# On the Differences Observed in the Fracture Behaviour of Centre Cracked and Centre Notched Specimens and Their Effect on Structural Integrity Assessments

Cicero, S.[1,a], Gutiérrez-Solana, F.[1,b], Horn, A.J[2,c]

[1] Departamento de Ciencia e Ingeniería del Terreno y los Materiales, Universidad de Cantabria, Santander, Spain.

[2] CORUS UK Ltd., Swinden Technology Centre, Rotherham, UK

[a]ciceros@unican.es, [b]gsolana@unican.es, [c]Anthony.J.Horn@corusgroup.com

**Keywords:** Crack, notch, structural integrity assessment, toughness, failure assessment diagram

**Abstract.** This paper analyses the experimental differences found between the behaviour of cracked and notched specimens. These differences are defined in terms of local strains, global strains, stresses and CTOD values during testing, and also through the correlations established between these variables. The experimental programme has been performed at very distinct temperatures (from -100ºC to -20ºC), providing an outline of the notch effect throughout the transition region. The corresponding effects on structural integrity assessments (through Failure Assessment Diagrams) are also analysed. From the results obtained, a clear notch effect in all the mentioned parameters and in the assessment itself has been defined for temperatures below the Transition Temperature ($T<T_0$) of the material. The effect is less pronounced or even negligible at higher temperatures ($T>T_0$).

## Introduction

Cracks and notches produce different stress-strain fields ahead of their respective tip [i.e, 1-8]. The notch effect produces a stress relaxation in such a way that the bigger the notch tip radius, the greater the stress reduction [3,4]. Creager and Paris [1] defined the stress distribution ahead of the notch tip as that one ahead of the crack tip but displaced a distance equal to $\rho/2$ along the x axis, something that clearly indicates the mentioned stress relaxation.

This fact usually means that it is over conservative to perform structural integrity assessments of notched components by assuming that notches behave as cracks and using conventional Fracture Mechanics. In [7,8], a methodology to assess notches by means of Failure Assessment Diagrams (FADs) is presented and some differences between the behaviour of notched and cracked components are pointed out in terms of the critical stresses reached for different notch radii. Here, these differences are analysed in depth in terms of local strains, global strains, stresses and CTOD values during testing, and also through the various correlations established between these variables. This analysis is necessary for a better understanding of the causes that lead to different behaviour between cracked and notched components.

## 2. Experimental programme.

In order to compare the behaviour of notched and cracked components, a set of fourteen tests were proposed [7]. The specimens were taken from the flanges of structural profiles and their geometry is shown in Fig. 1. All of them were tested in tension. Tests were performed at different temperatures, from -100ºC to -20ºC, in order to consider the possible influence of temperature in the notch effect. The thickness of the specimens also varies, due to the different material fracture behaviour when this variable changes. Finally, there are also three different notch radii: near 0 mm, obtained by precracking processes in the case of cracked specimens, 1.2 mm and 2.0 mm. Table 1 shows a summary of the experimental programme.

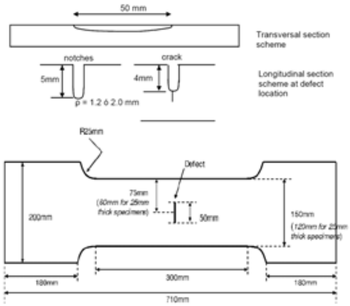


**Fig. 1.** Geometry of the specimens used in the experimental programme

**Table 1.** Experimental programme. Geometry and identification of the specimens tested.

| | | **TEST TEMPERATURE** | | |
|---|---|---|---|---|
| **THICKNESS** | **DEFECT TYPE** | | **-65 ºC** | |
| **15.4 mm** | *CRACK* | | Y1A13A1 | |
| | *NOTCH ρ=1.2 mm* | | Y1A13A2 | |
| | *NOTCH ρ=2.0 mm* | | Y1A13A3 | |
| | | **-100 ºC** | **-85 ºC** | **-20 ºC** |
| **21.3 mm** | *CRACK* | Y1A19A1 | Y1A19A2 | Y1A19A3 |
| | *NOTCH ρ=1.2 mm* | Y1A19A4 | Y1A19A5 | |
| | *NOTCH ρ=2.0 mm* | Y1A19A6 | Y1A19A7 | Y1A19A8 |
| | | **-80 ºC** | | |
| **25.4 mm** | *CRACK* | X4M4A1 | | |
| | *NOTCH ρ=1.2 mm* | X4M4A2 | | |
| | *NOTCH ρ=2.0 mm* | X4M4A3 | | |

2.1. Material characterization

The material used has been a ferritic-pearlitic S355JR steel [9], whose microstructure, chemical composition, tensile properties and fracture toughness values [10] (in terms of the Transition Temperature ($T_0$) of the Master Curve [11]) are presented in [7,8].

2.2. Tests Results

Fig. 2 shows the scheme of an instrumented sample.

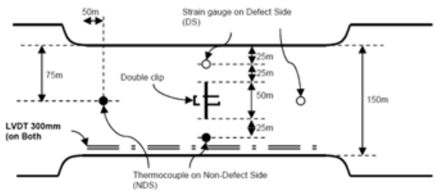


**Fig. 2.** Scheme of the instrumentation used in the tests.

The thermocouples measured the test temperature, the LVDTs measured the global displacements and the local strains were measured using strain gauges (located close to and far away from the defect). A double clip gauge was used in order to obtain the COD evolution and the applied loads were measured directly by the test machine. Fig. 3 shows the two extreme behaviours observed in the registered parameters. The graphs on the left correspond to a cracked sample (ρ≈0 mm, thickness 21.3 mm) tested at low temperatures (-85ºC, corresponding to the material Transition Zone, TZ, at Temperatures around $T_0$, as explained below) and mainly having a brittle failure. The graphs on the right correspond to a notched sample (ρ=2.0 mm, thickness 25.4 mm) tested below $T_0$ (-80ºC, corresponding to the material Lower Shelf, LS, as explained below) and having a plastic collapse failure.

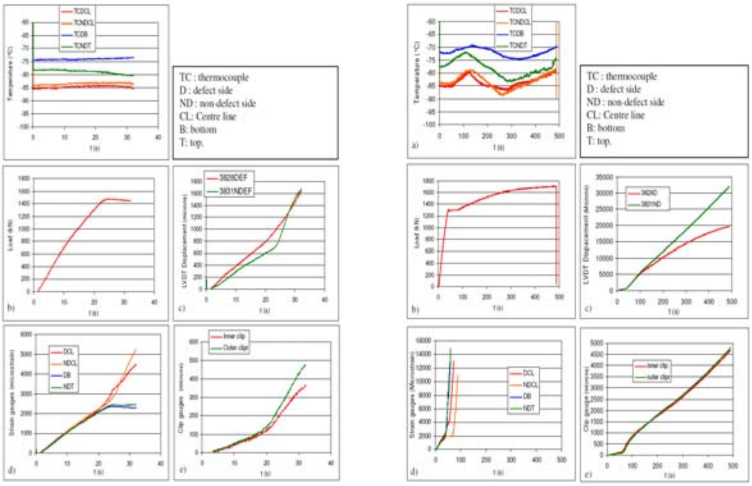


**Fig. 3.** Evolution of the different parameters registered during the testing of the cracked specimen Y1A19A2 (left, TZ, T=-85ºC≈$T_0$)) and notched specimen X4M4A3 (right, LS, T = -80ºC). a) Temperature; b) Applied load; c) LVDT displacement; d) Strain at gauges; e) COD.

Fig. 4 shows some of the correlations obtained from the registered parameters. a) and b) graphs show the classical stress-global strain and stress-local displacement curves, respectively; c) graphs show the global-local strain correlations at different specimen locations and d) graphs show the global strain-local displacement (near the defect) correlation. Table 2 summarises the results obtained in the tests. The specimens have been grouped according to their testing temperature relative to their respective Transition Temperature, $T_0$ [7,8].

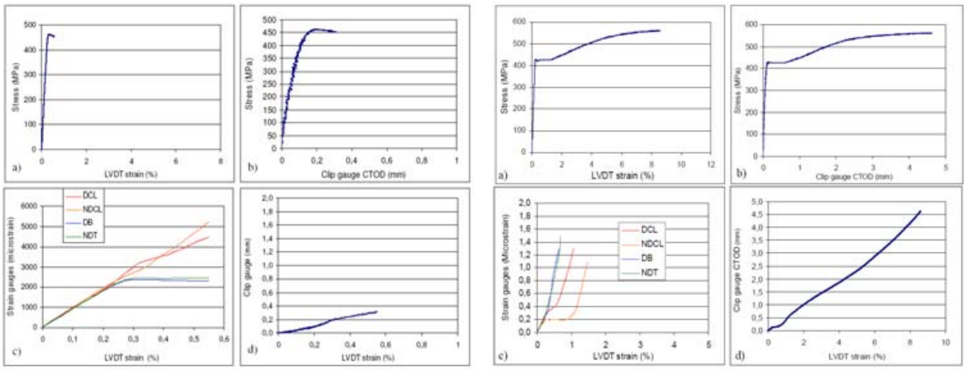


**Fig. 4.** Correlations obtained from the tests. Cracked specimen Y1A19A2 (left, TZ, Tª = -85ºC ≈ T0) and notched specimen (right, LS, T = -80ºC) . a) stress-LVDT: b) stress-COD; c) strain gauge-LVDT; d) COD-LVDT.

**Table 2**. Main results obtained in the tests

| Test conditions | Specimen | Critical Stress (MPa) | Strain at rupture (%) | Defect Size (mm) | $\mathbf{CTOD_i}$ (mm) | $\mathbf{CTOD_c}$ (mm) |
|---|---|---|---|---|---|---|
| **-20 ºC (*US*) 21.3 mm** | **Y1A19A3 (ρ~0 mm)** | 510.2 | 8.36 | 5.42 | 3.0 | 5.3 |
| | **Y1A19A8 (ρ=2.0 mm)** | 511.7 | 11.03 | 5.12 | 3.8 | 5.7 |
| **-65 ºC (*TZ, T>T₀*) 15.4 mm** | **Y1A13A1(ρ~0 mm)** | 514.4 | 6.02 | 5.50 | 2.8 | 3.3 |
| | **Y1A13A2 (ρ=1.2mm)** | 526.2 | 7.03 | 5.17 | 3.3 | 3.3 |
| | **Y1A13A3 (ρ=2.0 mm)** | 530.3 | 7.94 | 5.36 | 2.6 | 3.0 |
| **-85 ºC (*TZ, T=T₀*) 21.3 mm** | **Y1A19A2 (ρ~0 mm)** | 462.9 | 0.55 | 5.53 | 0.30 | 0.30 |
| | **Y1A19A5 (ρ=1.2 mm)** | 547.8 | 7.50 | 5.04 | 2.5 | 2.7 |
| | **Y1A19A7 (ρ=2.0 mm)** | 561.7 | 11.00 | 5.35 | - | - |
| **-100 ºC (*TZ, T<T₀*) 21.3 mm** | **Y1A19A1 (ρ~0 mm)** | 470.4 | 1.40 | 5.56 | 0.26 | 0.26 |
| | **Y1A19A4 (ρ=1.2 mm),** | 550.2 | 2.89 | 4.82 | - | - |
| | **Y1A19A6 (ρ=2.0 mm)** | Failure far away from the defect | | | | > 4.2 |
| **-80 ºC (*LS*) 25.4 mm** | **X4M4A1 (ρ~0 mm)** | 430.9 | 0.43 | 6.00 | 0.17 | 0.17 |
| | **X4M4A2 (ρ=1.2 mm)** | 544.1 | 7.03 | 5.00 | 2.5 | 2.7 |
| | **X4M4A3(ρ=2.0 mm)** | 556.4 | 8.60 | 5.00 | 3.0 | 4.6 |

## 3. Notch effect analysis and comparison of the different behaviours.

Some observations can be made from the analysis of the experimental results presented in the previous section. Firstly, for a given temperature, both the strain at the maximum load and the critical (maximum) stress increases as the notch radius increases. Moreover, the lower the test temperature is (compared to $T_0$), the more noticeable these increases are. In this manner, meanwhile the variation of the critical stress can be considered within the tests dispersion for the Upper Shelf tests, the variation of this parameter in the Lower Shelf tests is near the 30%.

In terms of the strain at maximum load, the most significant variations occurred at temperatures below $T_0$, where the failure mode of the components changed between pre-cracked and notched specimens. For pre-cracked specimens, brittle failure occurred primarily in the elastic regime (maximum LVDT or global strain in the order of 0.5-1.5%), and for notched specimens failure occurred by ductile behaviour after a global plasticity process, with a yield plateau and strain hardening (maximum global strain in the order of 7-11%, depending on the temperature and the notch stress). It can also be seen [7] that the curves for cracked and notched specimens follow quite similar paths in both the stress vs. LVDT strain and stress vs. clip gauge strain curves. Therefore, the unique difference between the cracked and notched specimens is the divergence in the values of stress and strain at failure: cracked specimens fail at much lower critical stresses and strains than notched specimens, and this difference between cracked and notched specimens is greatest at temperatures below $T_0$. Fig. 5 shows the evolution of the critical stress and the global strain at maximum load with the notch radius and the different states (brittle vs. ductile) of the material. A very moderate effect is observed for temperatures above $T_0$, meanwhile for more brittle situations the effect progressively increases.

Another observation is that for a given temperature (with respect to $T_0$), the behaviour of the material becomes less brittle as the notch radius increases. This means that for temperatures where cracked specimens are on the Lower Shelf, notched specimens behave as if the material was in the Transition Zone or even Upper Shelf. However, when the cracked specimens have the expected brittle behaviour, the notched specimens exhibit clear ductile behaviour with the degree of ductility increasing with increasing notch radius.

This notch effect also has implications in the fracture resistance values reached in the tests, something which constitutes the following observation. The critical CTOD (CTODc) is nearly constant for temperatures above $T_0$. However, there is a clear notch effect for temperatures around and below $T_0$, with an increasing sensitivity of $CTOD_c$ to notch radius. Low $CTOD_c$ values correspond to brittle mechanisms in the case of cracked samples ($CTOD_c$ between 0.15 and 0.30 mm) and $CTOD_c$ values between 2.5 and 6 mm corresponding to more ductile mechanisms for the notched specimens.

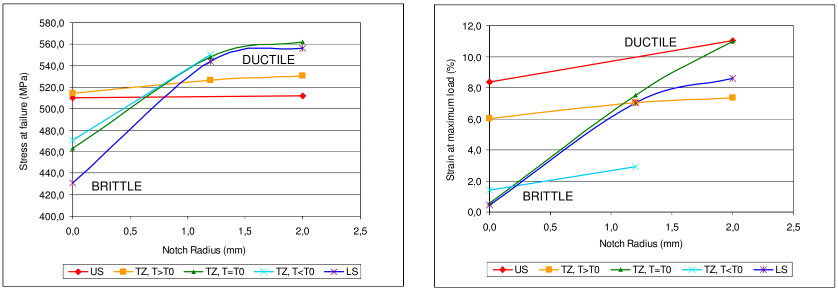


**Fig. 5.** Evolution of the stress at failure and strain under maximum load as a function of both the notch radius and the material state.

There is another observation related to the evolution of the local strain measurements provided by the strain gauges, specifically in the different local strain behaviour observed between the samples with ductile failures (all the notched samples and the cracked ones at temperatures above $T_0$) and the samples with brittle failures (cracked samples at temperatures below $T_0$). In accordance with previous observations, samples with similar behaviours (brittle or ductile) have a similar evolution of the local strains regardless of they are cracked or notched. It can therefore be said that notched samples have different behaviour than cracked samples at the same temperature, but they behave similarly to cracked samples at higher temperatures. This can be justified by the corresponding increase in the apparent fracture toughness [7,8]. Fig. 6 illustrates the phenomenon.

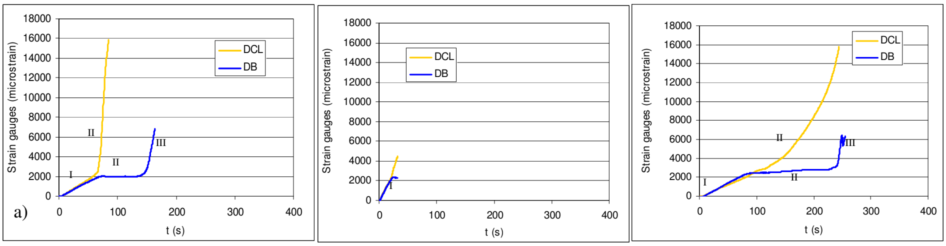


**Fig. 6**. Evolution of the strain gauges (defect side) measurements. a) cracked specimen Y1A19A3 (ductile behaviour); b) cracked component Y1A19A2 (brittle behaviour); c) notched specimen Y1A19A5 (ductile behaviour) tested at same temperature conditions than Y1A19A2. DCL: Defect Centre Line (close to the defect); DB: Defect Bottom (far away from the defect).

## 4. Implications of the notch effect on structural integrity assessments.

Once the stresses, global strains and local strains have been measured in both cracked and notched specimens, and after the analysis of the observed differences between the behaviour of both types of defects, it is important to analyse the effects of such differences in the structural integrity assessment of cracked and notched components. Traditionally, when performing structural integrity assessments of notched components, it is common to assume that these defects behave as cracks. This assumption provides conservative results because both the increases in the apparent fracture toughness and the yield load are not taken into account. If the assessment is performed by means of a FAD, the assessment point of a notched component can be positioned a long way outside the area defined between the Failure Assessment Line (FAL) and the coordinate axes (unsafe situation), when actually the component may be in a safe condition. Also, this assumption provides incorrect predictions of the failure mechanisms, due to the underestimation of the material fracture resistance. The notch corrections proposed in [7,8], based in [12] and the FAD methodology, mitigate this over-conservatism and provide correct predictions of the failure mechanisms through the estimation of the increase in the fracture resistance caused by the notch. Fig. 7 illustrates these situations through the FAD assessment of two specimens at failure (specimens X4M4A2 and X4M4A3). Notice that the area below the 0.4 slope line corresponds to plastic collapse failures; the area above the 1.1 slope line corresponds to a brittle fracture failure and the area between both lines corresponds to a mixture of failure mechanisms [7,8,13].

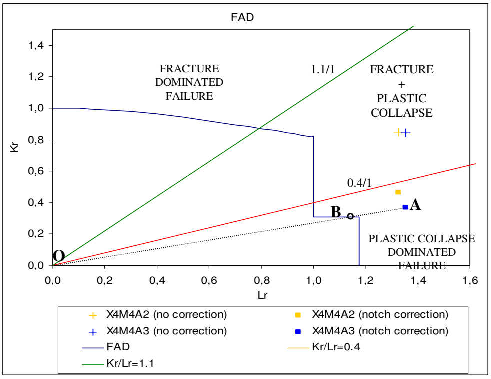


**Fig. 7.** Structural integrity assessment at failure of specimens X4M4A2 and X4M4A3. Safety Factor = OA/OB.

The initial assessment points (with no notch corrections) of the two components lie far away from the FAL (with safety factors of 1.33 and 1.36 respectively) and a combination of brittle fracture and plastic collapse failure is predicted [7,8] in both cases. However, after the corrections proposed in [7,8], the assessment point lies closer to the FAL (with safety factors of 1.33 and 1.19) and the actual failure mechanism (plastic collapse) is correctly predicted. A more complete description of this correction effect, both in the safety factor reduction and in the correct prediction of the failure mechanism, can be found in [7,8].

Fig. 8a shows the relation between the notch radius and the safety factor obtained without any notch corrections (considering the notch as a crack) in all the tests mentioned above. The safety factor has been defined in Fig. 7. The effect of the loss of constraint due to the applied tensile loading has been eliminated by means of the methodology proposed by the two parameters fracture mechanics [13-17]. A clear notch effect on the safety factor can be observed (especially at temperatures below $T_0$), with a clear increase when the notch radius increases.

Furthermore, the notch effect on the plastic collapse of a notched component was also analysed, as shown below. Fig. 8b shows the evolution of the parameter $L_r$ at failure ($L_r^c$) for the different tests, being:

$$L_r = \frac{P}{P_L}; \; L_r^c = \frac{P^c}{P_L} \qquad (2)$$

where P is the applied load, $P_c$ is the load at failure (critical load) and $P_L$ is the plastic collapse load for the cracked component.

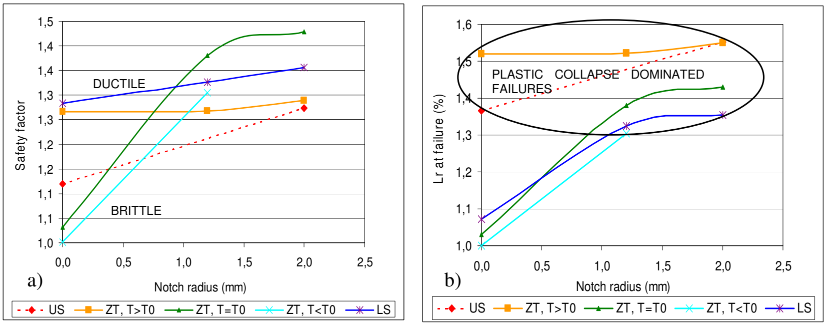


**Fig. 8.** Evolution of the safety factors (a) and $L_r$ at failure (b), obtained in the structural integrity assessment of the specimens as a function of the notch radius and for the different material states.

It is important to notice that the failures of the notched components (and part of the cracked ones) were plastic collapse dominated, so the critical parameter in the assessment is $P_L$ (with negligible influence of the fracture resistance). If $L_r^c$ is compared in the plastic collapse dominated failures (placed within the labelled area in Fig. 8b), a small notch effect (compared to the notch effect on the fracture resistance) can be observed, given that $L_r^c$ slightly increases with notch radius. In case there were no notch effect on the plastic collapse load, $L_r^c$ should be insensitive to the notch radius.

## 5. Conclusions.

This paper has presented the experimental results obtained from the testing of fourteen specimens that combine different notch radii and different temperatures with respect to the corresponding Transition Temperature, $T_0$. The aim has been to establish the differences in behaviour between cracked and notched specimens at different temperatures and the processes occurring in the material that explain these differences. Some considerations about the implications of the notch effect on structural integrity assessments have also been made. The main conclusions are the following:

- A clear notch effect has been observed at temperatures below $T_0$, which produces an increase in the critical stress, the global strain at failure and the critical CTOD value. This notch effect has little importance for temperatures above $T_0$, where even cracked specimens develop significant plasticity.
- At temperatures where cracked specimens behave in a clearly brittle manner, the corresponding notched specimens behave in a ductile manner. This has its origin in the fracture resistance curve of the material for a notched component, with an increase of the

Upper Shelf value and a shift of the Transition Zone towards lower temperatures. As stated above, the notch effect produces a stress relaxation at the defect tip. This produces an increase in the apparent fracture toughness and allows notched specimens to behave in a ductile manner at temperatures where cracked specimens behave in a brittle manner.

- The load-strain paths of cracked and notched specimens are very similar. The difference between the specimens is the failure point which occurs at higher stresses and strains under maximum load as the notch radius increases.
- The evolution of global and local strains clearly illustrates the different processes occurring in specimens with brittle or ductile failure (cracked or notched). In specimens behaving in a ductile manner, local plastic strains ahead of the notch tip are followed by plastic strains in the rest of the specimen and finally to failure. In contrast, for specimens behaving in a brittle manner, local strains quickly reach critical values and failure occurs with no development of plasticity in the rest of the component.
- A clear effect of the notch radius on the safety factor obtained in the FAD has also been observed. This implies that the assumption of notches behaving as cracks can be very conservative and also that the assessment point in a FAD can be positioned in areas corresponding to incorrect failure mechanisms predictions.

**References**

[1] Creager M. Paris C. International Journal of Fracture. Vol. 3 (1967) p. 247
[2] Bao Y. Jin Z. Fatigue Fract. Eng. Mater. Struct. Vol. 16 (1993) p. 829
[3] Niu LS. Chehimi C. Pluvinage G. Engineering Fracture Mechanics. Vol. 49 (1994) p. 325
[4] Pluvinage G. Nuclear Engineering and Design. Vol. 185 (1998) p. 173
[5] Fenghui W. Journal of Material Science. Vol. 35 (2000) p. 2543
[6] Kim JH. Kim DH. Moon S.I. Materials Science and Engineering A. (2004); 387-389: 381-384.
[7] Cicero S. Evaluación de la integridad estructural de componentes sometidos a condiciones de bajo confinamiento. PhD Thesis, University of Cantabria, Santander, Spain, 2007.
[8] Cicero S. Gutiérrez-Solana F. Álvarez JA. Engineering Fracture Mechanics. Vol. 75 (2008) p. 3038
[9] BS EN 10025-1:2004. Hot rolled products of non-alloy structural steels. General delivery conditions. British Standard, 2004.
[10] BS 7448: Fracture mechanics toughness tests. Part 1. Method for determination of KIC, critical CTOD and critical J values of metallic materials. British Standard, 1991.
[11] ASTM E1921-05: Standard test method for determination of reference temperature, T0, for ferritic steels in the transition range, 2005.
[12] Taylor D. Cornetti P. Pugno N. Engineering Fracture Mechanics. Vol. 72 (2005) p.1021
[13] FITNET Fitness for Service Procedure, Draft MK7. Prepared by European Fitness for Service Network-FITNET. EU´s Framework 5, Contract No. G1RT-CT-2001-05071.
[14] O´Dowd NP. Engineering Fracture Mechanics. Vol. 52 (1995) p. 445
[15] SINTAP: Structural Integrity Assessment Procedures for European Industry. Brite-Euram Project No. BE95-1426, Contract No. BRPR-CT95-0024, Final Report, 1999.
[16] R6: Assessment of the integrity of structures containing defects. British Energy Generation Limited, Revision 4, 2001.
[17] VOCALIST: Validation of Constraint Based Assessment Methodology in Structural Integrity, FIKS CT-2000-00090, (EURATOM), 2001