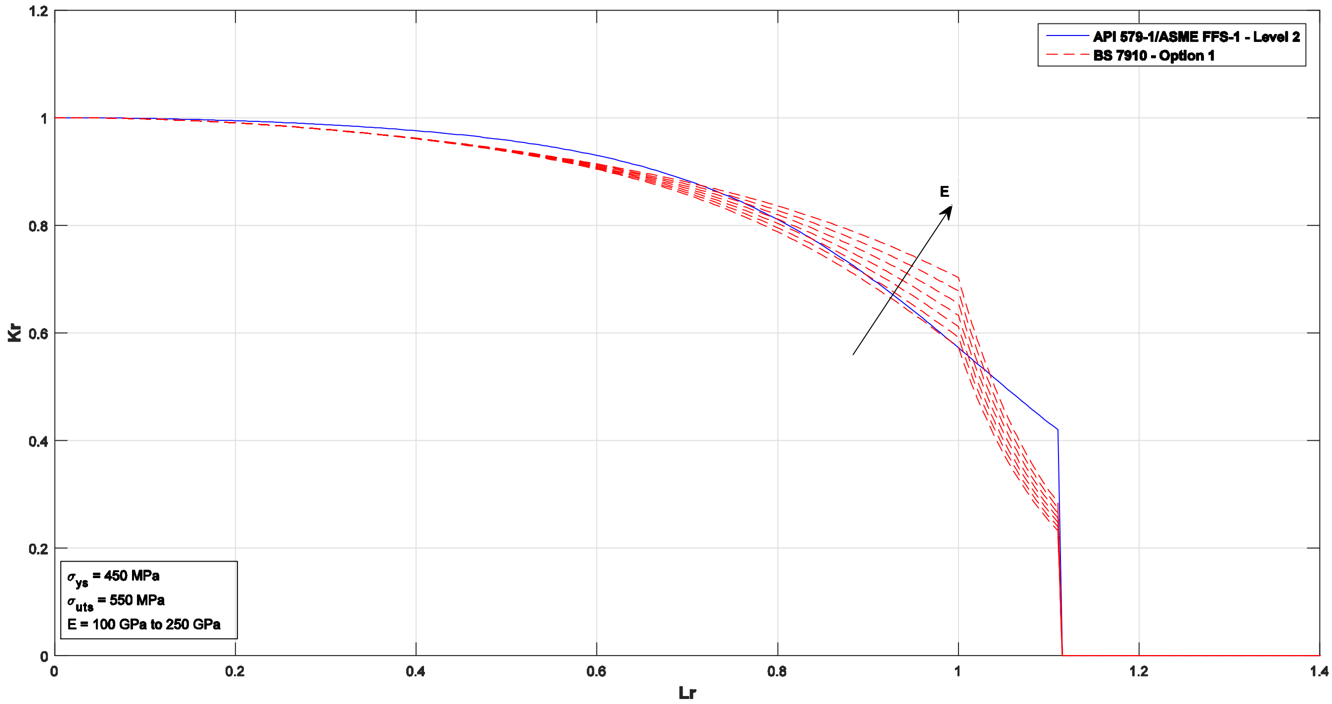

Figure 5: Influence of young modulus on FAD shape

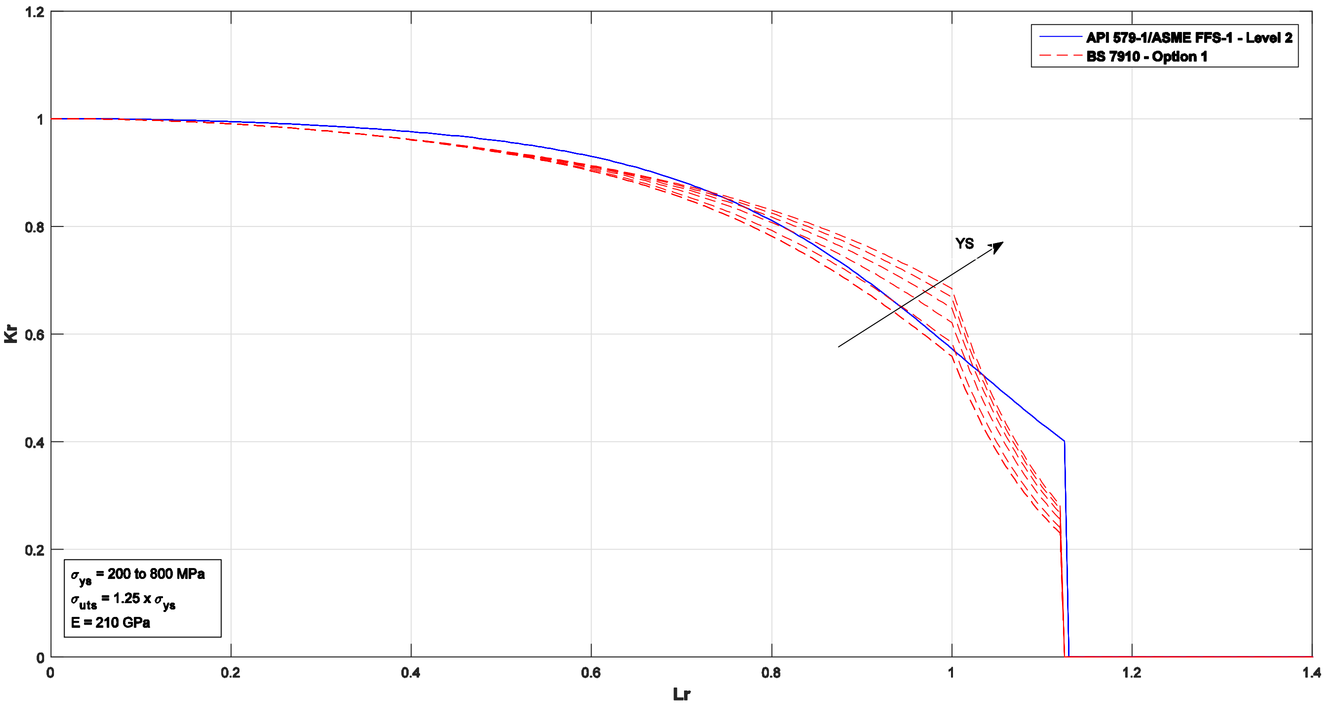

Figure 6: Influence of ratio yield stress to ultimate tensile stress on FAD shape

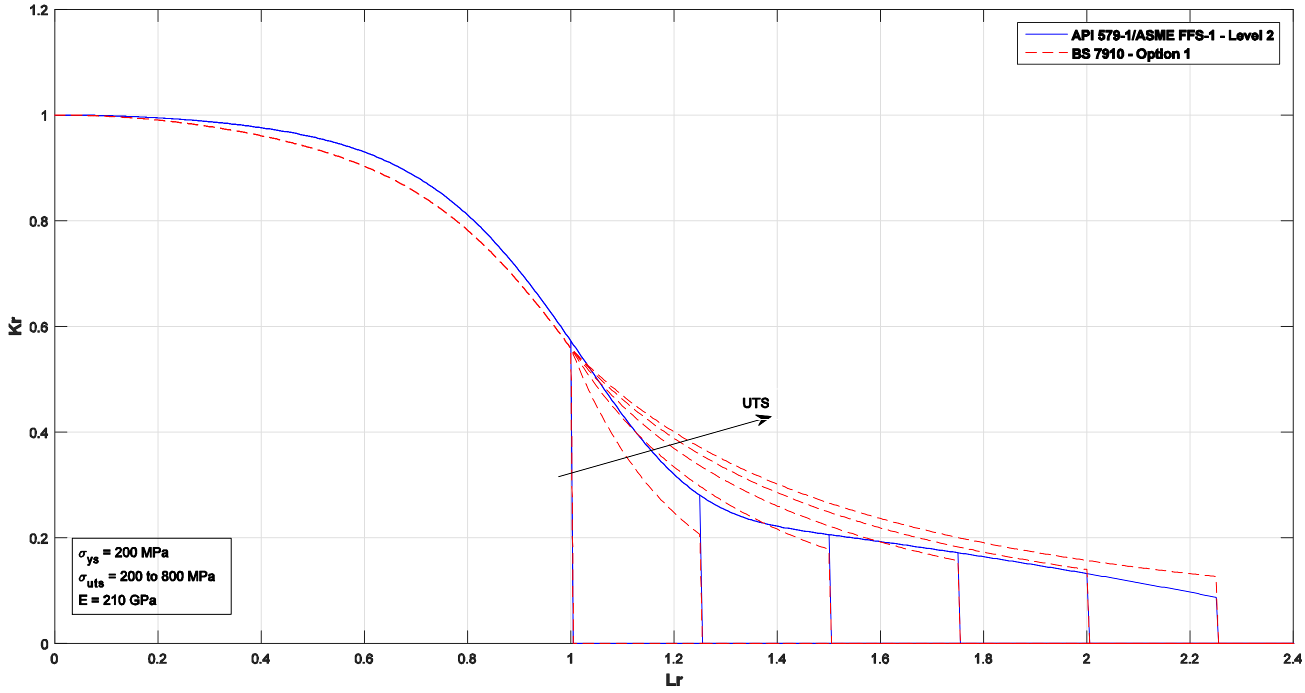

Figure 7: Influence of yield stress on FAD shape

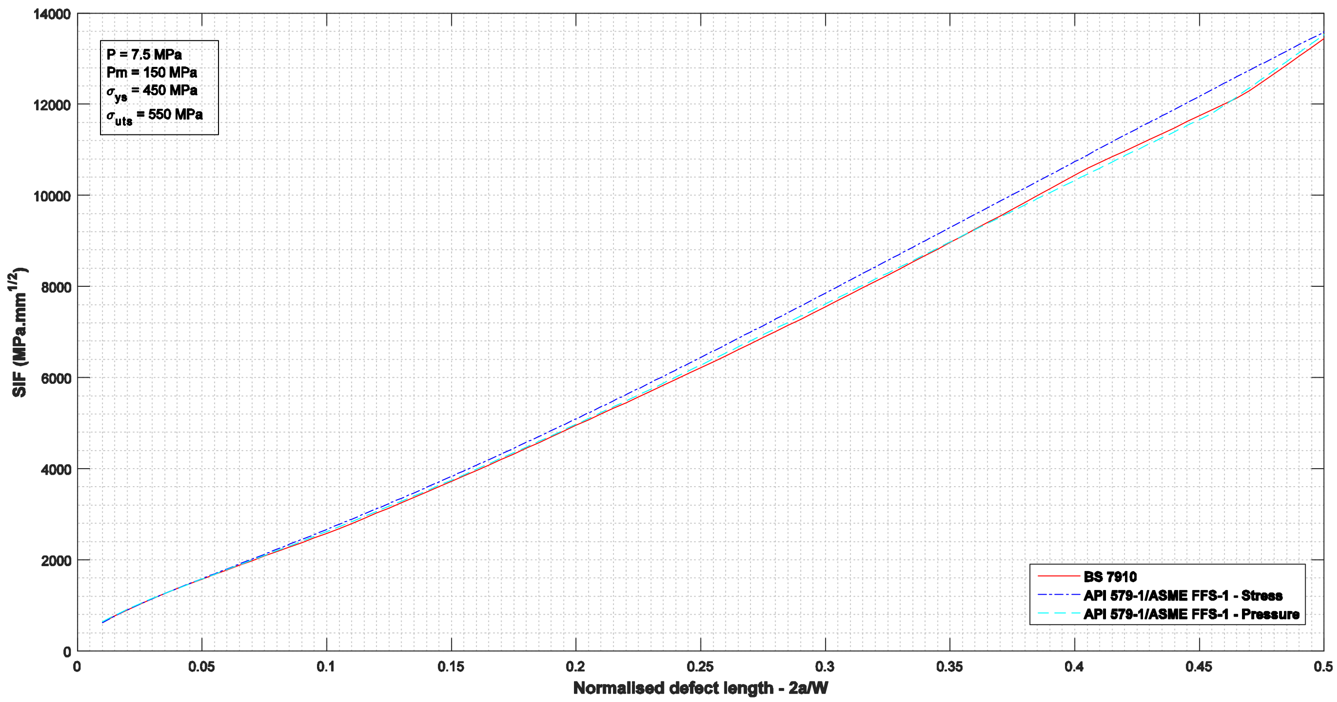

Figure 8: SIF - Pipe/cylinder containing through-thickness axial defect

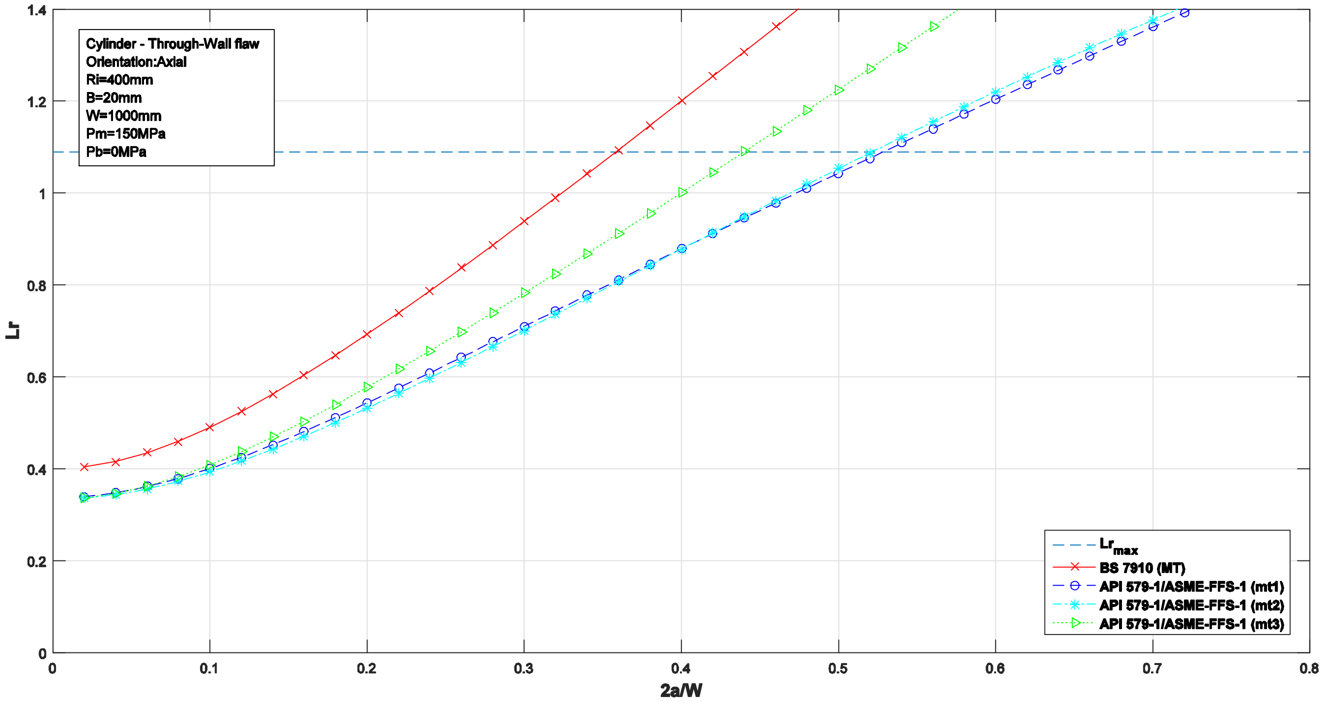

Figure 9: RS - Pipe/cylinder containing through-thickness axial defect - Membrane stress only

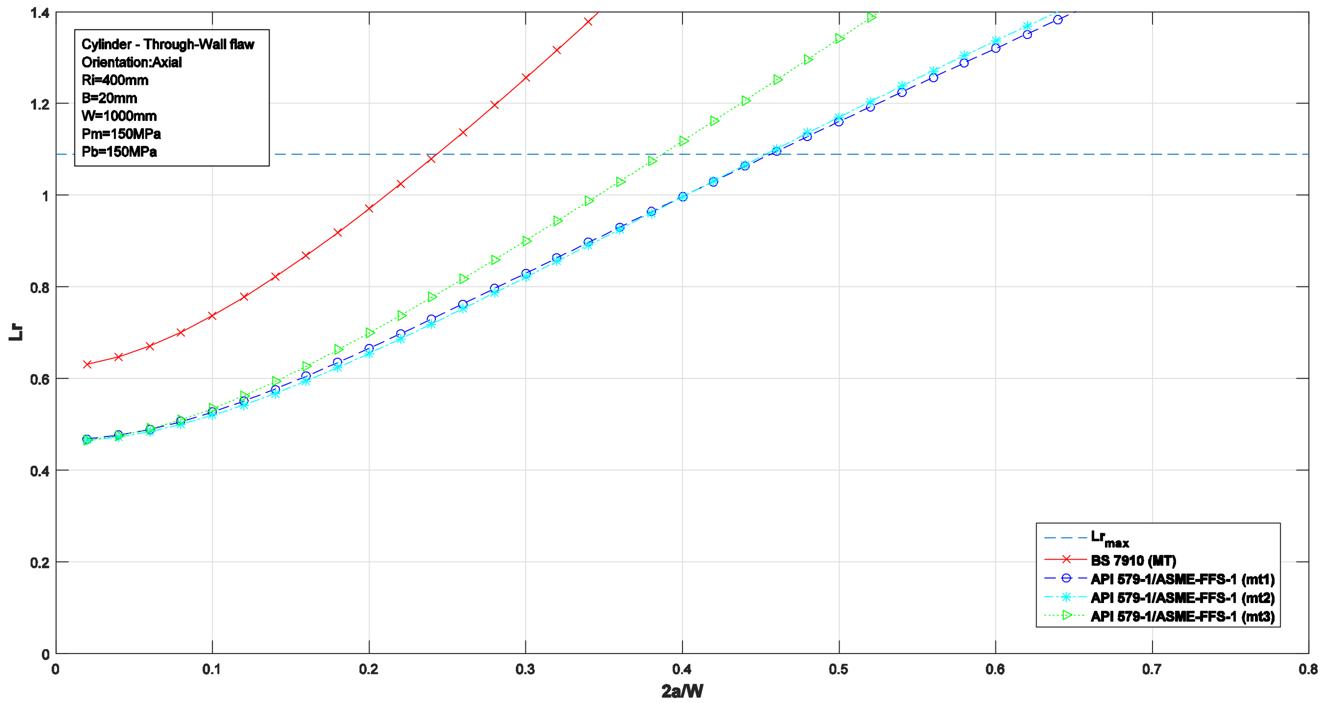

Figure 10: Pipe/cylinder containing through-thickness axial defect - Membrane & Bending stress

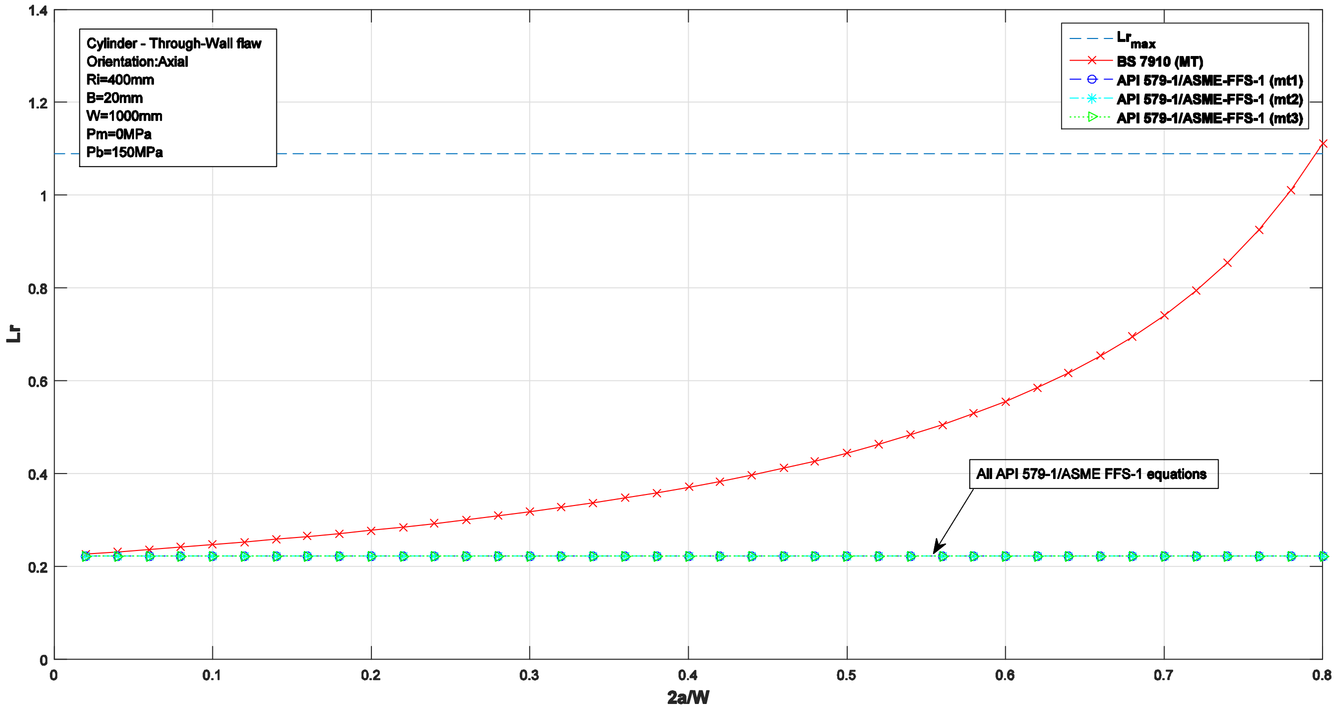

Figure 11: RS - Pipe/cylinder containing through-thickness axial defect - Bending stress only

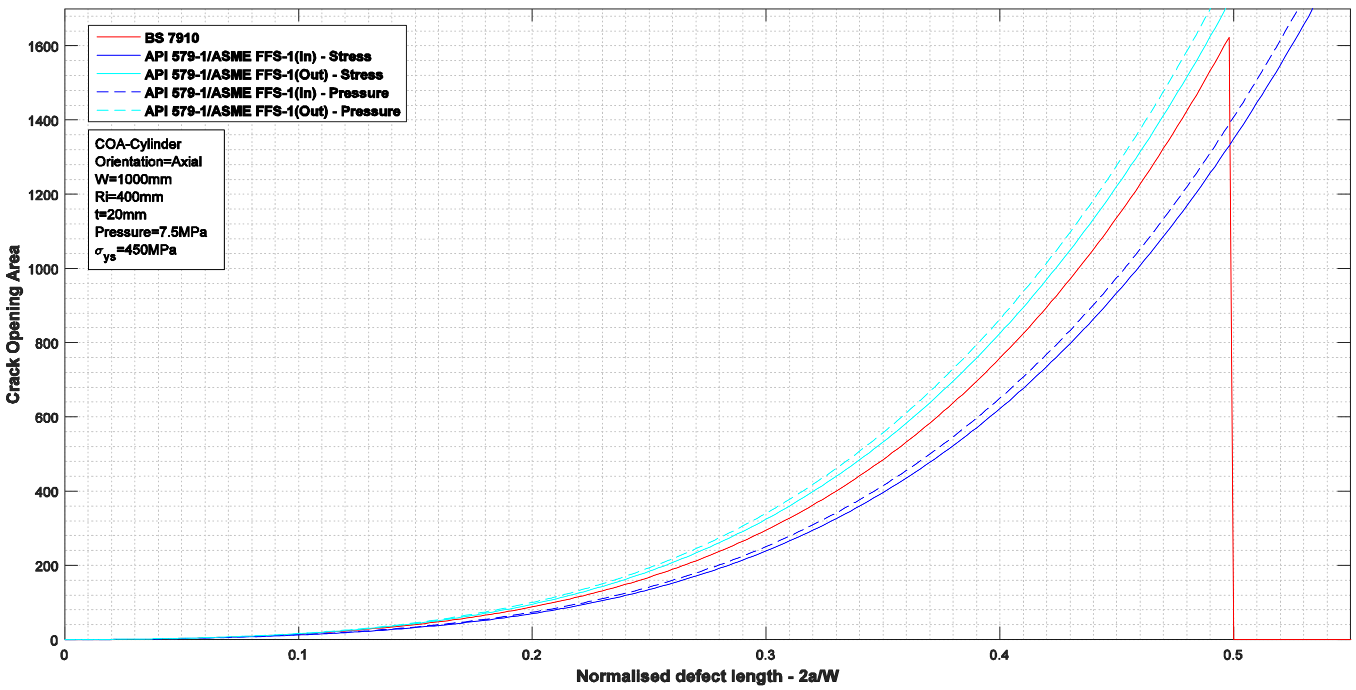

Figure 12: COA - Pipe/cylinder containing through-thickness axial defect

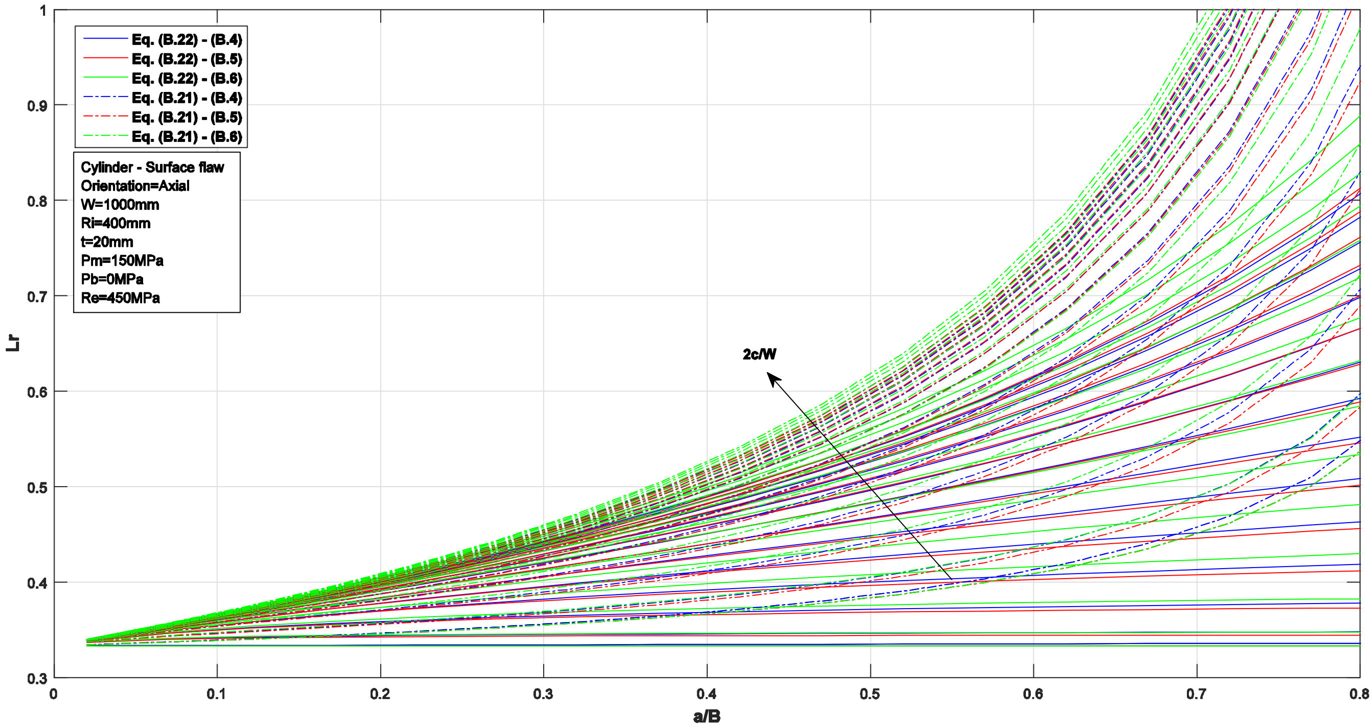

Figure 13: RS - Pipe/cylinder containing surface axial defect - API 579-1/ASME FFS-1 - Membrane stress only

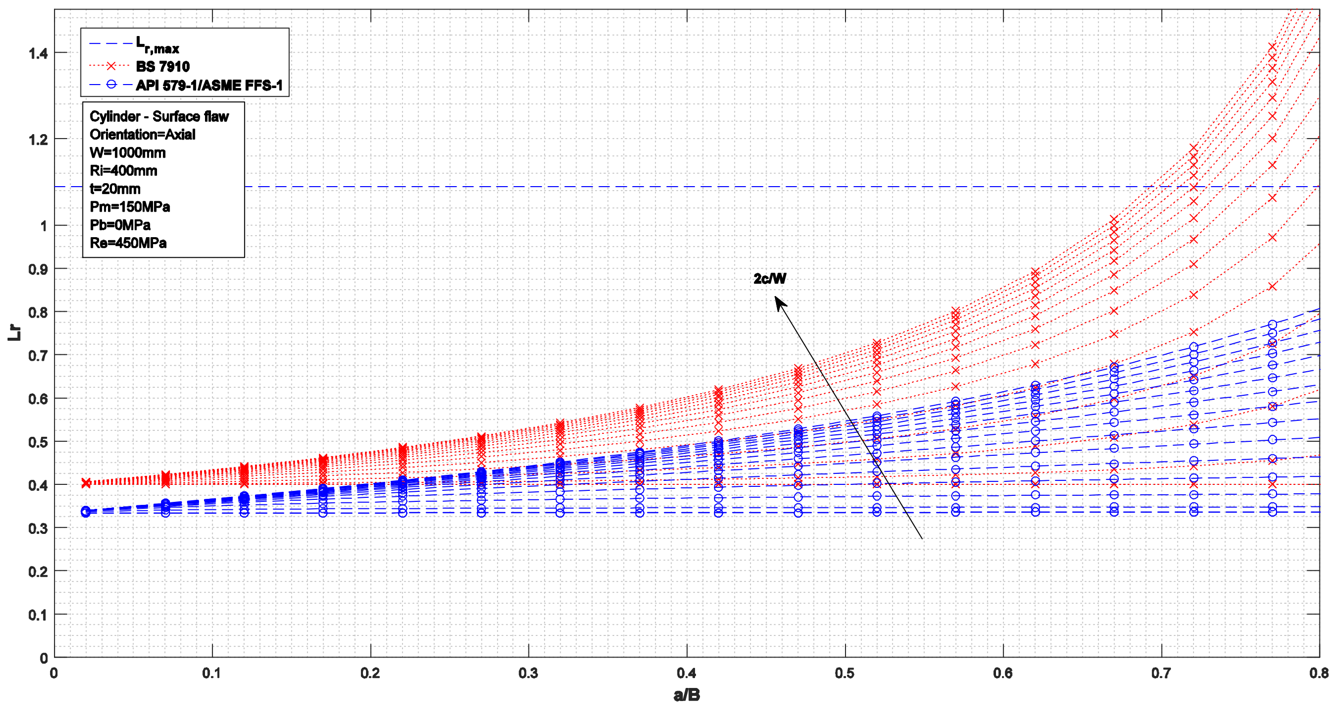

Figure 14: RS - Pipe/cylinder containing surface axial defect - Membrane stress only

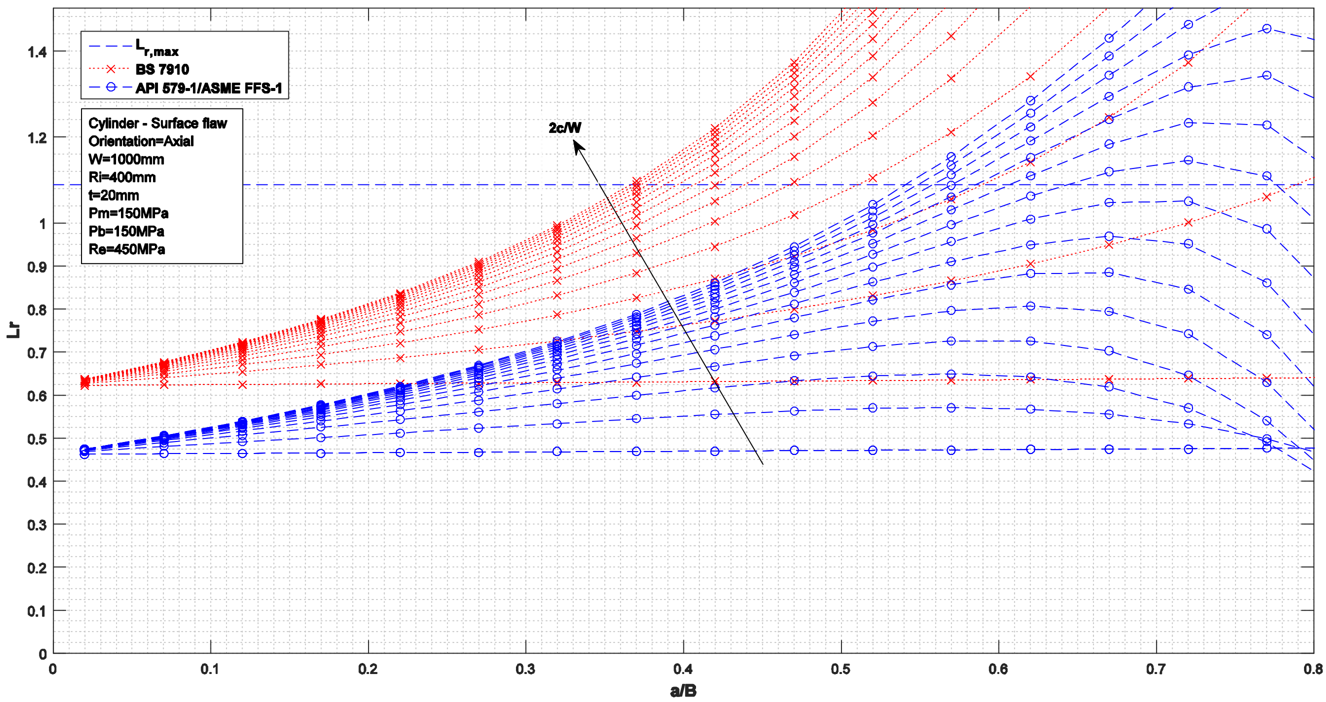

Figure 15: RS - Pipe/cylinder containing surface axial defect - Bending stress only

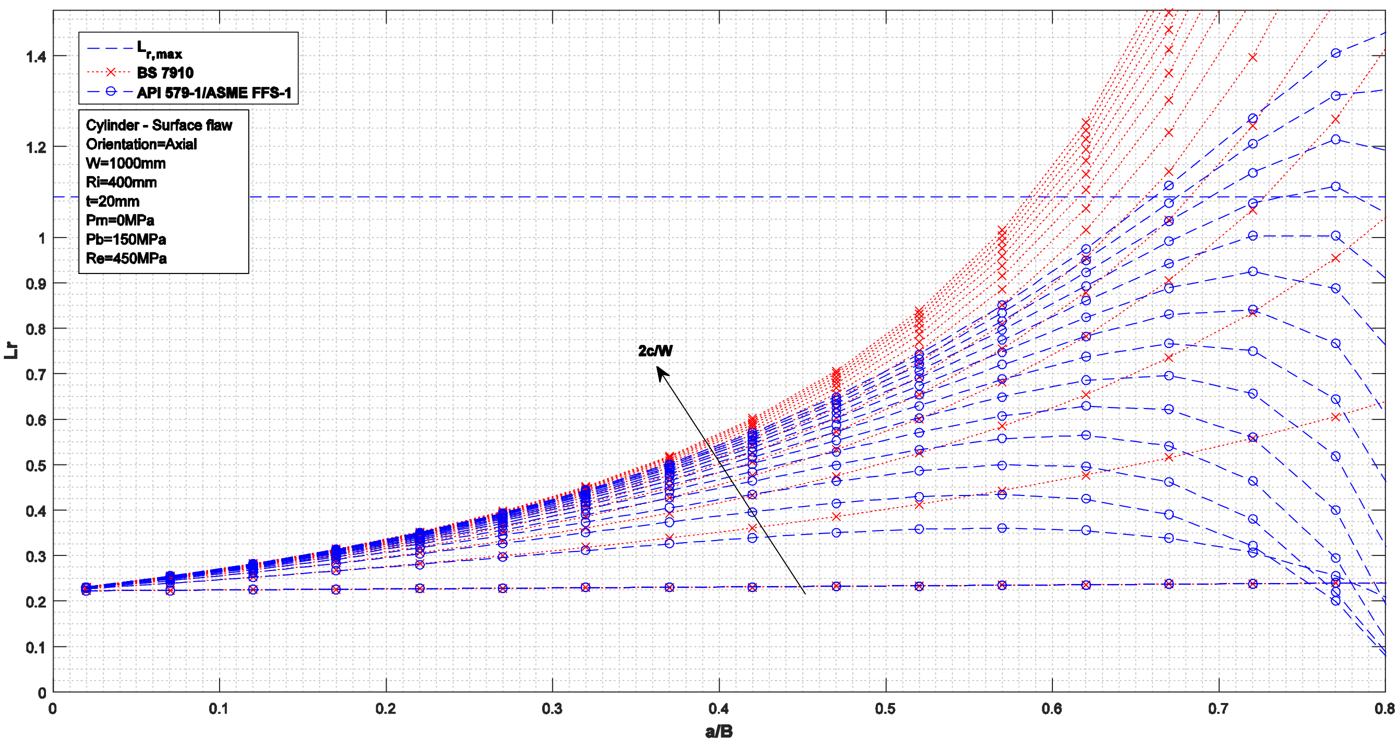

Figure 16: RS - Pipe/cylinder containing surface axial defect - Membrane & Bending stress

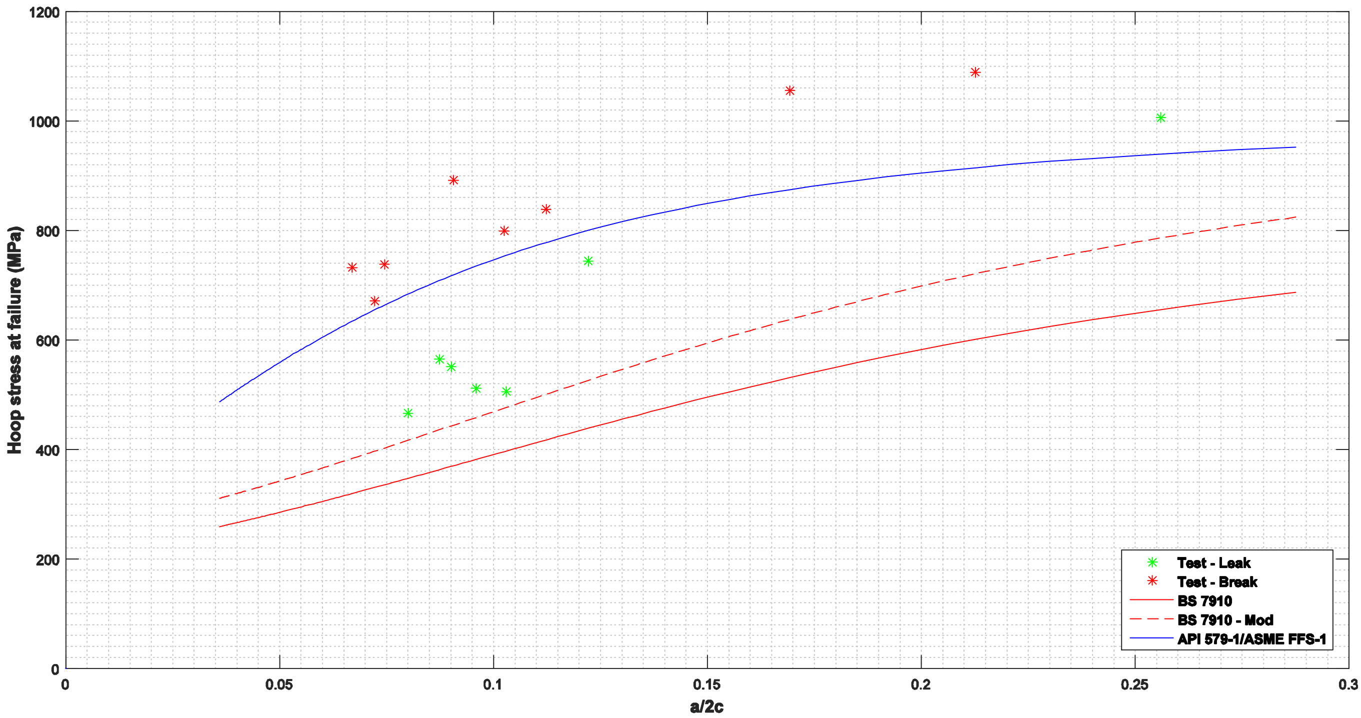

Figure 17: Experimental data and failure boundaries as per BS 7910 and API 579-1/ASME FFS-1

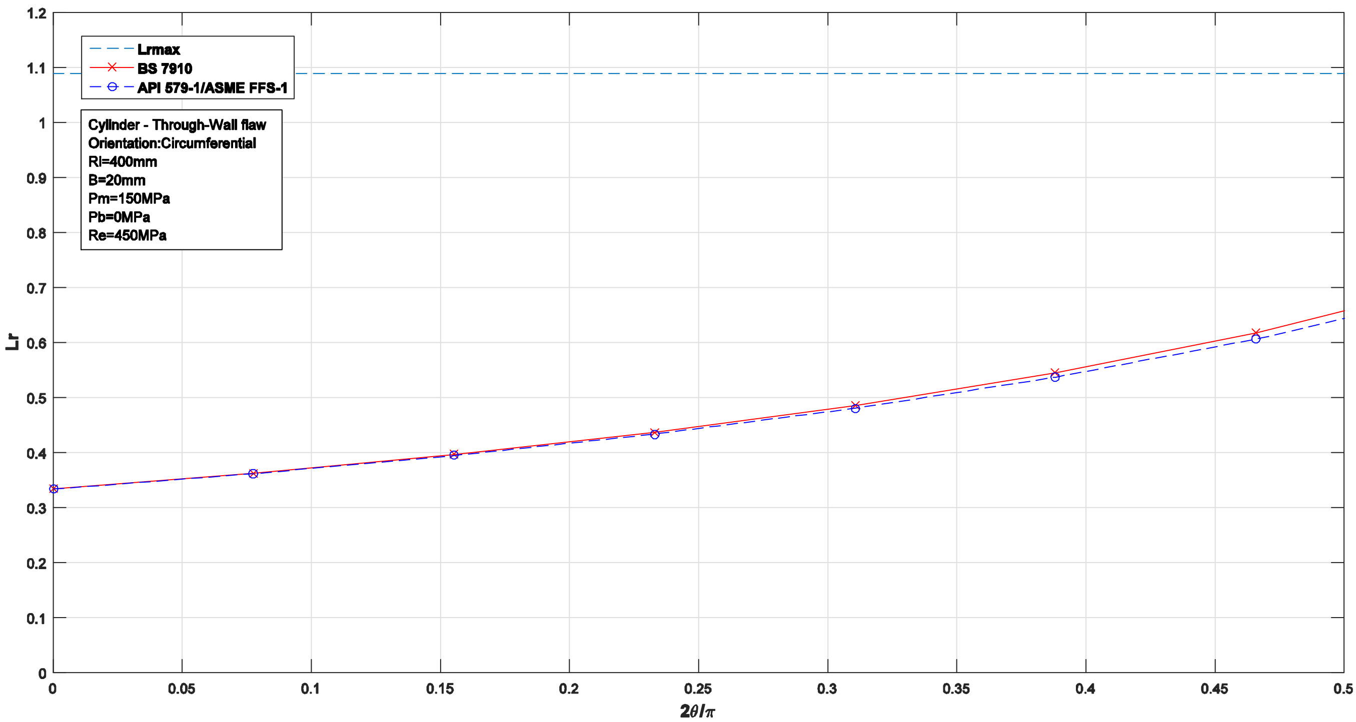

Figure 18: RS - Pipe/cylinder containing through-thickness circumferential defect - Pure tension only

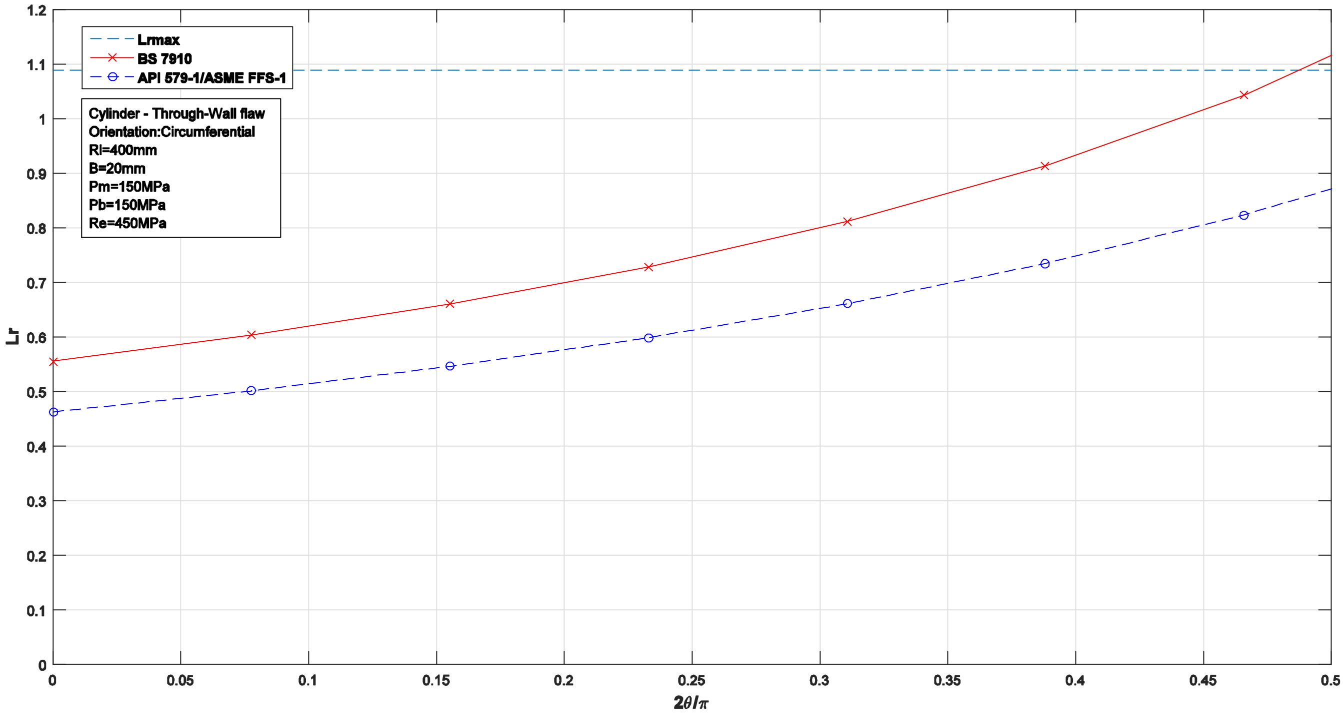

Figure 19: RS - Pipe/cylinder containing through-thickness circumferential defect - Combined tension and bending

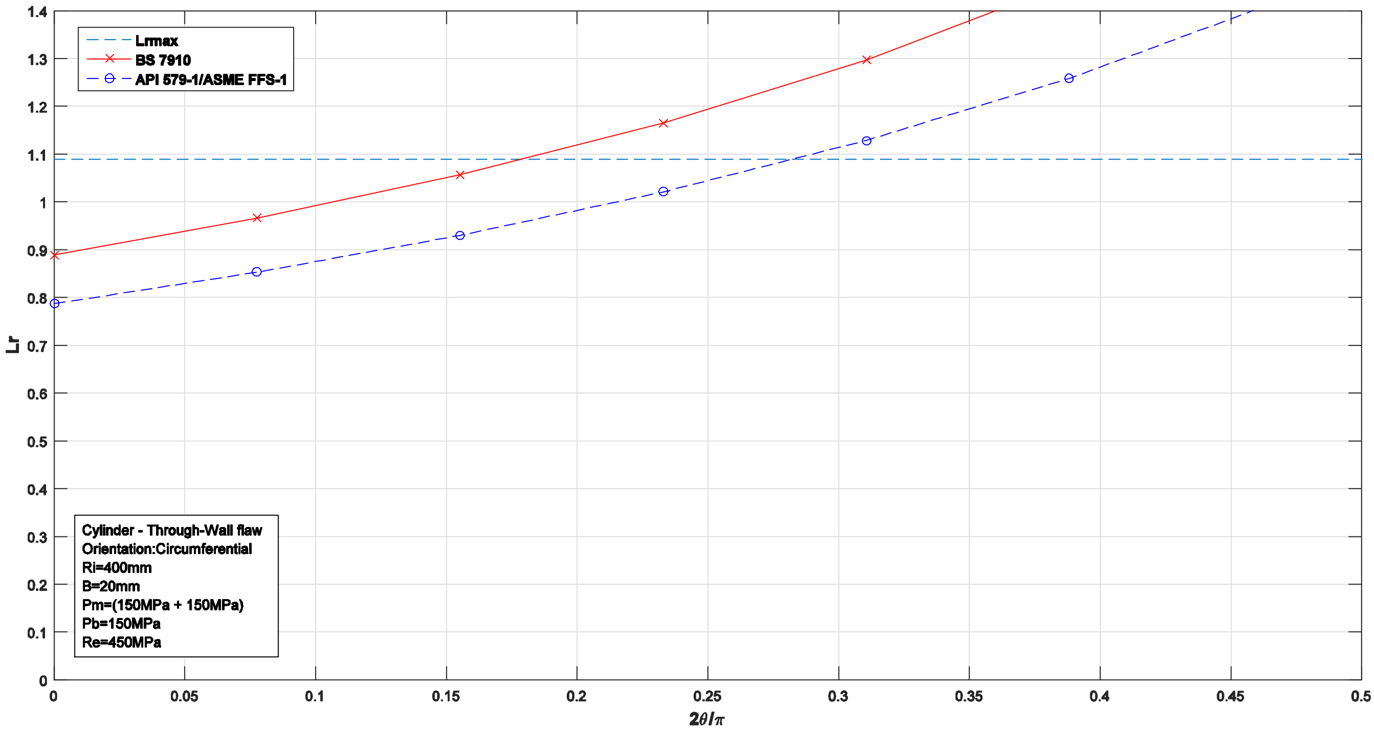

Figure 20: RS - Pipe/cylinder containing through-thickness circumferential defect - Combined tension, bending and internal pressure

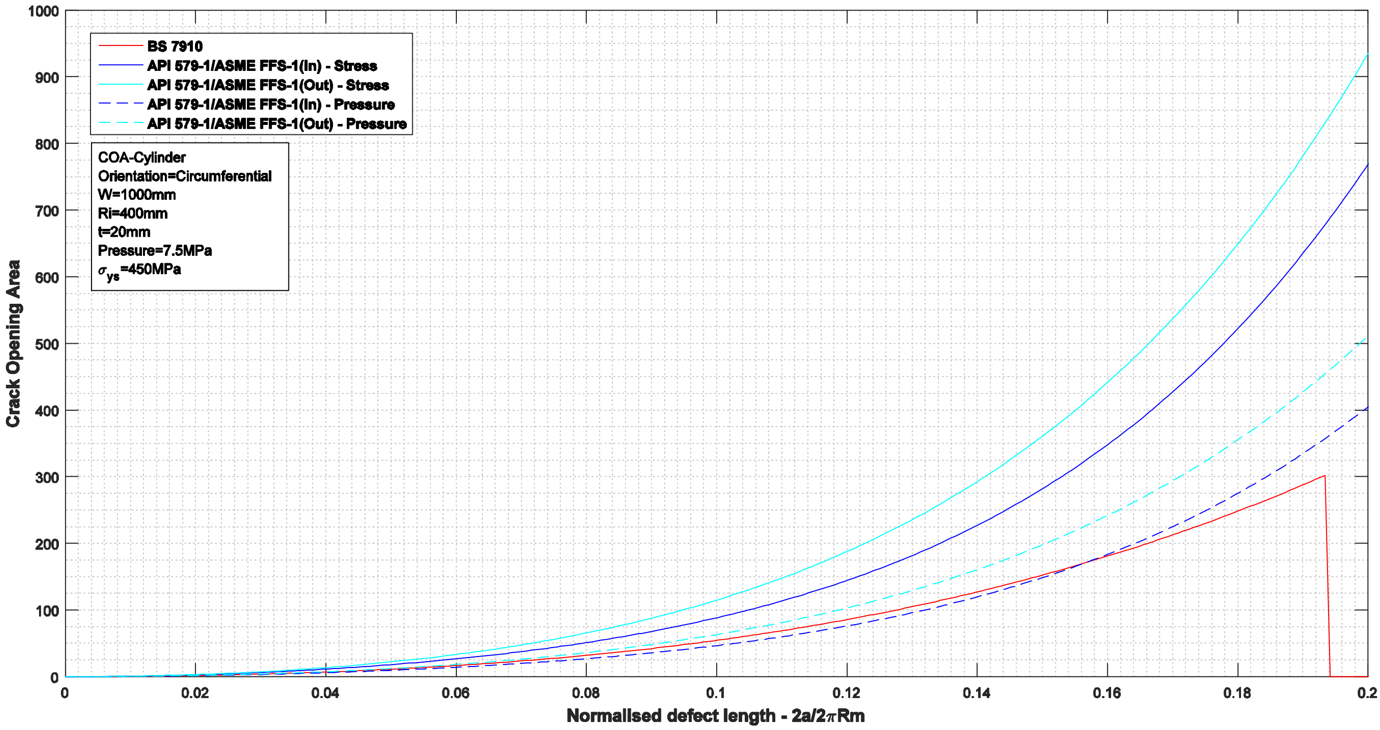

Figure 21: COA - Pipe/cylinder containing through-thickness circumferential defect

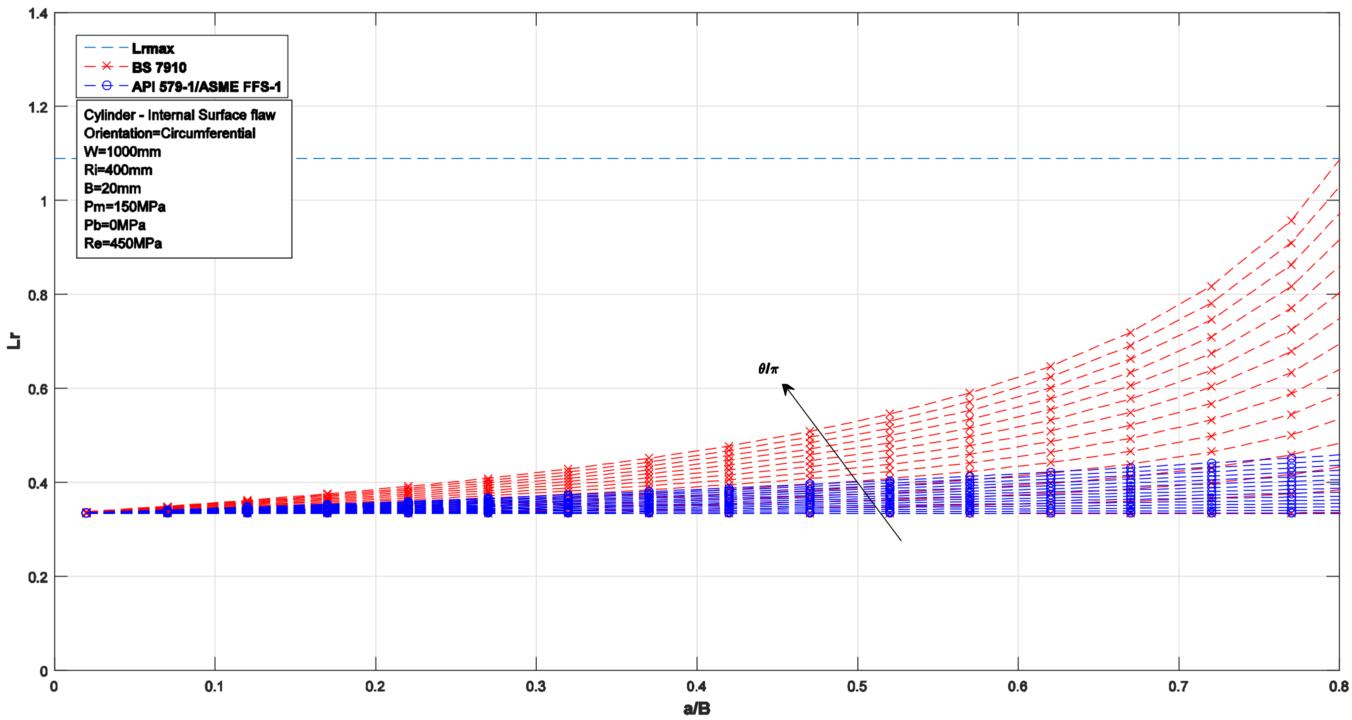

Figure 22: RS - Pipe/cylinder containing surface circumferential defect - Membrane stress only

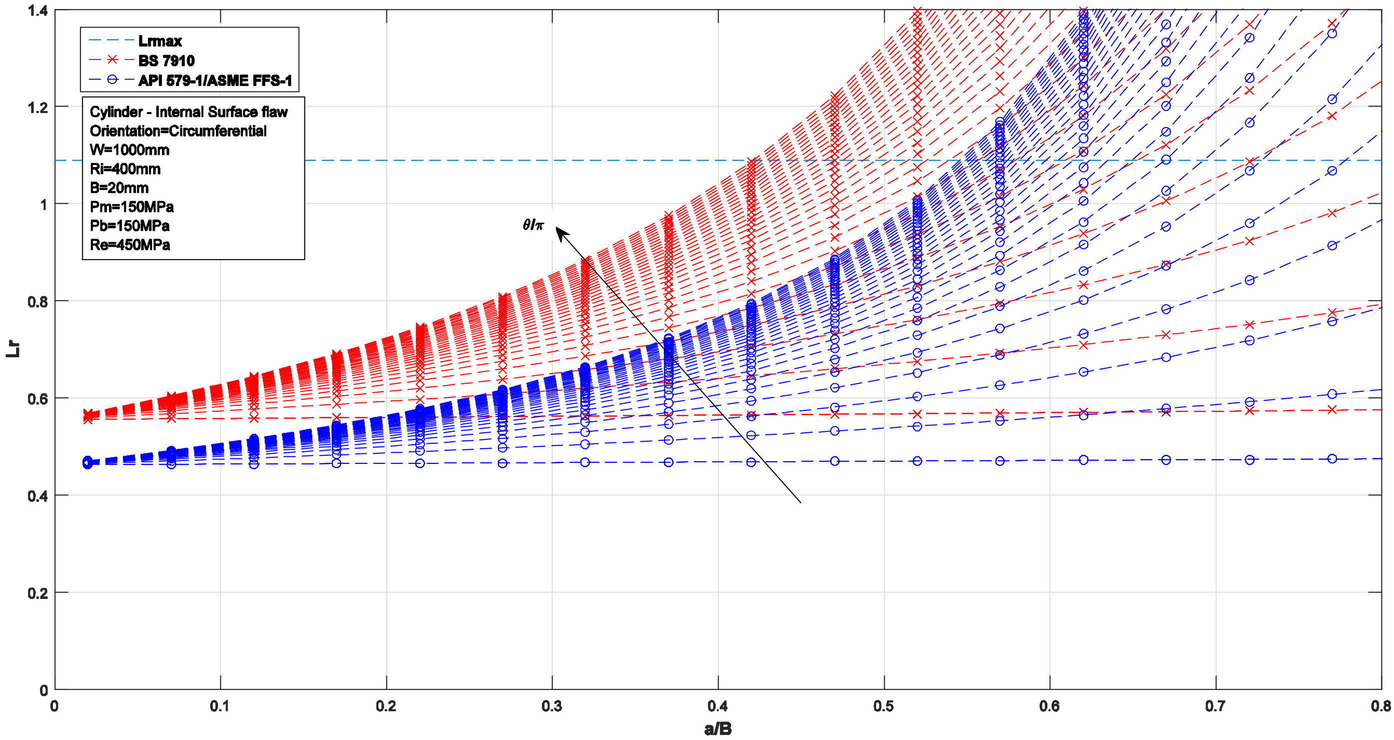

Figure 23: RS - Pipe/cylinder containing surface circumferential defect - Combined membrane and bending stress

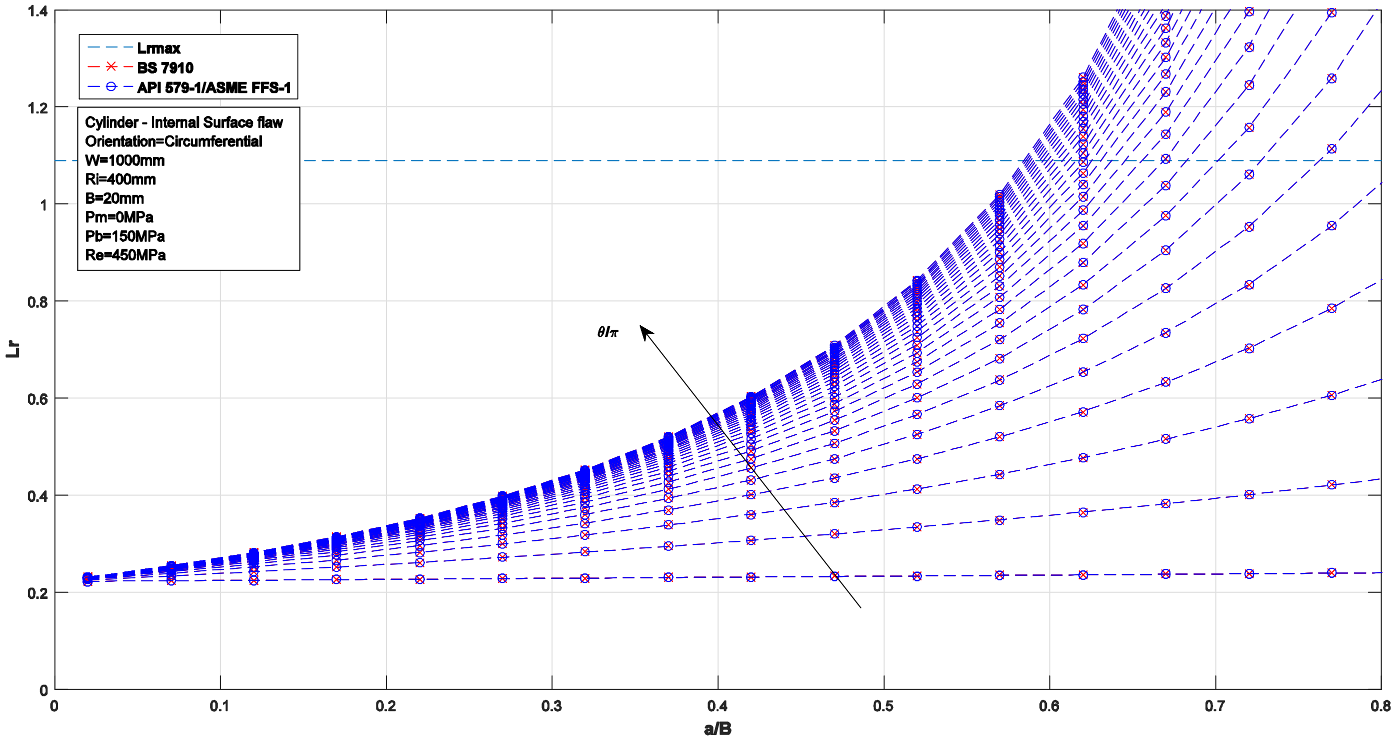

Figure 24: RS - Pipe/cylinder containing surface circumferential defect - Bending stress only

Table 1: Experimental data of leak/break tests on 4134V steel [10]

Test	Ro (mm)	t (mm)	a (mm)	c (mm)	Re (MPa)	Rm (MPa)	Av (J)	Pexp (Mpa)	Leak / Break
5	118.6	7.6	6.2	25.4	1097.1	1179.9	117.7	49.3	Leak
8	118.25	7.1	6.1	38.1	1097.1	1179.9	112.4	28.8	Leak
9	118.35	7.8	6.5	12.7	1097.1	1179.9	95.2	68.5	Leak
11	118.6	7.1	6.1	34.95	1097.1	1179.9	123.5	34.8	Leak
12	118.25	7.4	6.7	34.95	1097.1	1179.9	124	33	Leak
14	118.35	7.4	6.3	34.95	1097.1	1179.9	121.6	35.6	Leak
15	118.25	7.4	7.2	34.95	1097.1	1179.9	138.3	32.6	Leak
1	118.5	7.6	5.7	25.4	1097.1	1179.9	119.3	55.5	Break
2	118.5	7	4.3	12.7	1097.1	1179.9	74.5	64.2	Break
3	118.35	7.4	4.6	25.4	1097.1	1179.9	99.8	57.5	Break
4	118.35	7.5	5.2	25.4	1097.1	1179.9	102.3	52.3	Break
6	118.25	7.4	5.1	38.1	1097.1	1179.9	127.9	47.3	Break
7	118.5	7.7	5.5	38.1	1097.1	1179.9	126.7	45.1	Break
10	118.25	7.4	5.4	12.7	1097.1	1179.9	90.6	70.3	Break
13	118.1	7.5	5.2	34.95	1097.1	1179.9	120.1	48.4	Break