



SINTAP Validation Report



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J. Ruiz Ocejó
F. Gutiérrez-Solana

Departamento de Ciencia e Ingeniería del Terreno y de los Materiales
E.T.S. de Ingenieros de Caminos, Canales y Puertos
Universidad de Cantabria
Avda de los Castros s/n
39005, Santander (Spain)
Tel. 34-942-201819, Fax 34-942-201818
ruizj@ccaix3.unican.es
gsolana@ccaix3.unican.es

I. INTRODUCTION

This report is a companion document to the “*Structural Integrity Assessment Procedure for European Industry*”, SINTAP [1], and provides its validation for homogeneous structures by comparing the analytical results obtained by using the procedure with test experimental data [2]. This comparative analysis has been done over seven wide plate tests with differences approaches in the first example performed.

The report also represents a helping hand for the future user as different structures subjected to different features are analysed. Hence, the application of the procedure is shown by means of the resolution of other examples.

II. EXAMPLE 1

II.1. DESCRIPTION

In this first example seven wide plates of different materials, all steels, are analysed for an extended range of Y/T ratio. These plates were always subjected to single uniform tension and all of them were 450 mm wide. Particular data both on the geometry and on the material properties, mechanical behaviour and toughness, are presented in Table 1.

Plate	1	2	3	4	5	6	7
Material	S275J0	355EMZ	450EMZ	S690Q	ABR.400	S690Q	S690Q
Thickness (mm)	25	25	25	25	25	12	40
R _{el} or R _{P0.2} (MPa)	303	436	471	713	991	820	746
R _m (MPa)	467	548	565	792	1408	864	859
LYS/UTS $\equiv$ Y/T	0.649	0.796	0.834	0.900	0.704	0.949	0.868
Type of curve	Discont.	Discont.	Discont.	Contin.	Contin.	Discont.	Contin.
N (measured)	0.231	0.282	0.151	0.092	0.157	0.071	0.068
Charpy T27J (°C)	-65	-115	-115	-50	-45	-85	-85
Charpy at -20°C (J)	70	220	>250	100	35	180	170
CTOD at -20°C (mm)	0.974	0.765	1.450	0.083	0.022	0.140	0.235
CTOD R-curve (mm)	$1.03\Delta a^{0.50}$	$1.04\Delta a^{0.63}$	$1.31\Delta a^{0.71}$	-	-	-	$0.44\Delta a^{0.62}$

Table 1. Summary of known data for wide plate assessments.

The true stress-strain curve of each material was known and can be seen in Figure 1.

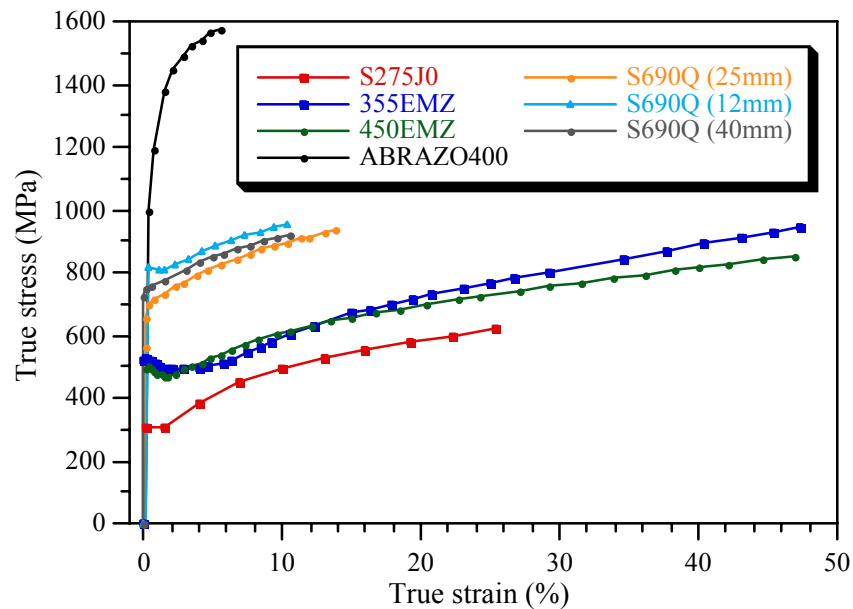


Figure 1. Stress-strain curves for the seven materials.

The steel S275J0 is a general structural steel supplied to BS EN 10025 and is used typically in building, bridge and general structural applications. In the present work S275J0 is studied in the Normalised (N) condition.

The steel 355EMZ is an offshore grade in which the required strength and toughness are achieved through thermomechanical controlled rolling, thereby enabling low CE values and weldability to be maintained. The composition is low in carbon and niobium but with small additions of titanium for HAZ refinement.

450EMZ is also an offshore steel but is produced by the Quench & Temper route to achieve a higher yield stress coupled with low CEV. Molybdenum is added to ensure through-thickness hardening.

S690Q is a high strength structural steel used in applications such as mobile cranes, large scale rotating components, pressure vessels and mobile offshore installations such as jack-up rigs. Its use is particularly suited to applications where weight is a critical issue. The steel composition includes molybdenum and boron for hardenability with additions of chromium and molybdenum for strength. This grade is produced in various compositions

depending on thickness, a richer composition being necessary to achieve a high strength through the full thickness in thicker materials. This steel is studied in three thicknesses (12, 25 and 40 mm) in this work.

The highest strength steel in the programme is ABRAZO 400. This is a wear plate grade and is sold to a minimum hardness specification rather than a yield strength. The minimum Brinell hardness is 360, although plates typically meet 400. The steel is used specifically for its wear-resistant properties in applications such as mechanical handling construction and earth moving equipment and conveyors. It is a highly alloyed steel with a relatively high carbon content and contains elements added to enhance hardenability such as molybdenum and boron. It should be noted that this steel is not usually used in critical, welded load-bearing applications, it is included in this work to complete the range of strength levels.

Table 2 shows the chemical composition of these materials [2].

Material	S275J0	355EMZ	450EMZ	S690Q	ABR.400	S690Q	S690Q
Thickness (mm)	25	25	25	25	25	12	40
C	0.130	0.089	0.093	0.090	0.180	0.140	0.130
Si	0.200	0.370	0.290	0.410	0.391	0.400	0.400
Mn	1.05	1.44	1.24	1.42	1.39	1.39	1.41
P	0.018	0.009	0.015	0.015	0.010	0.013	0.012
S	0.006	0.003	0.002	0.002	0.003	0.002	0.004
Cr	-	<0.020	0.020	0.023	0.131	0.017	0.170
Mo	-	<0.005	0.140	0.003	0.151	0.002	0.150
Ni	0.030	0.510	0.430	0.022	0.242	0.018	0.230
Al	0.026	0.041	0.043	0.042	0.036	0.041	0.033
Cu	0.030	<0.020	<0.020	0.012	0.152	<0.020	0.140
N	-	0.006	0.007	-	-	-	0.006
Nb	0.002	0.023	<0.005	0.034	0.034	0.037	0.032
Ti	-	0.005	<0.005	0.038	0.025	0.026	0.029
V	0.013	<0.005	0.050	0.063	0.004	0.064	<0.005
B	-	-	-	0.002	0.002	0.003	0.002
CEV	0.312	0.370	0.372	0.387	0.449	0.390	0.508

Table 2. Chemical composition of test plates (weight %).

II.2. OBJECTIVE

The wide plates were tested, so, real failure values were known. The objective of the example is to validate, through the experimental results, the analytically obtained values. This can be achieved in two ways:

- Guaranteeing that the values are conservative when compared to the experimental ones.
- Checking that the points representing the actual failure situations fall outside the Failure Assessment Diagrams.

Also, the evolution of the reserve factors through the different analysis levels can be established, thus, pointing out the hierarchy of the procedure established by the different approach levels.

II.3. METHODOLOGY

In order to reach the objective of this study, different calculations have been performed by varying:

- a) The quality of input data by means of.
 - Different hypothesis of knowledge of tensile properties, therefore, changing the Failure Assessment Line and, therefore, the degree of conservativeness.
 - Different toughness consideration, correlations from Charpy tests or transformation from CTOD values.
- b) The crack size, either under nominal or real dimensions.

These combinations result in 63 calculations of the critical applied stress for a given crack for each structural situation.

II.4. CALCULATIONS

II.4.1. CALCULATIONS TO DERIVE THE DIFFERENT FAILURE ASSESSMENT LINES

Depending on the data inputs, different parameters were derived (Table 3) to describe the following FADs considered in the analysis:

- Level 0: *Default*, known YS only.
- Level 1: *Basic*, known YS and UTS.
- Level 3: *SS*, known stress-strain curve.

Plate	1	2	3	4	5	6	7
R_F (MPa)	385	492	518	752.5	1199.5	842	802.5
$L_{r \max}$	1.271	1.128	1.100	1.055	1.210	1.027	1.076
$\Delta\epsilon$	0.0261	0.0212	0.0198	-	-	0.0068	-
μ	-	-	-	0.295	0.212	-	0.282
λ	19.12	11.19	9.84	-	-	2.73	-
N	0.105	0.061	0.050	0.030	0.089	0.015	0.040
$L_{r \max}^{\text{est}}$	-	-	-	1.020	1.009	-	1.018

Table 3. Failure Assessment Diagram parameters derived from tensile data.

II.4.2. TOUGHNESSES CONSIDERED

From the Charpy values, different toughnesses can be taken into account depending upon the test temperature (-20°C for all plates) whether this is higher than the transition one or not, thus depending if the material is either on the lower or on the transition regime or on the upper shelf of its energy-temperature curve.

If the material is above or near the transition temperature (T_{27J}), two different equations from Section IV.1.3 can be used: Eq. IV.1.3 -lower bound- and Eq. IV.1.4 -Master curve- of SINTAP. Only Plate 5, of ABRAZO 400, can be said that behaves on the lower shelf. If the material is on the upper shelf, Equation IV.1.5 should be used instead the previous ones.

These three options have been noted as toughness $K_{\text{mat}} 1^*$ (lower bound), $K_{\text{mat}} 1^{**}$ (Master curve) and $K_{\text{mat}} 1$ (upper shelf) respectively in Table 4 and the following figures.

On the other hand, if CTOD-values are considered, these are translated into K-values by means of Equation II.2.1.1.b from Table II.2.1. Plane strain has been supposed and the following elastic parameters used $E=210$ GPa and $\nu=0.3$. The results are also summarised in Table 4 and have been noted as toughness $K_{\text{mat}} 2$.

Plate	1	2	3	4	5	6	7
$l=2c$ (mm)	135	135	135	135	135	135	135
t (mm)	25	25	25	25	25	12	40
K_{mat25} (MPa·m ^{1/2})	-	-	-	-	71.0	-	-
P_f	-	-	-	-	0.05	-	-
$K_{mat 1^*}$ (MPa·m ^{1/2}) ⁽¹⁾	-	-	-	-	53.5	-	-
$K_{mat 1^{**}}$ (MPa·m ^{1/2}) ⁽²⁾	-	-	-	-	59.9	-	-
$K_{mat 1}$ (MPa·m ^{1/2}) ⁽³⁾	106.5	189.8	201.9	128.1	-	172.1	167.3
$K_{mat 2}$ (MPa·m ^{1/2}) ⁽⁴⁾	319.6	339.8	486.2	143.1	86.9	199.3	246.3

Table 4. Calculated K_{mat} values.

- (1) Estimated from SINTAP lower bound, lower shelf correlation.
(2) Estimated from Master Curve with failure probability = 0.05.
(3) Estimated from upper shelf Charpy correlation.
(4) Estimated from relationship between K_{mat} and CTOD.

II.4.3. CRACKS CONSIDERED

All the flaws analysed within this work have been considered as finite surface crack in a plate (Figure 2).

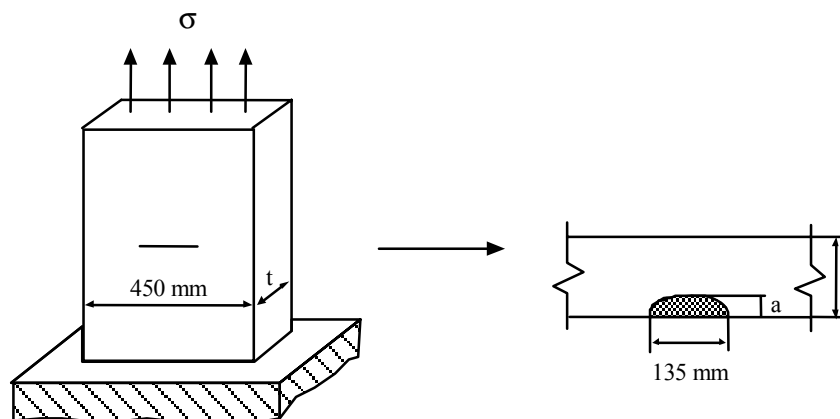


Figure 2. Geometrical definition of Example 1.

For some plates two different crack sizes have been studied; the real one and a nominal one of 5 mm. The dimensions are summarised in Table 5:

Plate	1	2	3	4	5	6	7
a real (mm)	5	6.5	6.8	5.5	5	3.1	8.4
a nominal (mm)	-	5	5	5	-	-	-

Table 5. Crack dimensions considered (real and nominal values).

II.4.4. L_r AND K_I SOLUTIONS

From Stress Intensity Factor and Limit Load Handbook, Issue 2, April 1999 [3], of SINTAP Project:

L_r (AII.42):

$$L_r = \frac{\sigma}{(1 - \zeta)\sigma_y}$$

where

$$\zeta = \frac{al}{t(l + 2t)}$$

K_I (AI.3) -deepest point of the crack-:

$$K_I = \sigma f_0 \sqrt{\pi a}$$

Linear interpolation has been used for the determination of f_0 . Table 6 details the corresponding factor ζ and f_0 values obtained for the plates.

Plate	1	2	3	4	5	6	7
ζ (real a)	0.1459	0.1897	0.1985	0.1605	0.1459	0.2193	0.1319
f_0 (real a)	1.2151	1.2904	1.3026	1.2421	1.2151	1.3991	1.1753
ζ (nominal a)	-	0.1459	0.1459	0.1459	-	-	-
f_0 (nominal a)	-	1.2151	1.2151	1.2151	-	-	-

Table 6. Factor ζ and f_0 values for each plate and crack combination.

II.4.5. ASSESSMENT POINTS CALCULATED

For all cases, the applied stress was varied from 0 to 800 MPa in steps on one MPa in order to calculate the critical value for each case. Also, the point corresponding to the actual failure load was evaluated to achieve that this falls outside the Failure Assessment Diagram.

Figures 3 to 9 summarise these calculations. The figures show the assessment points which correspond to stresses that are multiple of 50 MPa up to the experimental failure stress if this is lower than 800 or up to 800 in the opposite case. They also show the points that would be plotted for each certain situation under the failure stress (these ones are noted like the other points but the marker is a bit bigger than the corresponding for that issue).

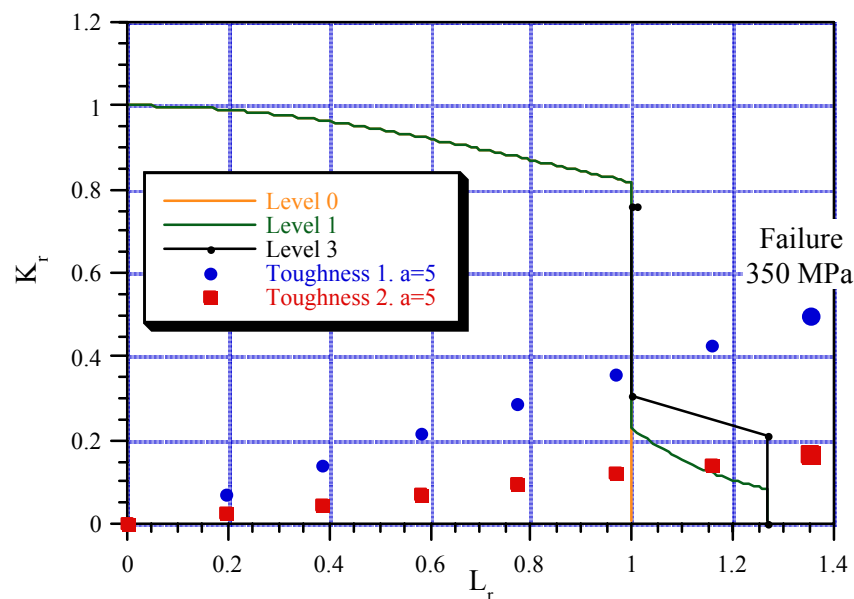


Figure 3. Plate 1 results. Material: S275J0, thickness: 25 mm.

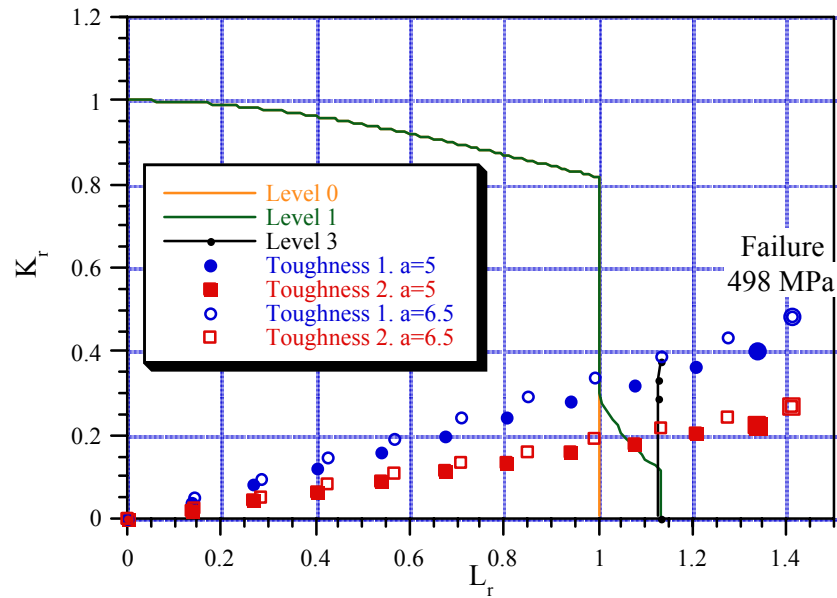


Figure 4. Plate 2 results. Material: 355EMZ, thickness: 25 mm.

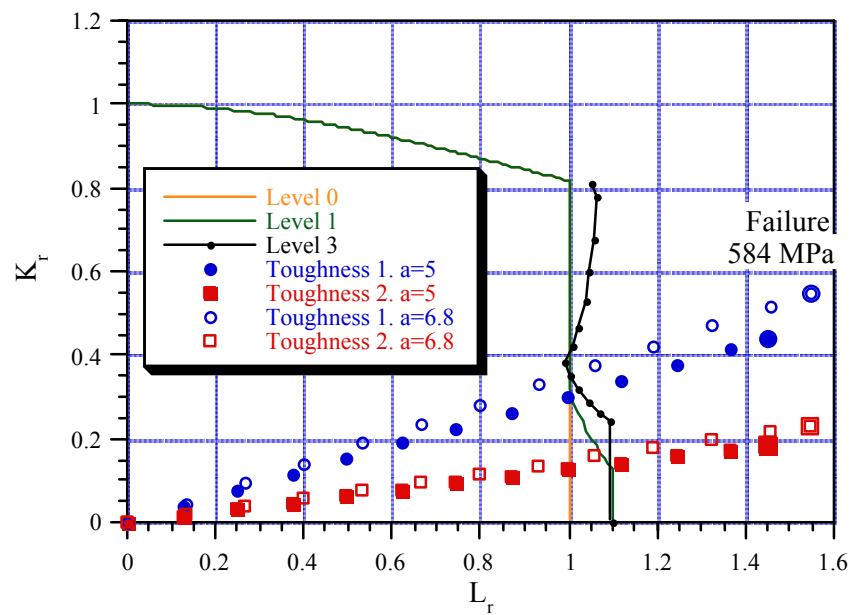


Figure 5. Plate 3 results. Material: 450EMZ, thickness: 25 mm.

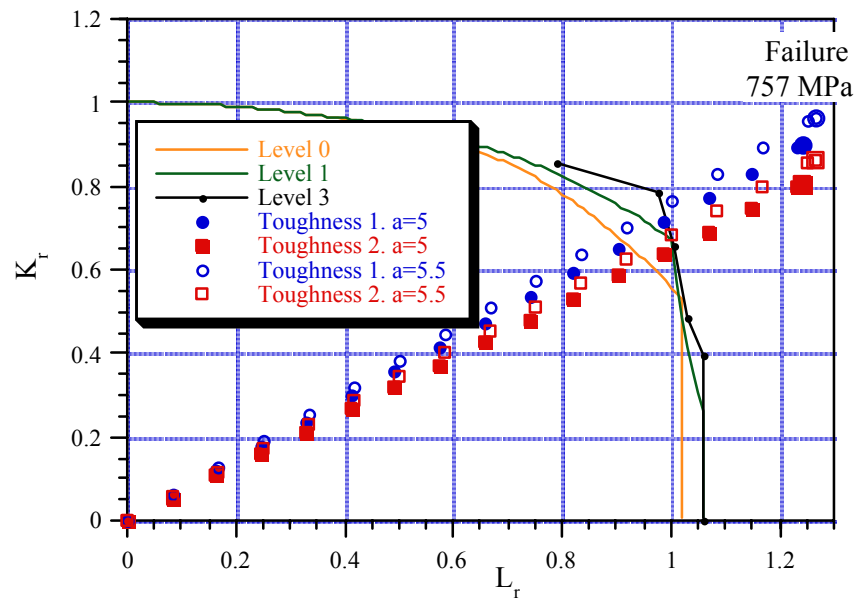


Figure 6. Plate 4 results. Material: S690Q, thickness: 25 mm.

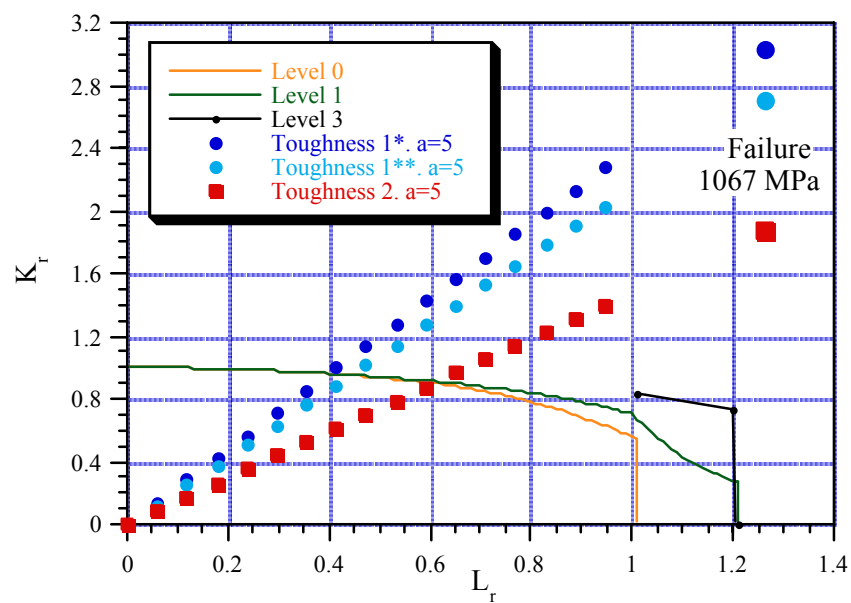


Figure 7. Plate 5 results. Material: ABRAZO 400, thickness: 25 mm.

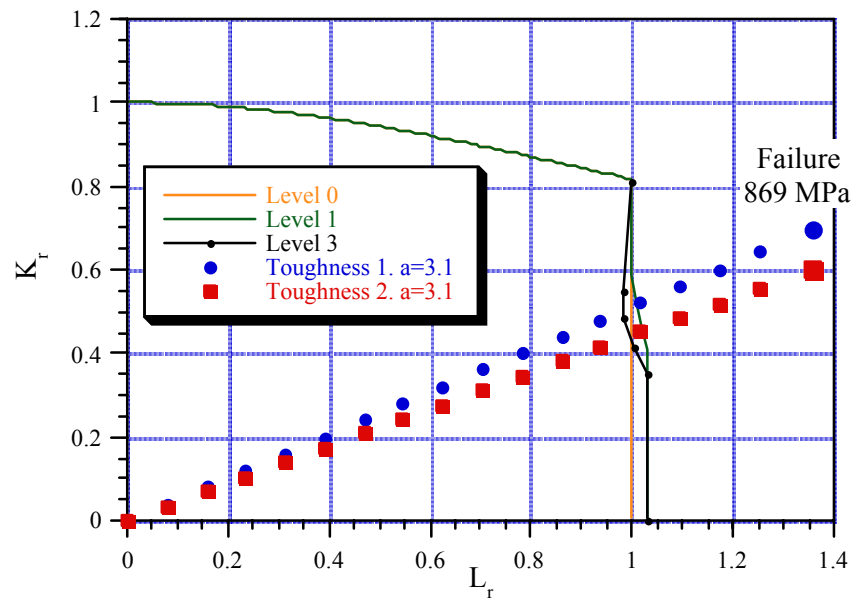


Figure 8. Plate 6 results. Material: S690Q, thickness: 12 mm.

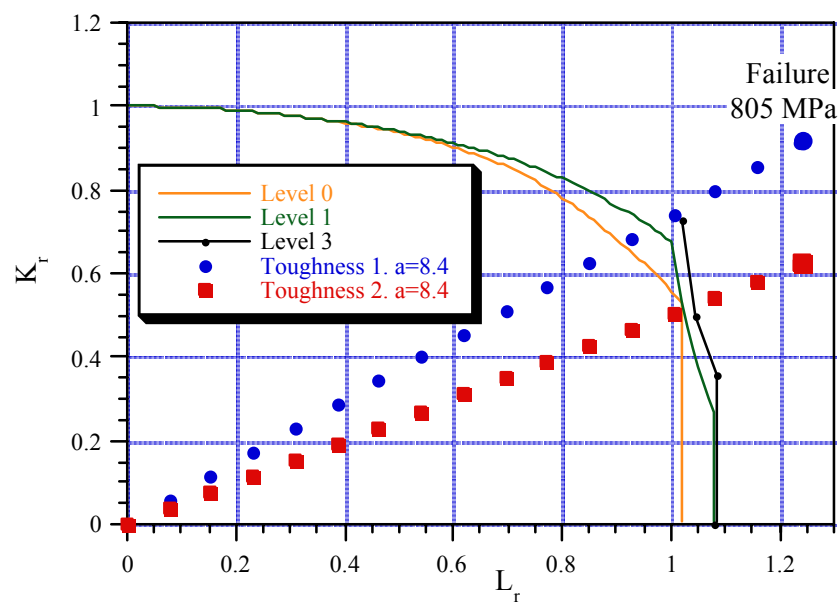


Figure 9. Plate 7 results. Material: S690Q, thickness: 40 mm.

II.5. RESULTS

The maximum acceptable applied stress for each plate, crack, toughness and FAD considered are pointed out in Table 7 where the results are in MPa as well as the experimental failure stress.

Plate	Crack size	Toughness	FAD 0	FAD 1	FAD 3	Failure Stress
1	5	1	259	259	259	350
		2	259	291	329	
2	5	1	372	372	419	498
		2	372	398	420	
	6.5	1	353	353	398	
		2	353	371	398	
3	5	1	402	404	412	584
		2	402	440	441	
	6.8	1	378	378	378	
		2	378	406	413	
4	5	1	558	589	604	757
		2	581	610	613	
	5.5	1	537	566	589	
		2	560	594	599	
5	5	1*	337	338	>338	1067
		1**	374	375	>375	
		2	513	519	>519	
6	3.1	1	640	647	629	869
		2	640	654	638	
7	8.4	1	589	623	≈660	805
		2	659	663	674	

Table 7. Predicted failure load for each structural situation and actual failure load.

For all cases, the safety factor was calculated as the ratio between the predicted failure stress and the real one shown in the tests. Figures 10 and 11 show schematically these ratios.

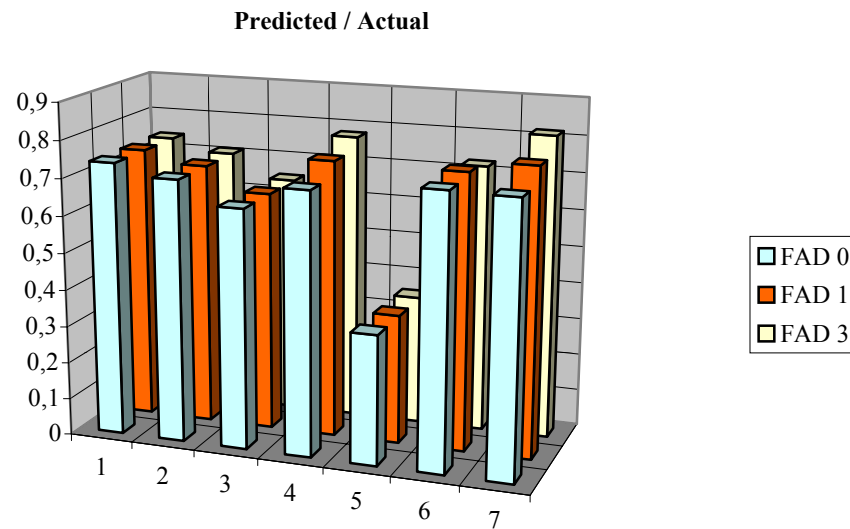


Figure 10. Predicted maximum stress to actual failure ratio for real crack sizes and Charpy toughness.

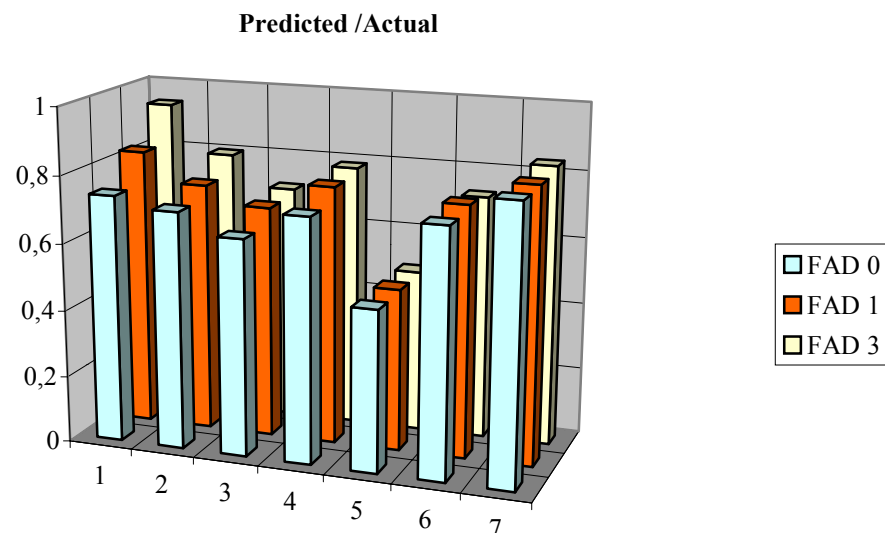


Figure 11. Predicted maximum stress to actual failure ratio for real crack sizes and CTOD toughness.

II.6. CONCLUSIONS

- Normally, the maximum ratio between prediction and actual failure stress is obtained with CTOD data when Level 3 is used (Plates 1, 2, 3, 4, 5 and 7) as expected.
- Generally, the hierarchy of the procedure has been satisfied, i.e. analytically obtained values for Level 0 lower than the ones for Level 1 which are also lower than the corresponding for Level 3.
- The ratio of predicted failure stress / actual failure stress generally decreases with increasing Y/T ratio when failure is dominated by limit load conditions..
- In all cases, the predicted failure stresses calculated when using CTOD toughness are greater than the ones using Charpy values as could be expected, except those cases where failure is dominated by plastic collapse and so fracture values are not specially relevant.
- The predicted failure stresses when Level 0 is used with either Charpy or CTOD data, are the same for plates 1, 2, 3 and 6. These results are obtained because the failure stress is dictated by $L_T^{\max}$ and is independent of the route used to calculate fracture toughness. Contrarily, when Level 1 or Level 3 are used for these plates, the results are different, depending on the fracture toughness quality.

III. EXAMPLE 2

III.1. DESCRIPTION

This second example covers a centre-cracked panel subjected to single tension. The particular input data are summarised in Table 8 while Figure 12 shows schematically this geometry.

W (mm)	R_c (MPa)	R_m (MPa)	K_{Ic} (MPa·m ^{1/2})
1000	430	580	100

Table 8. Summary of known data for Centre-Cracked-Panel.

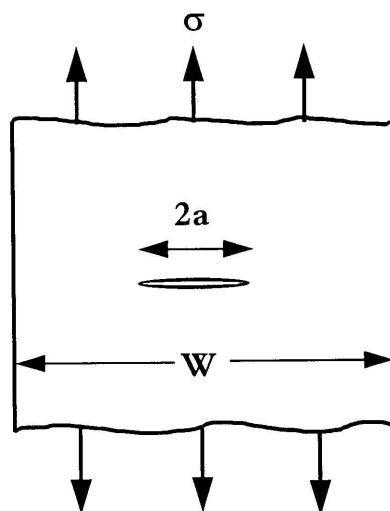


Figure 12. Geometrical definition of Example 2 (taken from [4]).

III.2. OBJECTIVE

This example has also been run by AEA Technology plc [4] using R6 Method [5] so a comparison can be made between SINTAP Procedure and a very well known and widespread procedure, R6. Therefore a relative validation by means of this comparative analysis between procedures can be performed.

III.3. METHODOLOGY

All possible calculations have been performed by varying:

- a) The quality of input data.
 - Knowledge of tensile properties (thus, changing the Failure Assessment Line and, therefore, the degree of conservativeness).
- b) The aim of the assessment. Two different cases have been analysed.
 - Evaluation of critical stress for a given crack whose semi-length is 100 mm.
 - Evaluation of critical crack dimension for a given applied stress of 180 MPa.
- c) The formulae considered for limit load and stress intensity factor solutions. Besides the set proposed in SINTAP Handbook [3], a different set of solutions from the bibliography [4] was taken.

These combinations result in 8 different calculations on the structure under consideration.

III.4. CALCULATIONS

III.4.1. CALCULATIONS TO DERIVE THE DIFFERENT FAILURE ASSESSMENT LINES

Depending on the data inputs, different parameters were derived (Table 9) to describe the following FADs considered in the analysis:

- Level 0: *Default*, known YS only.
- Level 1: *Basic*, known YS and UTS.

R _F (MPa)	Y/T	L _{r max}	μ	N	L _{r max} ^{est (1)}
505	0.741	1.174	0.49	0.078	1.072

Table 9. Failure Assessment Diagram parameters derived from tensile data.

(1) To be used in Level 0.

III.4.2. TOUGHNESS AND DEFECT

The fracture toughness was known in terms of K directly and had a value of 100 MPa·m^{1/2} as presented in Table 8.

With respect to the defect characterisation, all flaws were assumed as planar through-thickness cracks. Depending on the assessment, the crack was, on the one hand, fixed at a total length of 200 mm or, on the other hand, the variable to evaluate.

III.4.3. L_r AND K_I SOLUTIONS

- Option 1: from Stress Intensity Factor and Limit Load Handbook, Issue 2, April 1999 [3]:

L_r (AII.46):

$$L_r = \frac{\sigma}{\sigma_Y}$$

K_I (AI.13):

$$K_I = \sigma \sqrt{\pi a}$$

- Option 2: from [4]:

L_r:

$$L_r = \frac{\sigma}{(1 - 2a/W)\sigma_Y}$$

K_I:

$$K_I = \sigma \sqrt{\pi a} \sqrt{\sec \frac{\pi a}{W}}$$

A different set of formulae to use in SINTAP is perfectly justified, in fact, ref. [3] clearly states that the handbook provides a single source reference but “It should not be inferred that the solution selected is the only satisfactory one. Solutions other than those given may be used in the analysis provided that they are validated.”

III.4.5. ASSESSMENT POINTS CALCULATED

In the case of the evaluation of the maximum allowed stress value for a given flaw of 200 mm long, the stress was assessed up to 180 MPa in steps of one MPa while for the critical crack dimension calculation for a given stress of 180 MPa, the defect semi-length was varied from 0 to 100 mm in steps of one mm.

Figures 13 and 14 show these calculations. Figure 13 shows the assessment points which correspond to stresses that are multiple of 10 MPa up 180. Figure 14 presents the assessment points for cracks semi-lengths that are multiple of 10 mm up to a value of 100.

III.5. RESULTS

The results of the example are shown in Tables 10 and 11 as well as the values obtained in [4] using R6.

The same results are presented for both Level 0 and Level 1 as they are almost identical as can be seen in Figures 13 and 14. The failure conditions are in the toughness controlled region and the Failure Assessment Line of both levels are not so relevant.

SINTAP Formulae Opt 1	SINTAP Formulae Opt 2	R6 [5]
90 mm	83 mm	88 mm

Table 10. Critical crack dimension for an applied stress of 180 MPa.

SINTAP Formulae Opt 1	SINTAP Formulae Opt 2	R6 [5]
172 MPa	164 MPa	163 MPa

Table 11. Maximum applied stress for a defect size of 200 mm.

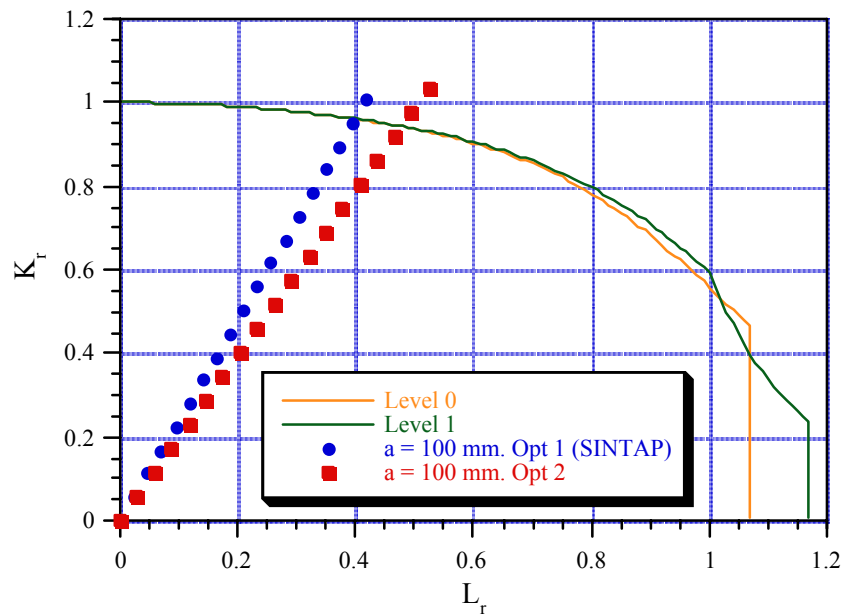


Figure 13. Calculation of critical stress for a given crack size.

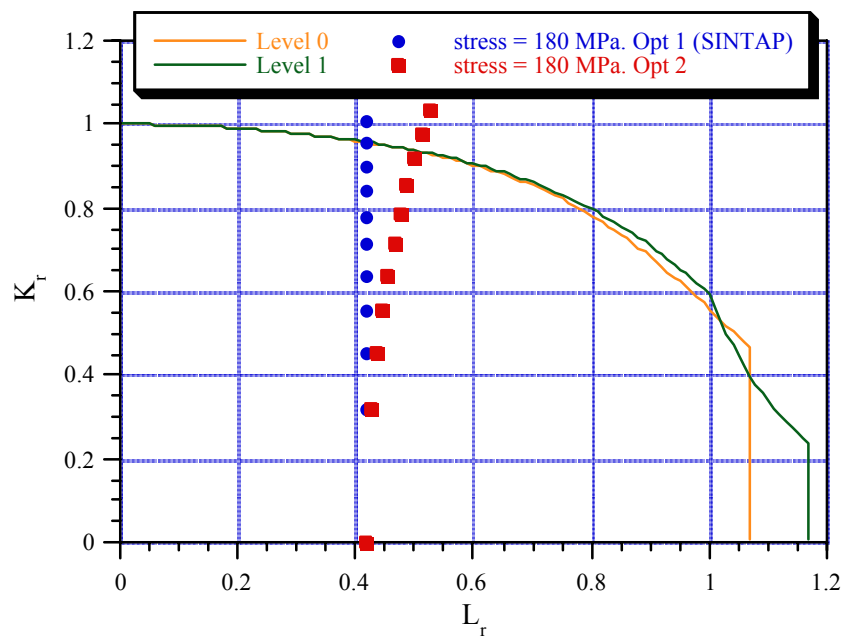


Figure 14. Calculation of critical crack size for a given crack stress.

III.6. CONCLUSIONS

The following conclusions can be highlighted from this example:

- Same results for Level 0 and Level 1 are obtained in both cases (constant stress or defect).
- The values obtained by using both SINTAP and R6 are very close. Also, when using a different solution to SINTAP considering the finite width of the plate, the figures are, once again, very similar.

IV. EXAMPLE 3

IV.1. DESCRIPTION

This third example deals with a circumferential butt weld joining two pipe sections subjected to:

- Internal pressure.
- A global bending moment.
- A known residual stress profile.

Two different crack types were assessed:

- Circumferential internal surface crack.
- Circumferential through-thickness.

The available geometrical data and material characteristics are summarised in Table 12.

Outer radius (mm)	Thickness (mm)	R_e (MPa)	R_m (MPa)	E (MPa)	ν	K_{mat} (MPa·m ^{1/2})
420	40	175	492	173.5	0.3	120

Table 12. Summary of input data for Example 3.

The true stress-strain curve of the material was assumed to follow perfectly a Ramberg-Osgood law:

$$\frac{\epsilon}{0.001009} = \frac{\sigma}{175} + 1.634 \left(\frac{\sigma}{175} \right)^7$$

The forces acting over the structure are presented in Table 13 where all values are in MPa:

Internal pressure	$p = 10$
Stress due to pressure	$\sigma = (p \cdot r_m) / (2 \cdot t) = (10 \cdot 400) / (2 \cdot 40) = 50$
Stress due to global bending	$\sigma_{bg} = 120$
Residual stresses	$\sigma_{rs} = 175 \cdot [0.9918 + 0.5182 \cdot (a/t) - 26.913 \cdot (a/t)^2 + 35.883 \cdot (a/t)^3]$

Table 13. Stresses considered in Example 3.

IV.2. OBJECTIVE

The aim of this assessment is to present a running example to the user in order to ease the application of SINTAP in future integrity evaluations. This structure supports a more complex stress field than the formers as well as takes into account the consideration of residual stresses due to the welding process.

IV.3. METHODOLOGY

All possible calculations have been performed by varying:

a) The quality of input data by means of:

- Different levels of tensile properties knowledge, therefore changing the Failure Assessment Line.

b) The crack type and dimensions. Three different cases have been studied:

- Calculation of the critical depth of a circumferential internal crack 628.4 mm long.
- Calculation of the critical length of a circumferential internal crack 10 mm deep.
- Calculation of the critical through-thickness crack.

These combinations result in 9 different evaluations of the maximum allowed flaw for a given set of stresses.

IV.4. CALCULATIONS

IV.4.1. CALCULATIONS TO DERIVE THE DIFFERENT FAILURE ASSESSMENT LINES

Depending upon the material characteristics that could be available for an assessment, different parameters were calculated (Table 14) to describe the Failure Assessment Lines considered within this example:

- Level 0: *Default*, known YS only.
- Level 1: *Basic*, known YS and UTS.
- Level 3: *SS*, known stress-strain curve.

R_F (MPa)	Y/T	$L_{r \max}$	μ	N	$L_{r \max}^{\text{est (1)}}$
333.5	0.356	1.906	0.60	0.193	1.680

Table 14. Failure Assessment Diagram parameters derived from tensile data.

(1) To be used in Level 0.

IV.4.2. TOUGHNESS AND DEFECT

The fracture toughness was known in terms of K and had a value of $120 \text{ MPa}\cdot\text{m}^{1/2}$.

As has been previously said, three different cracks were assessed, a part circumferential internal surface crack with a given depth, 10 mm, a part circumferential internal surface crack with a given length, 628.4 mm and a circumferentially through-wall defect. Figure 15 shows schematically the configuration of the defects.

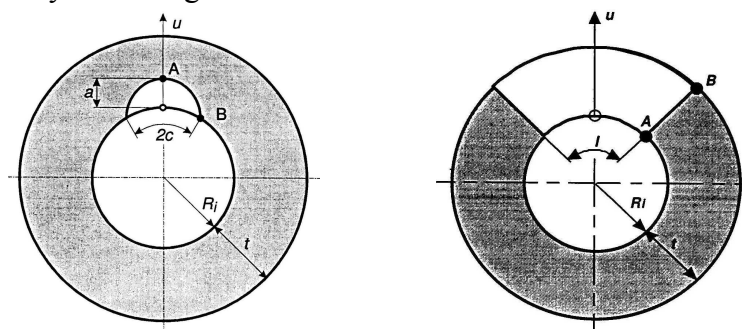


Figure 15. Geometry of cracks in Example 3 (taken from [3]).

IV.4.3. L_r AND K_I SOLUTIONS

From Stress Intensity Factor and Limit Load Handbook, Issue 2, April 1999 [3]:

Part Circumferential Internal Surface Crack in a Cylinder

L_r (AII.53):

$$L_r = \frac{\sigma_m}{s_m} = \frac{\sigma_{bg}}{s_{bg}}$$

where the parameters s_m and s_{bg} are obtained by solving the equation system:

$$\left\{ \begin{array}{l} \frac{s_m}{\sigma_y} = 1 - 2 \frac{\beta}{\pi} - \frac{a}{t} \frac{\alpha}{\pi} \\ \frac{s_{bg}}{\sigma_y} = \frac{4}{\pi} \sin \beta - \frac{2}{\pi} \frac{a}{t} \sin \alpha \\ \sigma_m s_{bg} - \sigma_{bg} s_m = 0 \end{array} \right\}$$

β and α are defined in the handbook.

K_I (AI.25) –deepest point of the crack-:

$$K_I = \sqrt{\pi a} (\sigma_0 f_0 + \sigma_1 f_1 + \sigma_2 f_2 + \sigma_3 f_3 + \sigma_{bg} f_{bg})$$

Care should be taken when defining σ_i . They are stated in the procedure as the components which define the axisymmetric stress state according to a polynomial function whose variable is $\mathbf{u}/a$ and not $\mathbf{a}/t$ as could be more usual. If any function is expressed in terms of $\mathbf{a}/t$ ratio, it can be transformed to $\mathbf{u}/a$ co-ordinate following the expression:

$$\left(\frac{\mathbf{a}}{t} \right) \equiv \left(\frac{\mathbf{u}}{a} \right) \left(\frac{a}{t} \right)$$

where $\mathbf{a}$ and $\mathbf{u}$ are variables while a and t are the actual geometrical sizes of each example.

Linear interpolation has been used for the determination of f_0 , f_1 , f_2 , f_3 and f_{bg} .

Circumferential Through-Thickness Crack in a Cylinder

L_r (AII.57):

$$L_r = \frac{\sigma_m}{s_m} = \frac{\sigma_{bg}}{s_{bg}}$$

where the parameters s_m and s_{bg} are obtained by solving the equation system:

$$\left\{ \begin{array}{l} \frac{s_m}{\sigma_y} = 1 - 2 \frac{\beta}{\pi} - \frac{\theta}{\pi} \\ \frac{s_{bg}}{\sigma_y} = \frac{4}{\pi} \sin \beta - \frac{2}{\pi} \sin \theta \\ \sigma_m s_{bg} - \sigma_{bg} s_m = 0 \end{array} \right\}$$

β and θ are defined in the handbook.

K_I (AI.57):

For hoop stresses:

$$K_{I_{out}} = \sigma_a \sqrt{\pi a} (G_2(\rho) + g_2(\rho))$$

For bending stresses:

$$K_{I_a} = \sigma_b \sqrt{\pi a} G^* 2(\rho, \beta)$$

For through wall self-equilibrated bending stresses:

$$K_{I_{out}} = \sigma_b^s \sqrt{\pi a} (H_2(\rho) + h_2(\rho))$$

Parameters and functions as ρ , β , G_2 , g_2 , H_2 and h_2 are defined in the handbook.

IV.4.5. ASSESSMENT POINTS CALCULATED

Part Circumferential Internal Surface Crack, 10 mm Deep

Five different crack lengths were analysed corresponding to $2c/a$ ratios of 2, 4, 8, 16 and 32 respectively, hence, the longest crack assessed was 320 mm long which finishes with the applicability range of the equation for the stress intensity factor solution applicable for this structure.

All the calculations and numerical steps are summarised in Table 15. Figure 16 shows the assessment points in the different Failure Assessment Diagram levels of SINTAP.

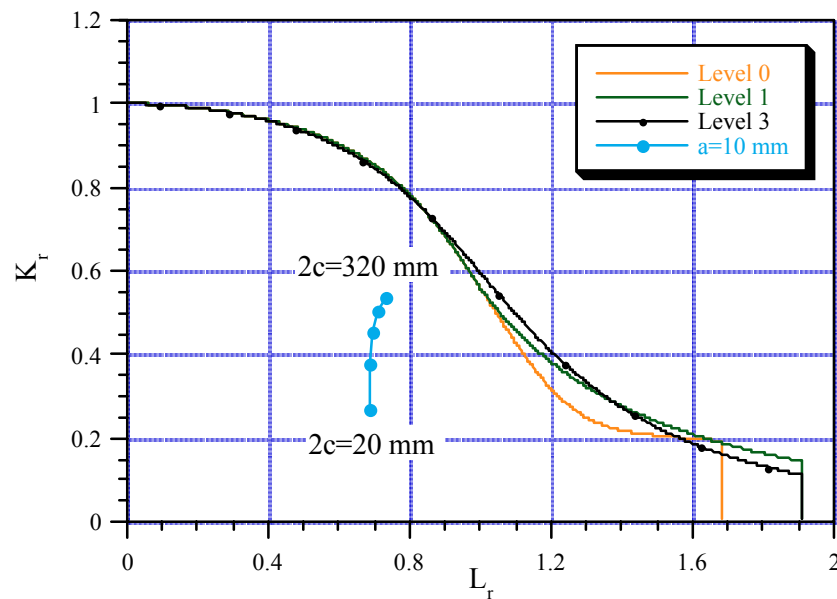


Figure 16. 10 mm deep part circumferential internal surface crack assessment.

The longest crack evaluated to be acceptable is 320 mm long, this means a total angle of 48.3° . Although extrapolating values could be a working option, it is supposed that the consideration of longer defects would hardly have sense as some parts of it would fall into compressive stresses and so the structural mechanism would be different. In order to support this determination, the reserve factor has been calculated, resulting a value of 0.8 which has been taken as a perfectly reasonable number for an assessment.

2c/a	2	4	8	16	32
2c	20	40	80	160	320
<i>Calculation of L_r</i>					
σ_m	50	50	50	50	50
σ_{bg}	120	120	120	120	120
θ	0.0263	0.0526	0.1053	0.2105	0.4211
α	0.0263	0.0526	0.1053	0.2105	0.4211
β	0.9115	0.9112	0.9104	0.9089	0.9053
s_m	73.08	72.75	72.11	70.81	68.28
s_{bg}	175.39	174.61	173.04	169.94	163.89
L_r	0.684	0.687	0.693	0.706	0.732
<i>Calculation of K_r</i>					
<i>Primary stresses</i>					
σ_0	50	50	50	50	50
σ_{bg}	120	120	120	120	120
<i>Secondary stresses</i>					
σ_0	173.57	173.57	173.57	173.57	173.57
σ_1	22.68	22.68	22.68	22.68	22.68
σ_2	-294.37	-294.37	-294.37	-294.37	-294.37
σ_3	98.12	98.12	98.12	98.12	98.12
σ_{bg}	0	0	0	0	0
f_0	0.668	0.907	1.083	1.201	1.278
f_1	0.462	0.563	0.640	0.692	0.726
f_2	0.372	0.428	0.479	0.510	0.533
f_3	0.318	0.351	0.388	0.411	0.429
f_{bg}	0.615	0.834	0.993	1.100	1.165
K_I^P	19.00	25.78	30.72	34.04	36.10
K_I^S	8.53	13.94	17.65	20.27	21.89
χ	0.307	0.371	0.398	0.420	0.444
ρ_1	0.042	0.048	0.051	0.053	0.055
ρ	0.042	0.048	0.051	0.053	0.055
K_r	0.271	0.379	0.454	0.506	0.538

Table 15. Numerical calculations for Example 3, internal crack 10 mm deep.

Part Circumferential Internal Surface Crack, 628.4 mm Long

Seven crack depths were calculated corresponding to $2c/a$ ratios of 20, 24, 25, 26, 27, 28 and 32 respectively, covering a/t ratio values from 0.79 to 0.49.

The numerical calculations needed to perform the evaluation are presented in Table 16 while these points can be seen in the corresponding FADs in Figure 17.

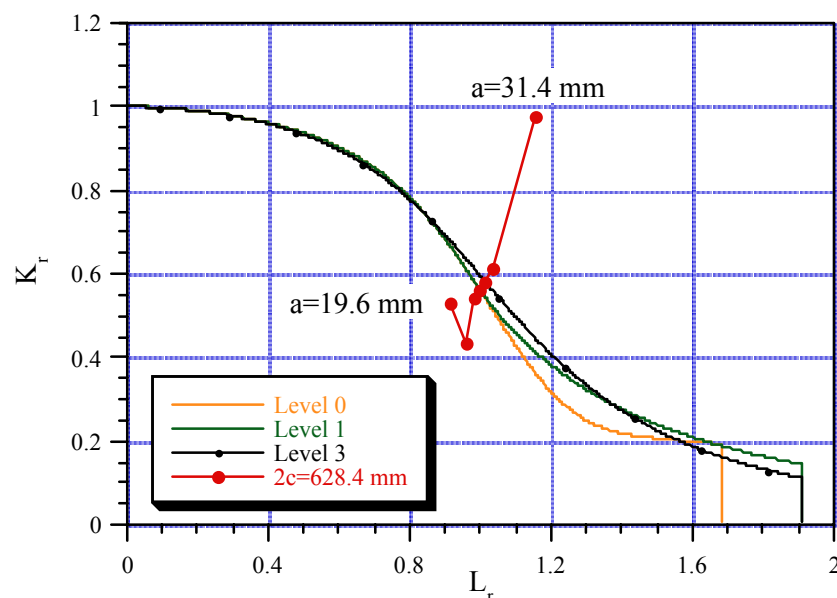


Figure 17. 628.4 mm long part circumferential internal surface crack assessment.

Depending on the assessment level, the critical depth values obtained are; for levels 0 and 1, 24.2 mm deep corresponding to a $2c/a$ ratio of 26 and, for level 3, 25.1 mm, $2c/a$, 25.

With respect to the the residual stresses consideration, it should be pointed out that they have been taken into account even when they are negative. The reason for this is that they are supposed to be perfectly assessed. Another option could be not to considerate them when the values are lower than zero, this would lead to more conservative results.

2c/a	20	24	25	26	27	28	32
a	31.4	26.2	25.1	24.2	23.3	22.4	19.6
a/t	0.79	0.65	0.63	0.60	0.58	0.56	0.49
<i>Calculation of L_r</i>							
σ_m	50	50	50	50	50	50	50
σ_{bg}	120	120	120	120	120	120	120
θ	0.8268	0.8268	0.8268	0.8268	0.8268	0.8268	0.8268
α	0.8268	0.8268	0.8268	0.8268	0.8268	0.8268	0.8268
β	0.8570	0.8661	0.8679	0.8695	0.8711	0.8726	0.8775
s_m	43.35	48.36	49.37	50.30	51.15	51.95	54.67
s_{bg}	104.04	116.09	118.49	120.70	122.77	124.69	131.21
L_r	1.153	1.034	1.013	0.994	0.978	0.962	0.915
<i>Calculation of K_r</i>							
<i>Primary stresses</i>							
σ_0	50	50	50	50	50	50	50
σ_{bg}	120	120	120	120	120	120	120
<i>Secondary stresses</i>							
σ_0	173.57	173.57	173.57	173.57	173.57	173.57	173.57
σ_1	71.23	59.36	56.99	54.79	52.77	50.88	44.52
σ_2	-2905.98	-2017.99	-1859.83	-1719.51	-1594.51	-1482.66	-1135.15
σ_3	3043.44	1761.19	1558.24	1385.27	1236.99	1109.15	743.03
σ_{bg}	0	0	0	0	0	0	0
f_0	2.051	1.871	1.830	1.790	1.764	1.741	1.663
f_1	1.034	0.955	0.937	0.920	0.910	0.901	0.873
f_2	0.713	0.664	0.653	0.642	0.637	0.633	0.617
f_3	0.554	0.520	0.513	0.506	0.501	0.499	0.488
f_{bg}	1.885	1.715	1.677	1.642	1.616	1.594	1.515
K_I^P	103.29	85.85	82.26	78.96	76.29	73.91	65.81
K_I^S	13.74	-12.24	-12.38	-11.54	-11.30	-21.64	-2.55
χ	-	-	-	-	-	-	-
ρ_1	-	-	-	-	-	-	-
ρ	0	0	0	0	0	0	0
K_r	0.975	0.613	0.582	0.562	0.542	0.436	0.527

Table 16. Numerical calculations for Example 3, internal crack 628.4 mm long.

Circumferential Through-Thickness Crack

Firstly, six initial cracks were analysed corresponding to lengths of 20, 30, 40, 50, 75 and 100 mm. Once again, the numbers to develop the assessment are in a separate table (Table 17) and the graphics are shown in Figure 18. All the calculations were, as throughout this Report, done by hand, nevertheless, in order to refine the evaluation, once the six crack lengths were studied, a range of lengths from 50 to 75 mm were also assessed in steps of 1 mm with the help of an in-house computer programme. Table 18 summarises the co-ordinates on a FAD plot for these flaws. Besides, Figure 19 shows a zoom for values of defect length ranging from 50 to 60 mm.

The critical crack lengths calculated are between 54 and 55 mm for the three FAD levels.

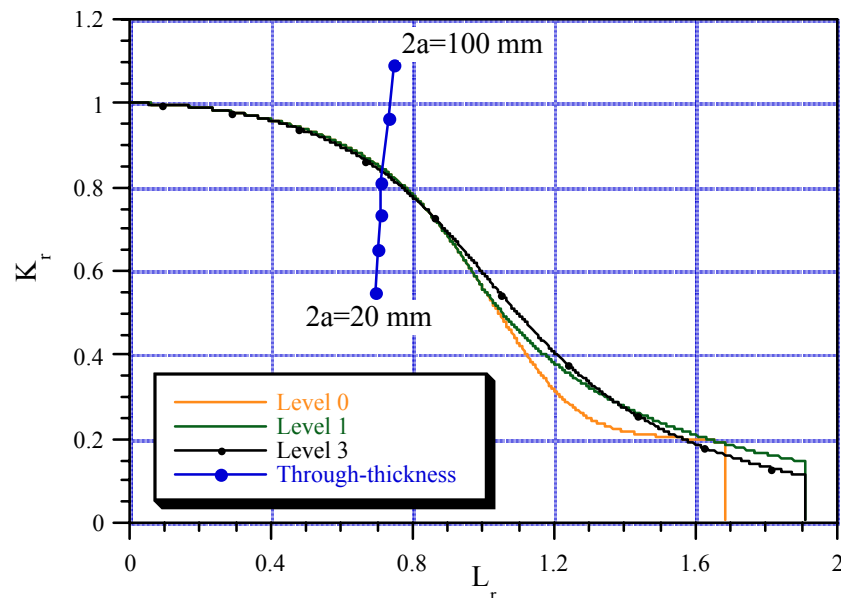


Figure 18. Circumferential through-thickness crack assessment.

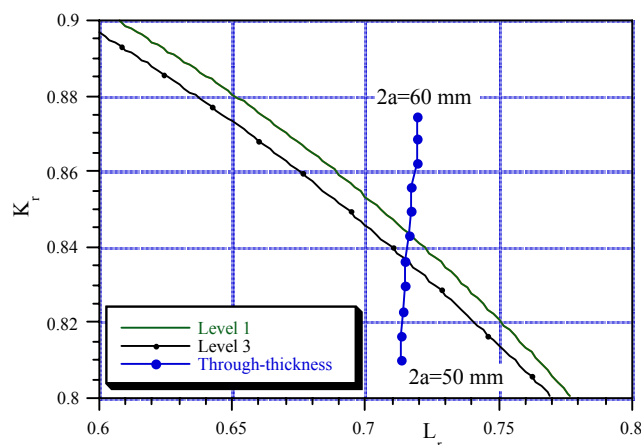


Figure 19. Circumferential through-thickness crack assessment (detail).

2a	20	30	40	50	75	100
<i>Calculation of L_r</i>						
σ_m	50	50	50	50	50	50
σ_{bg}	120	120	120	120	120	120
θ	0.0263	0.0395	0.0526	0.0658	0.0987	0.1316
β	0.9105	0.9097	0.9090	0.9083	0.9064	0.9045
s_m	72.10	71.45	70.80	70.14	68.52	66.90
s_{bg}	173.05	171.47	169.92	168.36	164.44	160.54
L_r	0.693	0.700	0.706	0.713	0.730	0.747
<i>Calculation of K_r</i>						
<i>Primary stresses</i>						
σ_a (hoop)	50	50	50	50	50	50
σ_b (bending)	120	120	120	120	120	120
<i>Secondary stresses</i>						
σ_b^s (self-eq)	173.57	173.57	173.57	173.57	173.57	173.57
β	0.0250	0.0375	0.0500	0.0625	0.0938	0.1250
ρ	0.0791	0.1186	0.1581	0.1976	0.2965	0.3953
$G2(\rho)$	1.0151	1.0227	1.0303	1.0379	1.0572	1.0767
$g2(\rho)$	0.0145	0.0278	0.0418	0.0565	0.0961	0.1402
$H2(\rho)$	0.8781	0.8501	0.8232	0.7974	0.7377	0.6844
$h2(\rho)$	0.0028	0.0049	0.0070	0.0089	0.0135	0.0176
$C1(\beta)$	1.0002	1.0005	1.0008	1.0013	1.0029	1.0052
$C2(\beta)$	1.0005	1.0011	1.0020	1.0031	1.0071	1.0127
$G*2(\rho, \beta)$	1.0153	1.0231	1.0311	1.0391	1.0601	1.0819
$K_{I out}$ (hoop)	9.13	11.40	13.44	15.34	19.79	24.11
$K_{I a}$ (bending)	21.59	26.65	31.02	34.94	43.66	51.46
$K_{I out}$ (self-eq)	27.10	32.22	36.12	39.22	44.75	48.29
K_I^P	30.72	38.05	44.46	50.28	63.45	75.57
K_I^S	27.10	32.22	36.12	39.22	44.75	48.29
χ	0.611	0.593	0.574	0.556	0.515	0.477
ρ_1	0.068	0.066	0.065	0.064	0.060	0.057
ρ	0.068	0.066	0.065	0.064	0.060	0.057
K_r	0.550	0.652	0.737	0.810	0.962	1.089

Table 17. Numerical calculations for Example 3, through-thickness crack.

2a	L _r	K _I ^P	K _I ^S	K _r
50	0.713	50.28	39.22	0.810
51	0.713	50.84	39.5	0.816
52	0.714	51.40	39.77	0.823
53	0.715	51.95	40.03	0.830
54	0.715	52.50	40.29	0.836
55	0.716	53.05	40.55	0.843
56	0.717	53.59	40.80	0.849
57	0.717	54.13	41.04	0.856
58	0.718	54.67	41.28	0.862
59	0.719	55.21	41.52	0.868
60	0.719	55.74	41.75	0.875
61	0.720	56.27	41.98	0.881
62	0.721	56.80	42.20	0.887
63	0.721	57.32	42.42	0.893
64	0.722	57.84	42.63	0.899
65	0.723	58.36	42.84	0.905
66	0.724	58.88	43.05	0.911
67	0.724	59.40	43.25	0.917
68	0.725	59.91	43.45	0.923
69	0.726	60.42	43.65	0.928
70	0.726	60.93	43.84	0.934
71	0.727	61.44	44.03	0.940
72	0.728	61.95	44.22	0.945
73	0.728	62.45	44.40	0.951
74	0.729	62.95	44.58	0.957
75	0.730	63.45	44.75	0.962

Table 18. L_r and K_r co-ordinates for cracks ranging from 50 to 75 mm.

IV.5. RESULTS

The results for the three cracks and different levels of analysis are summarised in tabular form in Table 19 where all results are in mm.

Crack	Level 0	Level 1	Level 3
Maximum allowed length of an internal surface crack 10 mm deep	>320	>320	>320
Maximum allowed depth of an internal surface crack 628.4 mm long	24.2	24.2	25.1
Maximum allowed length of a through-thickness crack	55	55	54

Table 19. Critical crack dimension for flaws considered in Example 3.

V. REFERENCES

- [1] *Structural Integrity Assessment Procedure for European Industry, SINTAP*, BRITE-EURAM Project BRPR-CT95-0024, June 1999.
- [2] A.C. Bannister, “Sub-Task 2.3 Report: Yield Stress/Tensile Stress Ratio: Results of Experimental Programme”, Report N° SINTAP/BS/25, February 1999.
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- [4] J.K. Sharples, Examples from AEA Technology.
- [5] Assessment of the Integrity of Structures Containing Defects, British Energy Procedure R/H/R6 – Revision 3, 1997.