THE APPLICATION OF INTEGRITY ASSESSMENT PROCEDURES IN OPTIMIZING THE VESSEL SURVEILLANCE PROGRAMS

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ABSTRACT

The effect on the component integrity prediction of the variation in toughness, even obtained through the different specimen configurations or calculated indirectly by Charpy impact testing, is analysed in this paper. The objective is to determine, as a function of radiation embrittlement, when the important effort to reconstitute irradiated specimens is effective for the surveillance and life-extension programs of power plants.

INTRODUCTION

The main goal of a fracture analysis is to assess the structural integrity of a cracked component as a function of its in-service conditions. In this way, it is very usual to determine the safety factors between the failure conditions and the applied stresses in the component.

However, in the structural integrity assessment of any cracked component the obtained results are strongly dependent on the quality of databases available from the material's characterisation. These may include tensile test characterisation, impact Charpy and fracture toughness results. In order to evaluate fracture toughness according to the standards in use it is necessary to have enough material available for testing. This can be a drawback specially in nuclear power plants because of the intrinsic limitation of material imposed by the whole surveillance programs, which are based on results obtained from Charpy impact tests providing very conservative safety margins. Direct determination of fracture toughness would allow the reduction of conservatism and a benefit for plant operations.

In order to overcome this problem, some alternative methods for fracture toughness evaluation have been developed. One of this methods is based on the use of Fracture Mechanics reconstituted specimens complying with these two conditions: firstly, its attainability from the available material previously tested in the surveillance programs and secondly, to provide a material representative value of fracture toughness.

To comply with the first condition, the reconstituted specimens should be able to be fabricated with halves of Charpy specimens already tested. The second condition is fulfilled if the reconstituted specimens are able to provide the complete J_R curve of the material, non dependent of the reconstitution techniques performed or geometries used on them.

In this work, the safety factors obtained in the structural integrity assessment of a pressure vessel from results of Charpy impact tests as well as the toughness values obtained from CT reconstituted specimens using standardised fracture toughness tests are compared. In this way, a simple cracked plate has been evaluated by analytical methods as it can represents a pressure vessel as a big in size cylindrical recipient submitted to internal pressure whose curvature can be neglected, behaving like an infinite plate in tension.

The procedure used for the structural integrity assessment has been the SINTAP (Structural Integrity Assessment Procedures for European Industry) [1]. It has been selected for its novelty, its possible use as future european standard and for agglutinating other procedures already in use from some years ago.

EXPERIMENTAL PROGRAM

For this work, two different materials, typical reactor pressure vessel steels have been selected: the forged steel ASTM A508 Cl. 3 [2] and the rolling plate steel ASTM A533 Gr. B Cl. 1 [3]. These materials were used in as-received non-embrittled conditions. The materials have been characterised in tensile tests and Table 1 shows the representative values to be used in the structural integrity assessment at the different levels.

TABLE 1
RESULTS OBTAINED FROM TENSILE TESTS

Material	Orientation	σ_y (MPa)	σ_R (MPa)	Elongation (%)
A508	L	505	655	10
	T	510	650	8.5
A533	L	485	625	9.5
	T	520	640	8

Also Charpy impact tests were used to define their transition curves, represented in Figure 1 for different orientations which have been identified following the recommendations of ASTM standards [4].

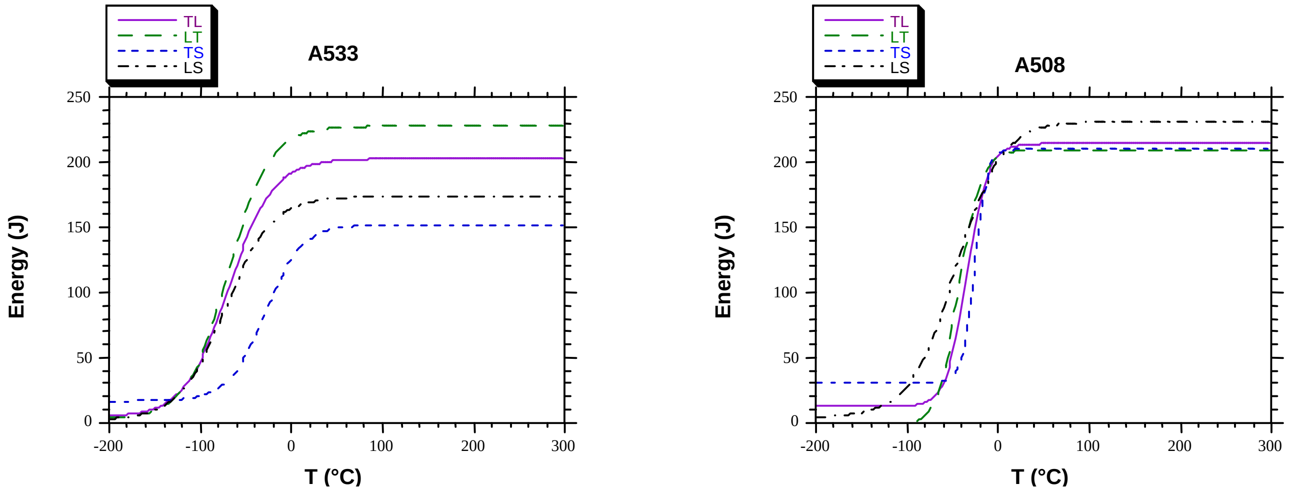
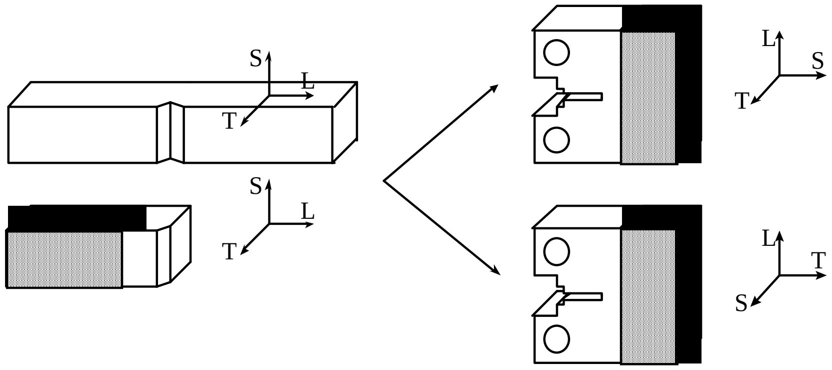


Figure 1. Charpy impact tests curves for A533 and A508 steels, respectively.

In order to simulate the fracture toughness characterisation of irradiated materials an experimental program based on the use of reconstituted CT specimens has been developed. These CT's were reconstituted from halves of Charpy specimens that had been previously tested. Three different geometrical configurations (Type-B, Type-C and Type-D) have considered depending on the available material and the orientation to be tested [4], as shown in Figure 2.



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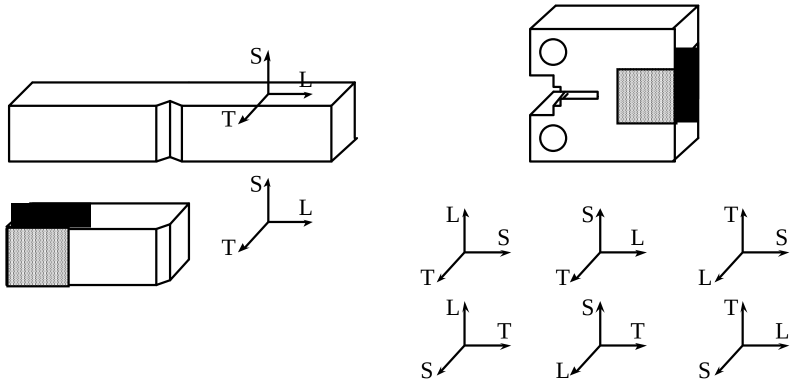

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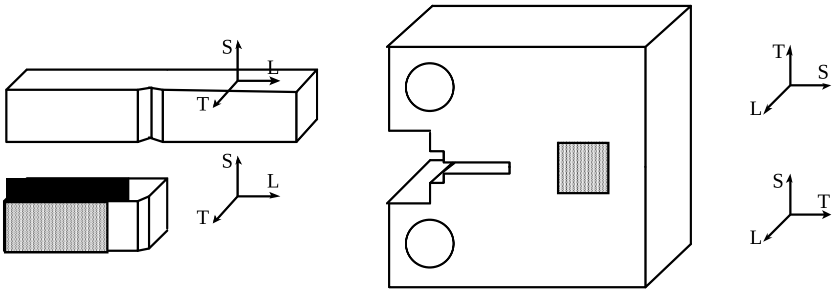
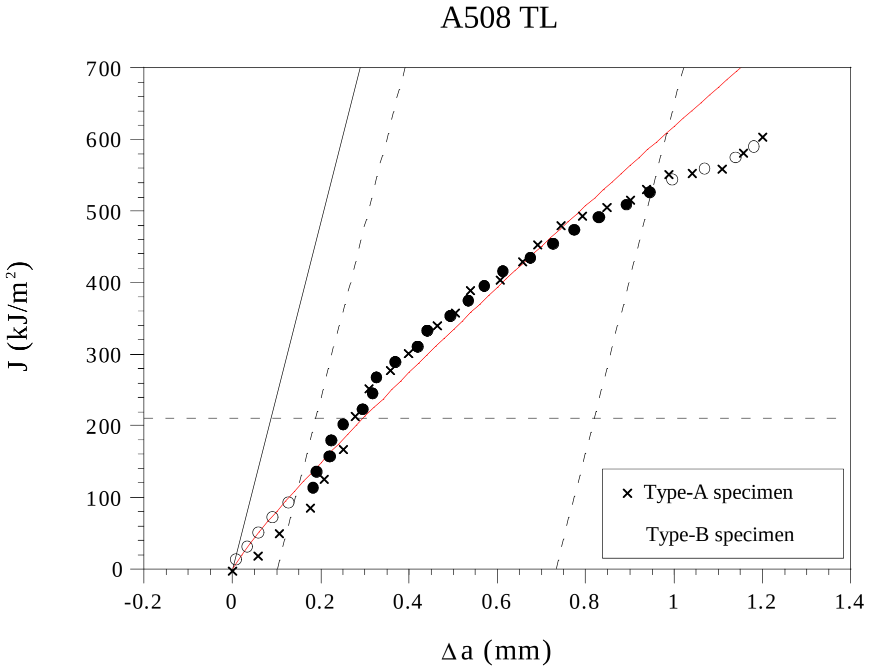


Type-D

Figure 2. Configurations of reconstituted CT specimens.

In order to validate the reconstitution process, fracture toughness measurements were obtained from non-reconstituted CT standardised reference specimens (Type-A) of all the selected materials and orientations. The validation has been successful when the results obtained from both reconstituted and reference specimens are comparable. There is a good agreement between the results obtained except in the cases of interaction of plastic zones at crack tips and heat-affected zones (HAZ) developed during the weld-reconstitution processes. When this interaction occurs the validation is not attained because the reconstituted specimens provide less fracture toughness values than the corresponding reference specimens [5]. Overcoming this situation, Type-B specimens are able to provide a representative toughness value for the implanted material.

As an example, in Figure 3 the J_R curve and characteristic parameters obtained from a Type-B reconstituted CT specimen of A508 steel in TL orientation are shown. This curve is compared in the same figure with the J_R results obtained from a standardised reference CT specimen of the same material and orientation. The similar behaviour obtained for both, the reference and the reconstituted specimens, supports the use of reconstitution programs for fracture toughness evaluations in the integrity assessment of the corresponding vessel.



$$J_R = 618.13\ \Delta a^{0.88564}$$
$$J_{0.2/BL} = 234.0\ \text{kJ/m}^2$$
$$K_{mat} = 229.17\ \text{MPa}\cdot\text{m}^{1/2}$$

Figure 3. J_R curve of forged steel A508 in TL orientation.

From the J_R curve, obtained following the ESIS standard procedure [6], $J_{0.2/BL}$ is the characteristic parameter of cracking initiation and K_{mat}, the SINTAP material's representative toughness, corresponds to the relation [1]:

$$K_{mat} = \sqrt{\frac{JE}{\left(1-\nu^2\right)}} \tag{1}$$

where E is the Young's Modulus, ν is the Poisson's ratio and J takes the value of initiation $J_{0.2/BL}$.

These results must be compared with those obtained from indirect fracture toughness measurements such as the Charpy impact tests values, being Charpy specimens the conventionally enclosed in the capsules of surveillance programs. Different correlations can be stated for the evaluation of fracture toughness (K_{mat}) of the material from the results obtained in Charpy impact tests (CV). In this work, the SINTAP correlation for the upper shelf value has been used [1], according with the temperature for which the structural analysis is going to be done. So:

$$K_{mat} = \sqrt{E'\left(0.53CV^{1.28}\right)\left(0.1^{0.133\cdot CV^{0.256}}\right)} \tag{2}$$

where E' = E for plane stress and E' = $E/(1-\nu^2)$ for plane strain.

In this way, Table 2 shows the fracture toughness values obtained for all the materials and orientations considered from both Charpy and CT Type-B reconstituted specimens using correlations (2) and (1), respectively.

TABLE 2

FRACTURE TOUGHNESS VALUES OBTAINED FROM CHARPY AND CT TYPE-B SPECIMENS

Material	Orientation	CV_{us} (J)	K_{mat} ($MPa \cdot m^{1/2}$) (2)	J_R curves for Type-B	K_{mat} ($MPa \cdot m^{1/2}$) (1)
A508	TL	212	183.87	$J_R = 661.12\Delta a^{0.87869}$	221.70
	TS	210	183.02	$J_R = 712.46\Delta a^{0.92564}$	247.31
	LT	210	183.02	$J_R = 525.64\Delta a^{0.75846}$	212.71
	LS	231	191.66	$J_R = 620.05\Delta a^{0.90889}$	213.14
A533	TL	202	179.60		
	TS	152	156.11	$J_R = 445.57\Delta a^{0.61673}$	218.24
	LT	228	190.46	$J_R = 664.28\Delta a^{0.78944}$	244.48
	LS	172	165.98	$J_R = 678.75\Delta a^{0.87715}$	230.78

STRUCTURAL ANALYSIS

In a nuclear power plant the reactor pressure vessel is exposed to neutron irradiation causing embrittlement of its material. As mentioned before, this particular element can be modelised through a simple plate in tension in order to simplify the structural analysis to be done. Figure 4 shows the geometrical configuration of the cracked component studied and the stress state in the whole plate.

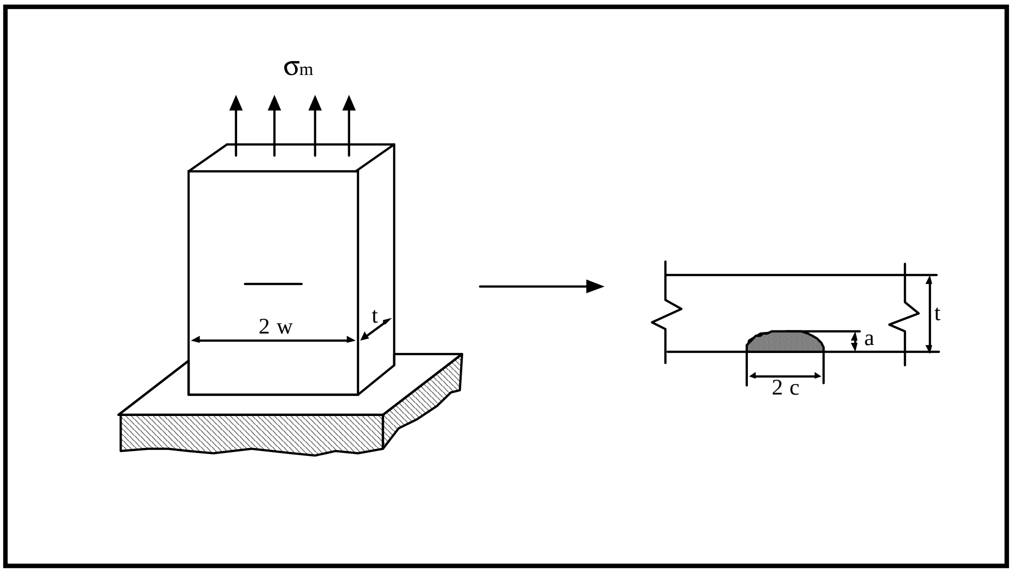


Figure 4. Geometrical configuration studied.

The structural analysis carried out on this component following the SINTAP procedure will allow to calculate its failure stress while Section III of ASME Code [7] provides the maximum admissible stress. In this way, it is possible to evaluate the safety factors for each fracture toughness value independently of the test method used to calculate it, and consequently to compare all the results obtained from different methods.

The SINTAP procedure offers two different methodologies to perform the structural analysis: the first one is based on the use of Failure Assessment Diagrams (FAD's) and the second one makes use of the Crack Driving Force Diagrams (CDFD's) [8].

The FAD is a graphical representation of two non dimensional parameters, L_r and K_r, representing the structural conditions and defined as follows:

$$L_r = \frac{\sigma}{\sigma_f} \qquad ; \qquad K_r = \frac{K_I}{K_{mat}} \tag{3}$$

being σ and K_I the applied values of stress and stress intensity factors, respectively, and σ_f and K_{mat} the corresponding values of yield strength and fracture toughness.

The structural condition position in the diagram is referred to the failure assessment line (FAL) that defines the safety limits. FAL equations are defined in the SINTAP procedure depending on the quality of data of the material's component behaviour, establishing different levels where the hierarchy of the analysis has been provided [9].

The CDFD represents a complete comparison between the applied J-integral (J_{total}) and the resistance J_R curve of the material, describing in this way the tearing processes at fracture phenomena.

The formulation used to determine the failure lines (FAL) in FAD's can be also used to determine the J_{total} in CDFD's as it has been shown the complete compatibility between the two methods following the SINTAP procedure [9, 10].

RESULTS AND ANALYSIS

Figure 5 defines the analysis done following the FAD methodology. Three different levels of FAL are defined: the basic, obtained only from the yield strength value of the steel of the component; the level 1, applied when yield strength and tension strength of the material are known, and the level 3, obtained from the complete stress-strain curve of the material. The lines defining the structural conditions show the evolution with the applied load (σ), by using the K_{mat} values obtained from Charpy and reconstituted CT specimens.

Figure 6 shows an analysis of the limit loading conditions of the component by using a CDFD.

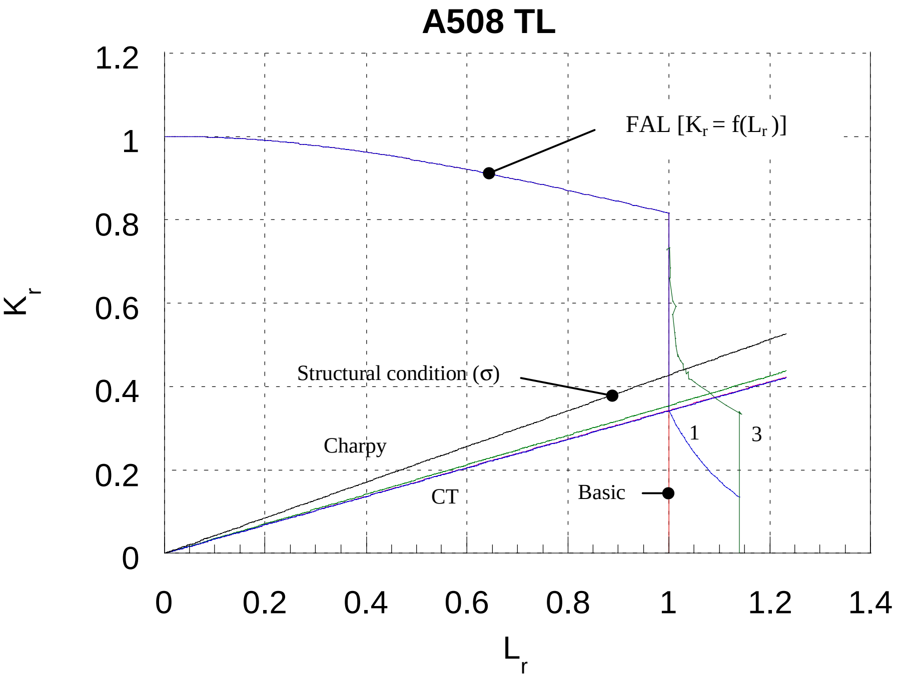


Figure 5. FAD for A508 steel in TL orientation.

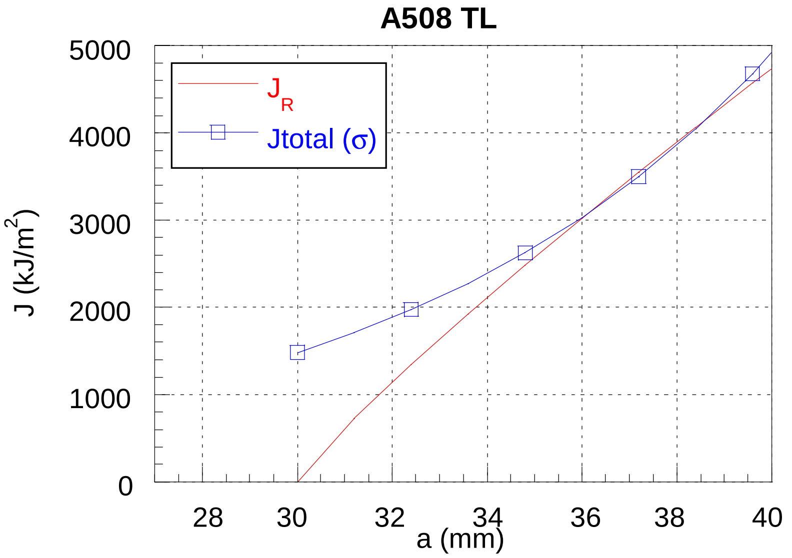


Figure 6. CDFD for A508 steel in TL orientation.

Once the critical loading values are obtained following the different available methodologies (FAD or CDFD) and level of analysis and toughness data were applied (K_{mat} from Charpy or CT specimens), Tables 3 and 4 show the values of safety factors obtained from FAD's analysis for A533 and A508 steels respectively, for two different levels of analysis, level 1 and level 3, in order to compare the results obtained when using Charpy tests or CT reconstituted or reference specimens.

TABLE 3
SAFETY FACTORS VALUES FOR A533 STEEL

Orientation	Level	Type-A	Type-B	Charpy
TL	1	2.6685		2.6250
TS		2.6957	2.6793	2.5761
LT		2.3533	2.3696	2.3533
LS		2.3533	2.3587	2.3533
TL	3	2.7663		2.6957
TS		2.8207	2.7826	2.6359
LT		2.5707	2.6141	2.4565
LS		2.5543	2.5707	2.4022

TABLE 4

SAFETY FACTORS VALUES FOR A508 STEEL

Orientation	Level	Type-A	Type-B	Charpy
TL	1	2.4239	2.4239	2.4239
TS		2.4620	2.4511	2.4239
LT		2.4239	2.4239	2.4239
LS		2.4565	2.4239	2.4239
TL	3	2.6467	2.6250	2.5
TS		2.7446	2.712	2.5
LT		2.6739	2.6087	2.5163
LS		2.7337	2.6087	2.5489

As can be clearly seen, the predictions obtained from Charpy tests are generally more conservative than the corresponding to CT specimens as it should be, considering their lower quality of toughness data. Only at level 1 when the lines defining the structural conditions intersects the FAL of the yield plateau region no differences are obtained. Also, a higher level of analysis means a greater difference between the values.

According with the high-fracture toughness materials in the as-received conditions analysed the failure is predicted to occur by plastic collapse. Therefore to increase the accuracy of the results the SINTAP procedure suggest the use of a better knowledge on tensile behaviour, considering that, in this case, the improvement in fracture toughness measurements has a poor significance.

So the increase in accuracy, that means a increase in the safety factor, is mainly observed when not level 1 but level 3 is used, being at this level when a higher difference can be obtained by using CT measured toughness values instead of those calculated from Charpy results.

Alternatively, Table 5 shows the safety factors values obtained from CDFD’s analysis of all the steels and orientations tested. The use of this method following a precise definition of the J_R curve establishes only small differences with the prediction of level 3 FAD results for this high-toughness materials.

TABLE 5

SAFETY FACTORS VALUES OBTAINED FROM CDFD’S ANALYSIS

Material	Orientation	Type-A	Type-B
A508	TL	2.8804	2.8967
	TS	2.9239	2.9293
	LT	2.788	2.7663
	LS	2.7446	2.8533
A533	TL	2.8641	
	TS	2.7826	2.7772
	LT	2.8098	2.75
	LS	2.7446	2.7826

Therefore the small improvement (a maximum value around 15%) obtained when using J_R curves obtained from reconstituted CT specimens instead of the results of energy derived from Charpy tests do not justifies the big expenses that represents the specimens reconstitution programs.

Nevertheless, this situation can change if neutron irradiation embrittlement processes are reported. Then, the representation of structural situation is modified by a global anticlockwise turn around the origin as shown in Figure 7.

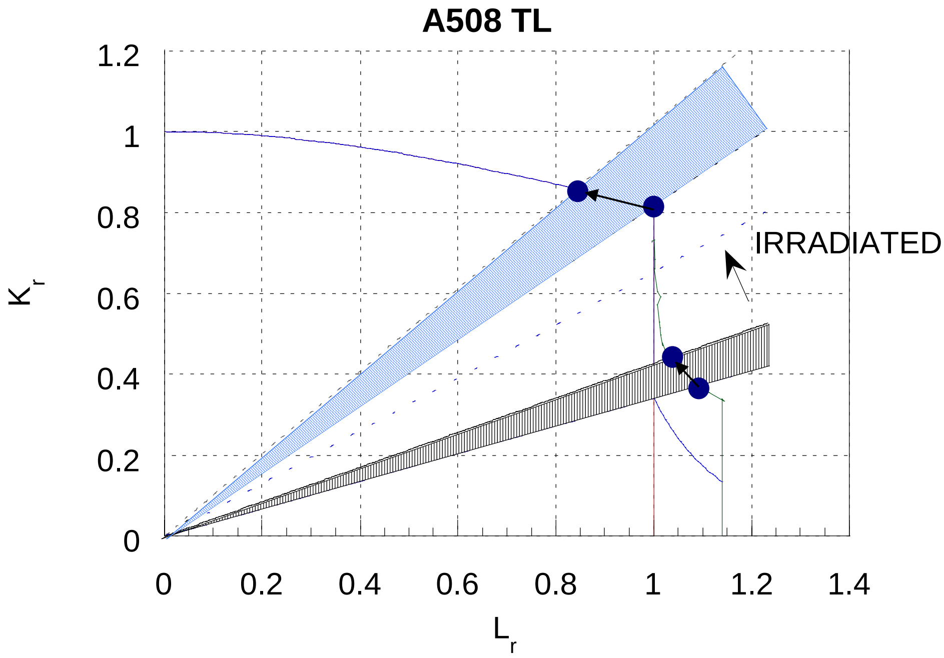


Figure 7. Change in failure stress for A508 steel in TL orientation associated to a growing irradiation embrittlement process.

In this case, the use of fracture toughness values obtained from CT specimens instead of Charpy tests results implies a significant improvement in failure stress predictions. This justifies why is important to use alternative methods for evaluating fracture toughness. Besides, is in high embrittlement conditions where reconstituted specimens are more reliable [5].

CONCLUSIONS

Different concluding remarks can be derived from this work depending on the material's conditions.

1. For high-fracture toughness materials or low embrittlement conditions, the failure of the component occurs by plastic collapse and consequently, the main efforts have to be made in order to improve the mechanical behaviour knowledge of the material instead of its fracture properties. Hence, the development of reconstitution programs from previously tested specimens is not recommended because substantial predictive improvements are not expected.

2. For low-fracture toughness materials or high embrittlement conditions, the use of reconstitution programs for life-extension analysis is strongly recommended in order to improve the quality of predictions on failure stresses. Besides, in these conditions, there are less probabilities of interactions between plastic zones and HAZ in reconstituted specimens, leading to more accurate results.

As a consequence, it is important to define the embrittlement state of the material of the component to be analysed by comparison with a threshold value of impact energy which indicates the separation between high and low embrittlement conditions. This threshold value can be derived from the line of structural condition that intersects the FAL at its $L_r = 1$ point. This threshold value will depend on the mechanical behaviour of the material, the geometrical conditions of the components, the cracking process and the applied stresses.

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