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Proposal Method to calculate T-stress by Modified Stress Difference Method (MSDM) for Specimens with U-notches

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Abstract

The importance of the two-parameter approach in linear elastic fracture mechanics analysis is increasingly being recognized for fracture assessments in engineering applications. The consideration of the second parameter, namely, the elastic T-stress, allows estimating the level of constraint at a crack or notch tip. It is important to provide T-stress solutions for practical geometries to employ the constraint-based fracture mechanics methodology. In the present research, T-stress solutions are provided for a V-shaped notch in the case of surface defects in a pressurised pipeline. The V-shaped notch is analyzed using the finite element method by the commercial Castem2000 software to determine the stress distribution ahead of the notch tip. The notch aspect ratio was varied in the following range a/t = 0.1, 0.2, 0.3, 0.4, 0.5, 0.6 and 0.7. The notch-tip radius was fixed for all geometries and equal 0.25 mm. In contrast to a crack, it was found that the T-stress is not constant and depends on distance from the notch tip. To estimate the T-stress in the case of a notch, a novel method, inspired from the volumetric method approach proposed by Pluvinage, has been developed. The method is based on averaging the T-stress over the effective distance ahead of the notch tip. The effective distance corresponds to the point with a minimum of the stress gradient in the fracture process zone. This approach was successfully used to quantify the constraints of notch-tip fields for various geometries and loading conditions. Moreover, the proposed T-stress estimation creates a basis to analyse the crack path under mixed mode loading from viewpoint of the two-parameter fracture mechanics.

keywords: Constraint, T -stress, effective distance, notch, finite element analysis.

Résumé :

L'importance de l'approche globale à deux paramètres dans l'analyse de mécanique linéaire élastique de la rupture est de plus en plus reconnue pour des évaluations de risque de rupture dans des applications d'ingénierie. La prise en considération du deuxième paramètre, à savoir la contrainte élastique T, ou T-stress en anglais, permet d'évaluer le niveau de confinement à la pointe de la fissure ou d'entaille. Il est important de fournir des solutions de la contrainte T pour une géométrie donnée pour employer la mécanique de la rupture associée à la contrainte de confinement. Dans la présente recherche, nous fournissant des solutions de la contrainte T pour une entaille en forme de U dans le cas de quatre éprouvettes : CT, DCB, SENT et Tuile Romaine. L'entaille en forme de U est analysée utilisant la méthode d'élément finie par le code de calcul Castem 2000 pour déterminer la distribution de contraintes à la pointe de l'entaille et le long du ligement. Le rapport du profondeur du défaut sur l'épaisseur a varié : a/w = 0.1, 0.2, 0.3, 0.4, 0.5, 0.6 et 0.7. Le rayon de l'entaille a été fixé pour toute la géométrie à 0.25 mm. Contrairement aux fissures, il a été trouvé que la contrainte T n'est pas constante et dépend de la distance de la pointe de l'entaille. Pour évaluer cette contrainte dans le cas d'une entaille, une nouvelle méthode, à savoir, la méthode de la ligne, inspirée de l'approche de méthode volumétrique proposée par Pluvinage a été développée. La méthode est basée sur la détermination d'une contrainte moyenne T sur une distance effective en avant de la pointe de l'entaille. Ainsi, l'approche à deux paramètres a été adoptée pour la mécanique de la rupture à deux paramètres pour les entailles en termes du Facteur d'Intensité de Contraintes d'entaille $K_{\rho c}$ et la contrainte moyenne (effective) T_{eff}. La courbe de transférabilité de ténacité à la rupture (Kρc -Teff) dans l'acier de pipeline X52 a été établie. Cette approche a été utilisée avec succès pour évaluer quantitativement le champ des confinements à la pointe de l'entaille pour des différentes géométries et conditions de chargements.

Mots-clefs : contrainte de confinement T, la distance effective, entaille, Analysis Numérique

1 Introduction

Many researchers have long advocated more pragmatic, engineering approach to assess the fracture integrity of cracked structures [1]. This approach requires that constraint in the test specimen approximate that of the structure to provide an "effective" toughness for use in a structural integrity assessment. The appropriate constraint is achieved by matching thickness and crack depth between specimen and structure. Experimental studies [2,3] demonstrate the validity of this approach. These studies show that the use of geometry dependent fracture toughness values allows more accurate prediction of the fracture performance of structures then it is possible to conventional fracture mechanics. However, the task of characterizing fracture toughness becomes more complex as testing of non-standard specimens is required, and different fracture toughness data are needed for each geometry of interest. Further, this approach cannot be applied economically to thick section structures, i.e., nuclear pressure vessels or non planar structures as pipelines. This limitation has motivated the development of theories which extend significantly the range of geometry and loading conditions over which fracture mechanics can be applied accurately to predict structural integrity of components damaged by defects. Many of the research results were discussed in the second ASTM/ESIS symposium on constraint [4]. The concept of relating the stress intensity factor to the crack-extension resistance is based on the assumption that K-dominance exists at a crack-tip; that is, in a region surrounding the crack-tip; the stress fields can be characterized by the mathematical solution

$$K = \sigma_{ij}\sqrt{2\pi r}.f_{ij}(\theta), \text{ as } \quad r \to 0, \qquad (1)$$

where K is the stress intensity factor fij(θ) defines the angular function. A polar coordinate system (r,θ) with origin at the crack tip is used. Note that Equation (1) is derived from a linear elastic assumption and predicts infinite stress at the crack-tip. In practice, there is always a region around the crack tip where plastic deformation, finite strain and damage occur. Consequently, the stresses do not follow Equation (1) inside this region and generally are levelled off due to damage of the material. The size of the K-dominant zone depends upon the specimen geometry, size, crack length, and loading configuration, it leads to the apparent constraint effect in fracture.

For highly stressed material along the crack front, the volume cited above plays a crucial role in driving the fracture process. When plastic regions ahead of the crack front stresses, stress distribution in terms of K, breaks down. The most general way to study near tip features is probably to construct a complete finite element model for the component or specimen, containing enough detail to allow the representation of near tip events. The main point, though, is to establish trends and so contribute to use low-order asymptotic expansions. Under such conditions, and in order to correlate the higher term effects to an appropriate physical parameter, some works [5-7] simplified the higher terms and define the T-stress. The Txx-stress, or simply the T in the direction xx is defined as constant stress acting parallel to the crack plane and its magnitude is proportional to the nominal stress in the vicinity of the crack.

$$K \approx \sigma_{ij}\sqrt{2\pi r}.f_{ij}(\theta) - T\sqrt{2\pi r}\delta_{1i}\delta_{1j} \quad \text{as} \quad r \to \infty. \qquad (2)$$

The non-singular term T represents a tension (or compression) stress. Positive T-stress strengthens the level of crack tip stress triaxiality and leads to high crack-tip constraint; while negative T-stress reduces the level of crack-tip stress triaxiality and leads to the loss of the crack tip constraint. It was noted that T-stress characterizes the local crack tip stress field for elastic linear material. Various studies have shown that T-stress has significant influence on crack growth direction, crack growth stability, crack tip constraint and fracture toughness.

Although many works have carried out estimation for the stress intensity factor with the presence of T-stress of pipeline, they have exclusively focused on classical fracture mechanics with crack to estimate the toughness. We present notch fracture mechanics (NFM) principles applied to study stress distribution at the notch tip of pipes submitted to internal pressure. Volumetric Method, presented by Pluvinage [8] is a meso-mechanical method belonging to this NFM. It is assumed, according to the mesofracture principle, that the fracture process requires a physical volume. This assumption is supported by the fact that fracture resistance is affected by loading mode, structural geometry, and scale effect. By using the value of the "hot spot stress" i.e. the maximum stress value, it is not possible to explain the influence of theses parameters on fracture resistance. It is necessary to take into account the stress value and the stress gradient in all neighbouring points within the fracture process volume. This volume is assumed to be quasi-cylindrical with a plastic zone of similar shape ahead of the notch tip. The diameter of this cylinder is called the " effective distance ". By computing the average value of stress within this zone, the fracture stress can be estimated, this leads to a local fracture stress criterion based on two parameters, the effective distance Xef and the effective stress σef. The graphical representation of this local fracture stress criterion is given in Figure 1-(a), where the stress normal to the notch plane is plotted against the distance from the notch tip. For determination of Xef, a graphical procedure is used; it has been observed that the effective distance is related to the maximum value of the relative stress gradient χ. This distance corresponds to the beginning of the pseudo stress gradient as it is indicated in Figure 1-(b). The opening stress distribution at the notch was calculated using FEM for elastic analysis of 2D model in plane strain conditions. The effective distance Xef was determined using normal stress distributions. The relative stress gradient (see Equation 3) plotted in bi-logarithmic graph allows obtaining an effective distance as follows

$$\chi(r) = \frac{1}{\sigma_{yy}(r)} \frac{\partial \sigma_{yy}(r)}{\partial r} \quad . \qquad (3)$$

Here, $\chi(r)$ and $\sigma_{yy}(r)$ are the relative stress gradient and maximum principal stress or crack opening stress, respectively. The relative stress gradient depicts the severity of the stress concentration around the notch and crack tips. However, the stress distribution effect is not solely a major parameter for the fracture process zone. The minimum point of the relative stress gradient in the bi-logarithmic diagram is conventionally taken into account as the relevant effective distance and signifies the virtual crack length. The effective stress is defined as the average of the weighted stress inside the fracture process zone:

$$\sigma_{ef} = \frac{1}{X_{ef}} \int_0^{X_{ef}} \sigma_{yy}(r).\Phi(r) dr \qquad (4)$$

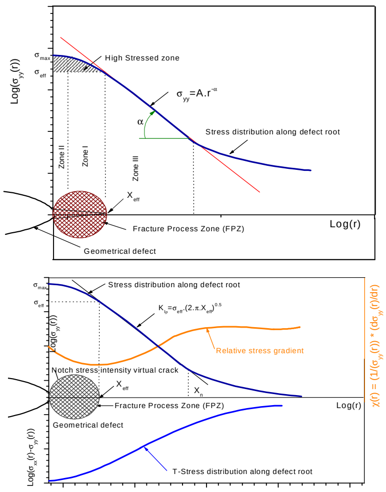

FIG. 1 : (a) Schematic representation of the opening stress evolution in a bilogarithmic scale and (b) procedures to determine the effective stress and the effective distance by the volumetric method.

where σ_{ef}, X_{ef}, $\sigma_{yy}(r)$ and $\Phi(r)$ are effective stress, effective distance, maximum principal stress and weight function, respectively. The unit weight function and Peterson's weight function are the simplest definitions of weight function of the effective distance. The unit weight function deals with the average stress and Peterson's weight functions gives the stress value at a specific distance and it is not required to compute numerical integration. Therefore, Notch Stress Intensity Factor (NSIF) is described as a function of effective distance and effective stress, namely,

$$K_\rho = \sigma_{ef} \sqrt{2\pi X_{ef}} \quad . \qquad (5)$$

In this case, NSIF is considered as a value of facture toughness with units $MPa\sqrt{m}$, and the minimum effective distance corresponds to the abscissa of the upper limit of zone II (Fig. 1) and its distance from notch tip was suggested to be the effective distance Xef.

2 Determination of the T-stress in the case of a notch

Several methods have been proposed in literature to determine the T-stress for cracked specimen. The stress difference method has been proposed by Yang et al. [9]. In this method, the T-stress is evaluated from stress distribution on the line of crack extension, generally computed by finite element method, as the difference between opening stress σ_{yy} and stress σ_{xx} parallel to crack plane. Chao et al. [10] computed and defined the T-stress as the value of σ_{xx} in direction θ = 180 ° (in the crack rear back direction) where this value is constant. Ayatollahi et al. [11] have determined the T-stress using the displacement method in finite element analysis and obtain a stabilised T stress distribution along ligament. Wang [12] has estimated the T-stress as a result of superposition of a crack free specimen and a specimen with crack faces submitted to a pressure distribution. T is then computed by the sum of two contributions, one to crack pressure distribution and the second to the difference (σ_{xx}-σ_{yy}) at a distance equal to crack length.

2.1 Calculation procedure

In this paper, the T-stress was determined in a notched body by stress difference method because it is the most simple and widely used approach which allows comparison of our results. The underlying idea is that the errors in the numerically obtained values of σ_{xx} and σ_{yy} near a crack tip disappear with distance from the crack tip and their difference must eliminate the errors effectively. The T-stress is calculated along θ = 0.

The considerate geometry in this study is a pressurized cylinder with a V-shaped longitudinal surface notch as shown in figure 2. The effect of three parameters: ratio of inner radius of the cylinder to the thickness, R_i/t, the ratio of the notch depth to the cylinder thickness, a/t, and pressure P on T-stress and Stress Intensity Factors (SIF) is systematically analysed. The wall thickness is 10 mm and the length of pipe is 40 mm. To cover practical and interesting ranges of these three variables, four different values of Ri/t= 5, 10, 20 and 40, were selected. Four different values of a/t were ranged from a/t = 0.1 to 0.75 as well as four different values of P ranging from pressure of

20 bars to 50 bars. As a result, 84 different experimental setups are considered in this investigation.

The finite element method was used to determine the notch-tip parameters T for the pipe specimens. The specimen was modelled by CASTEM 2000 [13] code in two dimensions under plane strain conditions using free meshed isoperimetric triangular elements only on half of the specimen. The elastic analyses comprise 31485 elements and 63526 nodes. A fan-like mesh focused at the notch-tip was employed, because this yields more accurate estimates of non-singular terms. Further, more detailed study of mesh sensitivity have shown that further refinement of the mesh leads to only small changes (<1%) in the pipe specimen geometry. Support and symmetric boundary condition are used in this model.

A detailed stress analysis was carried out in the vicinity of the notch front to emphasize the characteristics of the two dimensional stress fields. The coefficients of the higher order stress terms represent one part of a larger database which will also include information on various constraint parameters.

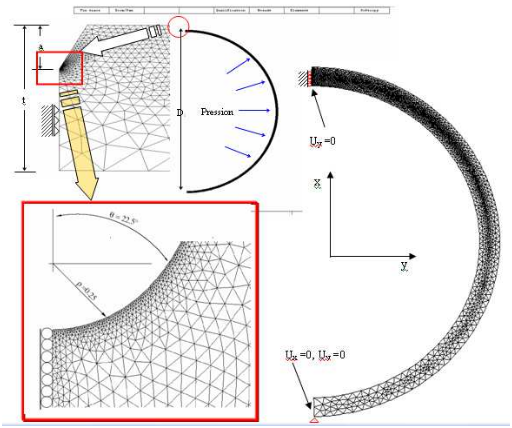

FIG. 2 : Typical 2D finite element mesh and boundary conditions used in the model of the cracked pipeline.

2.2 The T-stress distribution ahead of the notch tip

The opening stresses versus a distances r from the notch tip is illustrated in Figure 3 for R/t=5. These results show the variation of the opening stresses σ_{yy} with increasing the notch aspect ratio at the deep point of external longitudinal surface notch. The calculated stress was constructed in a non-dimensional form corresponding to the series expansion of Williams (1957) [14]. In this representation, the mode I opening stress ahead of the notch-tip can be written as follows $\sigma_{yy} = A_1/\sqrt{r} + A_3\sqrt{r} + A_5\sqrt{r^3}$. In this relation, the first term represents the singular stress having the well-known r-0.5 singularity. The second, third and the other order terms are non-singular. It is clear that the first term is dominant while the others are negligible in the vicinity of the notch-tip (for very small values of r).

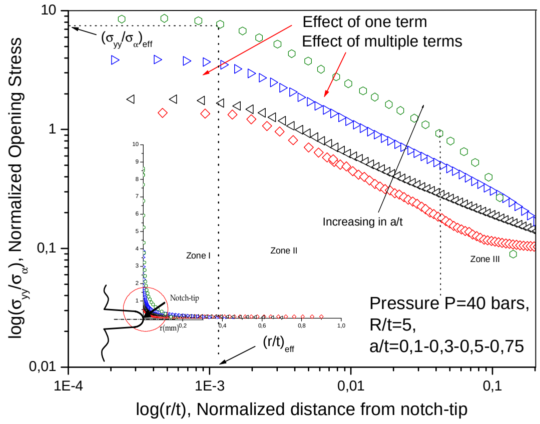

FIG. 3 : Typical variation of normalized opening stresses with a distance from the notch tip for different notch aspect ratios.

As the distance from the notch-tip increases, the other terms have an important influence and the one-term stress field approach is not valid anymore. This tendency is illustrated in Fig. 3. It can be seen that the non-dimensional stress decreases in the region r/t > $(r/t)_{ef}$ due to the influence of the second and higher order terms. Here, the value of (r/t) corresponds to the effective distance.

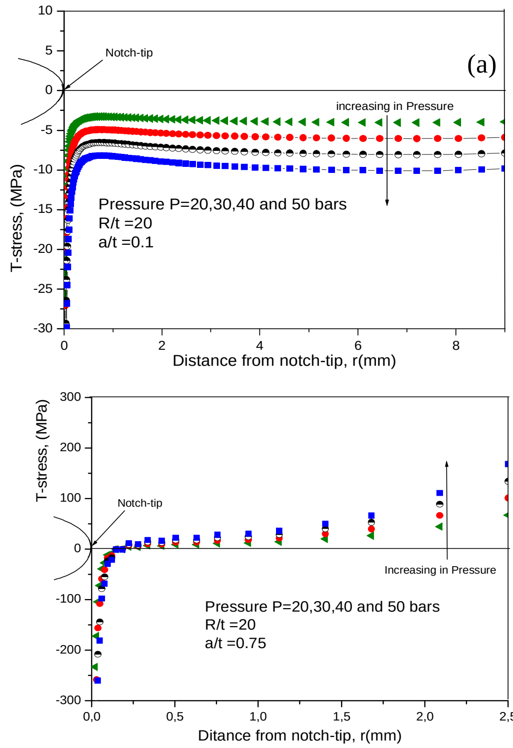

FIG. 4 : The T-stress distribution for a longitudinal surface notch under different internal pressure

(P = 20, 30, 40 and 50 bars) for (a) small and (b) deep notches (R/t=20).

It was observed that the T-stress values are negative (compressive stress) along the ligament when the notch aspect ratio is less than a/t <0.5 for any pressure and pipe diameter. On the other hand, the T-stress values become positives (tension case) when the ratios a/t exceeds 0.5.

The original Stress Difference Method does not produce constant values of the T-stress, except for short notches [15,17]. Moreover, this method concerning its production of the constant values of the T-stress at a certain distance ahead of the crack tip was criticized by several authors.

2.3 Averaging the T-stress inside the effective distance

A modification of the Williams formula has been proposed by taking into account the effects of several parameters observed in the evolution of the T-stress along the ligament.

Figure 5 illustrates a schematic representation of the evolution of the T-stress distribution along the ligament calculated by the Stress Difference Method. The smoothing the curve of the T-stress distribution is described by the following equation

$$T_{xx}(x) = \sum_{i=0}^{n} a_i x^i \qquad (7)$$

The gradient of the T-stress leads to Equation

$$\chi(x) = \frac{1}{T_{xx}(x)} \frac{dT_{xx}(x)}{dx} \frac{\sum_{i=0}^{n} i a_i x^{i-1}}{\sum_{i=0}^{n} a_i x^i} \qquad .(8)$$

The weight function can be written as follows

$$\phi(x) = 1 - \frac{x \sum_{i=0}^{n} i a_i x^{i-1}}{\sum_{i=0}^{n} a_i x^i} \qquad (9)$$

The effective distance in the vicinity of the notch tip can be obtained by the Taylor approach. It corresponds to the minimum point in the T-stress gradient

$$\frac{d\chi(x)}{dx} = 0 \qquad (10)$$

Substituting Eq. (9) in Eq. (10) gives the following relation to calculate the effective distance

$$\frac{d\chi}{dx} = \frac{\sum_{i=0}^{n} \left(a_i i^2 x^{i-2} - a_i i x^{i-2}\right)}{\sum_{i=0}^{n} a_i x^i} - \frac{\left(\sum_{i=0}^{n} a_i i x^{i-1}\right)}{\left(\sum_{i=0}^{n} a_i x^i\right)} = 0 \qquad (11)$$

Averaging the T-stress inside the effective distance, the effective T-stress (Tef) can be defined in the following form

$$T_{ef} = \frac{1}{X_{ef}} \int_0^{X_{ef}} T_{xx}(r).\Phi(r).dr \qquad (12)$$

Here, $T = T_{xx} = \left(\sigma_{xx} - \sigma_{yy}\right)_{\theta=0}$ is the T-stress distribution along of the ligament (r) in the xx direction and $\Phi(r)$ is the weight function. Figure 5 shows a graphic representation of the T-stress along the ligament, the gradient of this distribution and the technique to calculate the effective distance X_{ef} and the effective T-stress, T_{ef}.

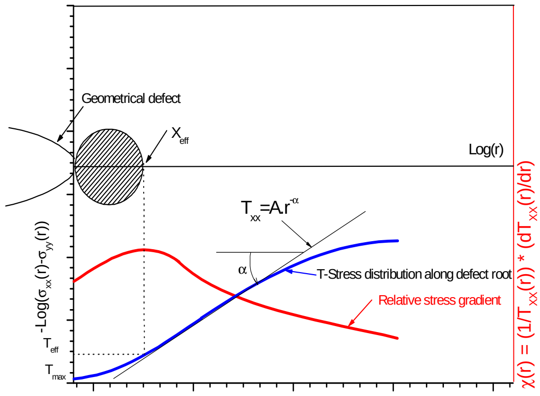

FIG. 5 : Schematic bilogarithmic diagram of the determination of the effective T-stress by averaging the T-stress inside the effective distance

A detailed example of employing this method is given in Figure 6, 7 and 8. The T-stress distribution is presented in a bilogarithmic diagram for a pipe of a diameter of R/t = 20 and one longitudinal surface defect of depth a/t =0.5 under internal pressure varying from 20 to 50 bars. Figure 6 shows the distribution of the T-stress and the various zones along the ligament. A detail of the zone (II) (Fig. 7) is presented in Figure 8. The polynomial approximation of the T-stress distribution according to Eq. (7) is presented in

Fig. 7. The gradient of this distribution corresponds to Eq. (11) (see Fig. 8).

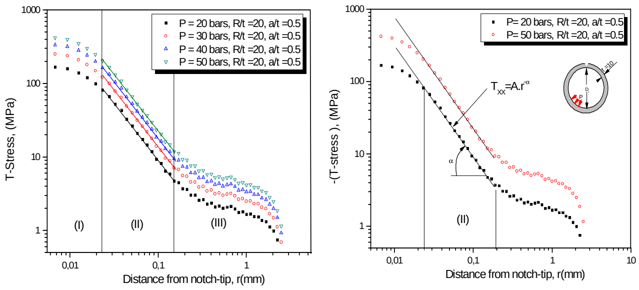

FIG. 6 : The T-stress distribution along ligament of the pipe under pressure

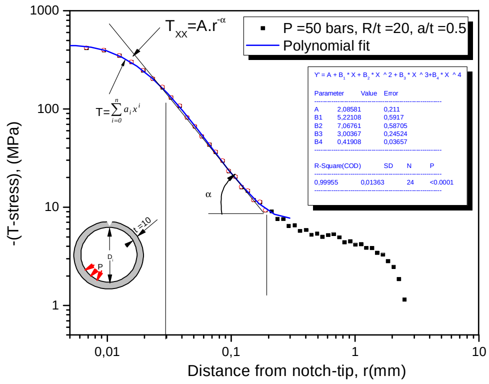

FIG. 7 : Approximation of the T-stress distribution

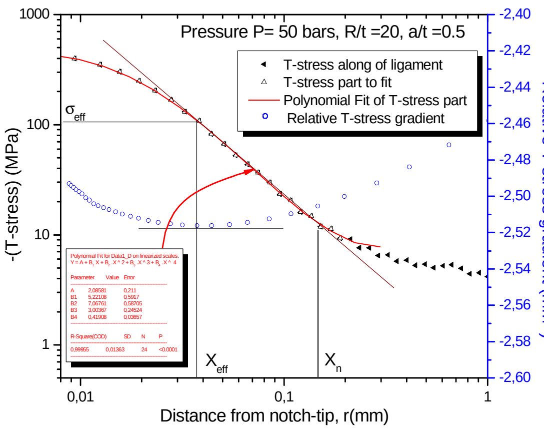

FIG. 8 : Gradient of the T-stress distribution according to Eq. (11) (P=50 bars, R/t =20, a/t =0.5)

2.4. Results of the effective T-stress estimation for the Roman tile specimen

The method of averaging the T-stress has been employed to estimate the effective T-stress in a Roman tile specimen with the V-notch of 0.25mm root radius. The notch aspect a/t was varied from 0.1 to 0.7

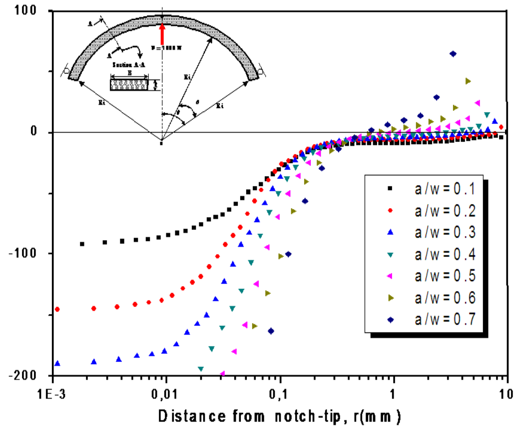

FIG. 9 : The T-stress distribution along ligament in a roman tile specimen

Similar to a pipe with a surface notch, the T-stress distribution is stabilised after some distance for short notches. At the same time, the T-stress increases linearly with ligament for long notches, except in a region close to the notch tip (Fig. 9). Estimating the effective T-stress by the proposed method is illustrated in Fig. 10.

It should be noted that the present results of the effective T-stress estimation is consistent with the results obtained by the method proposed by Maleski et al. [18]. It was suggested that the T-stress can be represented by the following relationship:

$$T(x) = T_0 + \lambda(x/a) \qquad (13)$$

By extrapolation to r > 0, the T0 stress can be obtained and considered as the acting T-stress. Comparison of the effective T-stress obtained by procedure of averaging the T-stress inside the effective distance and the T0 stress are shown in Fig. 10. It can be seen that the difference between T0 and T_{ef} is small for the case of a roman tile specimen

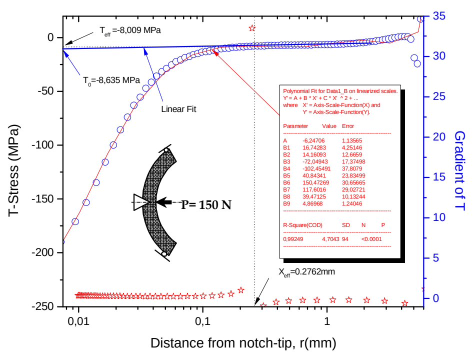

FIG. 10 : Determination of T_0 stress from Maleski [17] and comparison with the effective T-stress

3 Conclusion

The Williams's type solution has been employed to analyse the stress distribution ahead of the notch tip. It was shown that the T-stress is not constant along ligament ahead of the notch tip for pressurised pipes and Roman tile specimens. It was also found that the non-singular terms are not negligible for a notch as the distance from the notch tip increases. To avoid this difficulty, it has been proposed to use the effective T-stress. The effective T-stress is suggested to be the average T-stress inside the effective distance ahead of the notch tip. Thus, the concept of the T-stress in the case of the crack stress distribution has been extended to the notch stress distribution.

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