COBEM 99
XV Congresso Brasileiro de Engenharia Mecânica
15th Brazilian Congress of Mechanical Engineering
22 - 26 de Novembro de 1999 / November 22 - 26, 1999 Águas de Lindóia, São Paulo,

FRACTURE MECHANICS APPLIED TO THE STRUCTURAL DESIGN PARTE II: RECENT DEVELOPMENTS

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Abstract. *Fracture Mechanics has been demonstrating, in the last years, its great usefulness and importance to applications in the most diversified sectors of the industry, among which can be included the naval, aeronautics and aerospace, defense, heavy construction, petrochemical and nuclear industries. Today, it is further increasing, among professionals involved in the project and operation of structures and industrial components, the conscience of how difficult, or even impossible to fabricate structural parts that don't contain defects. Under the action of loads, the presence of those defects, mostly microscopic, can lead to a failure in situations much less unfavorable than the ones initially assumed in the design, therefore increasing the importance of the consideration of Fracture Mechanics in the design and in the definition of the life of those structures. This work presents a survey of Fracture Mechanics methodologies and formulations applicable to the design of industrial steel components. The work is divided in two parts. In the first stage, presented in a companion paper, Fracture Mechanics traditional methodologies applied to the design of structures were covered. This second part focus on the new developments obtained in the last few years and trends in research.*

Keywords: *Fracture Mechanics, Mechanical Design, Structural Integrity*

1. INTRODUCTION

The knowledge of results, obtained from fracture toughness tests of materials, makes possible several applications in engineering. The materials can be evaluated and classified in terms of its applicability to the production of components and structures. Design criteria can be defined and structural failures can be predicted and evaluated. For the effective exploration of those possibilities, the development of analysis tools and methodologies is mandatory to provide the bridge between the knowledge of materials properties and real applications.

In doing so, the fundamental step in the use of any application methodology, based on Fracture Mechanics (FM), relies on the capacity to transfer information generated in laboratory to the assessment of structural components. That transferability aspect is usually hindered by the fact that the components, in most cases, are subjected to factors not predicted or considered in a laboratory procedure, leading to the necessity of using approximations and/or extrapolations very often.

Generally, the two larger extrapolations to be done in the prediction of the fracture behavior of components with defects are related to size (here included the differences in geometry and in loading) and to time. The variable time is not usually considered in a fracture toughness test, and the time-dependent processes such as fatigue, stress corrosion cracking (SCC) and creep are excluded from the tests. In that sense, for the application methodologies discussed here, its influence is not important. On the other hand, the variable size / geometry / load is of crucial importance for those methodologies, because the transference of the experimental data to real situations is entirely dependent of it.

Most of the available fracture methodologies for engineering applications concentrates on predicting the real conditions that would cause the fracture, or in trying to establish conditions so that the fracture never comes to happen without a real prediction of the event. The prediction of safe operation conditions of a structure, to avoid fracture, is usually based on generic curves that incorporate coefficients of safety.

In the paragraphs that follow, a few methodologies developed in the last few years are introduced, to provide the reader a feeling of what lines of research are being most explored. These new developments can be divided into two different classes: those related to brittle fracture, with special attention to fracture in the ductile-to-brittle transition region, and the ones connected to problems on the prediction of ductile fracture behavior.

2. DEVELOPMENTS RELATED TO BRITTLE FRACTURE

A lot of research and new methodologies have been developed in the last few years in the area of fracture failure assessment, with emphasis in the brittle fracture occuring in ductile-to-brittle transition (DBT) region of steels. Fracture Mechanics methodologies have, traditionally, relied on phenomenological approaches, which use a single fracture parameter, the dominant term of the crack-tip stress field, in a correlative way to characterize the fracture behavior.

With the diversification of the studied applications, it was noticed that, unlike previously supposed, this type of approach was not applicable to a great number of situations. It was discovered that the solution of the crack-tip stress field based on a single parameter was only applicable under linear-elastic or SSY (Small Scale Yielding) load conditions.

Fracture testing in the DBT region was the most proeminent situation in which the use of methodologies based on a single fracture parameter were no longer applicable. In this very case, the absence of a parameter related to the crack-tip stress triaxiality level, associated to the loss of constraint, creates a geometry dependence on the toughness results, impeding their application to different geometries. In a general way, it was observed that the adoption of two-parameter approaches would fill this gap, allowing an adequate and correct characterization of the crack-tip stress field. This conclusion impelled the development of the so-called Two-Parameter Fracture Mechanics.

Numerous theoretical and numerical developments, purely based on mechanical approaches or, in some cases, on micomechanisms have been trying to quantify the effect of the loss of constraint and its influence on the crack-tip stress and strain fields. For linear-elastic analyses, K and T are the 2 proposed parameters, according to the methodology developed by Hancock et al. (1991). It is important to notice that this T has no relationship to the tearing modulus T, as proposed by Paris and collaborators (1979). In this current study, T is the constant stress component acting in the direction parallel to the crack plane, being a function of the geometry and of the load condition, but not of the position. The value of T can vary from 0 or a positive value, for a high constraint situation (deep cracks or bending loads), to a negative value corresponding to low constraint, as for shallow cracks or tension loads. Eqs. 1 to 3 present the mathematical expressions of the stress components, according to the K-T methodology. It can be observed that the y-normal and the x-y shearing components remain the same as in the Irwin-Williams single-parameter methodology (Irwin, 1957).

$$\sigma_{xx} = \frac{K}{\sqrt{2\pi r}} \cdot f_{xx}(\theta) + T \tag{1}$$

$$\sigma_{yy} = \frac{K}{\sqrt{2\pi r}} \cdot f_{yy}(\theta) \tag{2}$$

$$\sigma_{xy} = \frac{K}{\sqrt{2\pi r}} \cdot f_{xy}(\theta) \tag{3}$$

where fxx (θ), fyy (θ) and fxy (θ) are, respectively, the angular correction factor for the components of normal stress in the directions x and y and of the shearing stress in the xy plane.

In the elastic-plastic regime, the lack of a unique correspondence between fracture toughness and the crack-tip strain and stress fields can also be observed in some situations, when a minimum level of constraint is not present. In order to face the problem, a new methodology, very similar to the one presented for the linear-elastic regime, was introduced by O'Dowd and Shih (1991, 1992) and named the J-Q Theory. In this approach, the crack-tip stress field is defined by the following expression:

$$\sigma_{ij} = \left(\frac{J}{\alpha \varepsilon_{ys} \sigma_{ys} I_n r} \right)^{1/n+1} \cdot \bar{\sigma}_{ij}(\theta) + Q\sigma_{ys}\delta_{ij} \tag{4}$$

where

- σ_{ij} = elastic-plastic crack-tip stress field;
- J = crack driving force;
- α= Ramberg-Osgood coefficient;
- n = Ramberg-Osgood exponent;
- σ_{ys} = material's yield strength;
- ε_{ys} = deformation associated to yield strength;
- r = distance from the crack-tip to the considered point;
- Q = loss of constraint correction factor;
- θ = angle between the x-direction and the straight line connecting the origin of the axes to the considered point;
- $\bar{\sigma}_{ij}(\theta)$ = adimensional function of θ
- I_n = constant of integration;
- δ_{ij} = Kronecker delta.

In Eq. 4, the first term to the right of the equality corresponds to the stress field under small strain HRR conditions, as defined by Hutchinson (1968) and Rice and Rosengren

(1968), or under Small Scale Yielding conditions (SSY) and represents the intensity of the field. The second term, that is function of Q, is the responsible for the characterization of the existent level of constraint. The Q value can vary from 0, usually in C(T) and SENB specimens, to a maximum negative value of –1,5, in geometries subjected to tension loads, such as CCT, and for shallow cracks. Figure 1 presents a typical curve used in the computation of Q values from the knowledge of geometric properties of materials and J values.

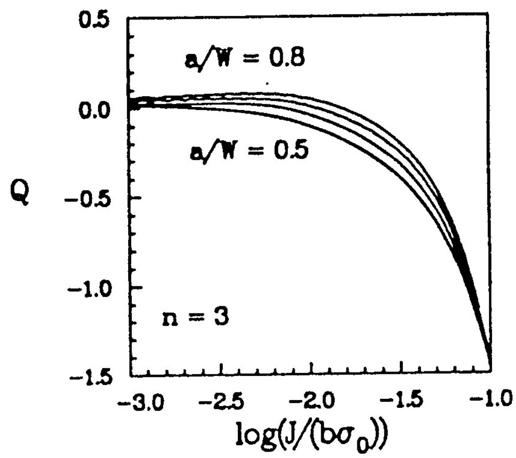

Figure 1 – Typical curve for obtaining the constraint correction factor Q (O'Dowd & Shih, 1992)

Such as in the single parameter based approaches, the K and T or J and Q parameters are frequently used in a correlative way to explain, in a qualitative way, the geometric dependence of the crack-tip stress field. However, for DTB transition region issues, in order to be possible to predict toughness results for different temperatures, geometries and sizes, starting from the knowledge of an only situation, there exists a need for the development and use of a mechanistic methodology. One possibility would be the adoption of ***FRAMTiC***, ***FRA***cture mechanics ***M***odel for the prediction of the transition ***T***oughness ***i***n ***C***leavage (DeAquino, 1997), a model initially proposed in the University of Tennessee by Landes and collaborators (DeAquino et al., 1995 and Landes, 1995), for the prediction of the transition fracture toughness. That model is based on a weakest-link assumption (Landes & Shaffer, 1980) associated to a two parameter J-Q approach (O'Dowd & Shih, 1991, 1992) and was successfully validated for nuclear pressure vessel steels. Figure 2 presents an example of toughness prediction in the transition using FRAMTiC. The good quality of the predictions can be concluded from the comparison between the predicted results and experimental testing data available for the temperature in which the predictions were performed. The FRAMTiC model, due to its statistical nature, provides predictions in terms of a median value and upper- and lower-bounds.

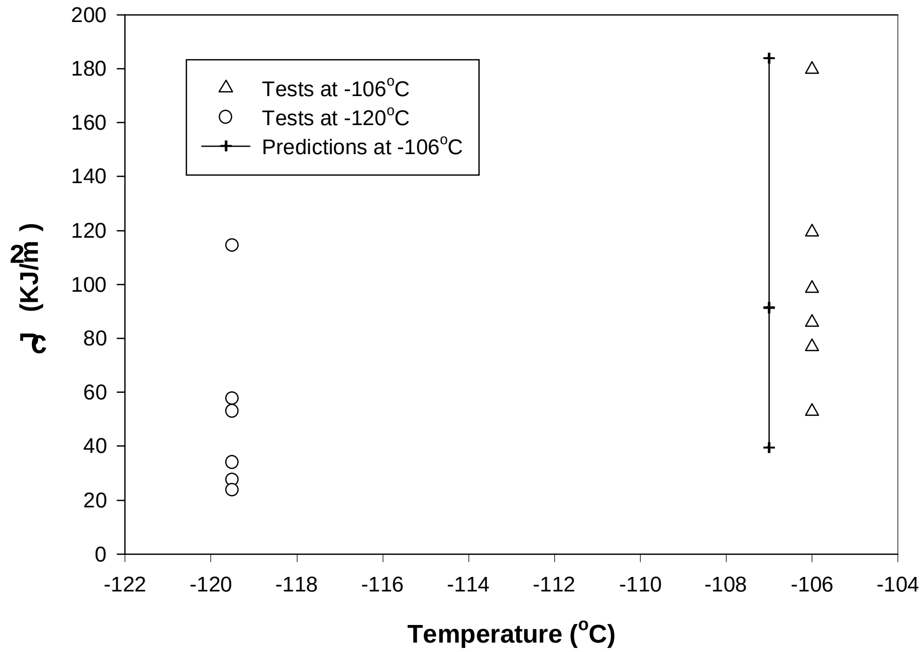

Figure 2 - Experimental Results x FRAMTiC Predictions - A 508 Class 3 Steel
T-L Orientation (DeAquino, 1997)

3. DEVELOPMENTS RELATED TO DUCTILE FRACTURE

Although the current research in fracture mechanics is concentrating more on brittle and transition fracture problems, there still remain unsolved some problems related to ductile fracture. One of those is the dependence of the J-R curve to size, geometry and load effects. To illustrate, it can be pointed out the situation in which as the loading type applied to a given specimen is changed from the bending mode, characteristic of the standard specimen types (C(T) or SENB) to the predominantly tension type of loading, that is more frequently found in structural components models (CCT, SENT and DENT), the J-R curve tends to present larger toughness values (Link et al., 1991).

Some investigators have suggested that the correct fracture parameter for the characterization of a resistance curve has not been used yet. Some researchers, as Heerens and collaborators (1992), prefered parameters based on CTOD and suggested that a R curve based on δ_5 would characterize the fracture behavior in a more consistent way. The δ_5 parameter was defined as the displacement measured at the surface of the specimen containing a crack being using a displacement gage with a 5 mm initial opening. Others, like Turner and Kolednik (1993), proposed the use of new parameters, such as the of energy dissipation rate. Numerical studies, accomplished by Xia and Shih (1994), that were capable to incorporate the micromechanical damage modelling to predict trends in R curve behavior for different geometries, as shown in for Fig.3, are also worth of mention. The assessment of the crack-tip stress field through two-parameter FM methodologies doesn't have great usefulness in the resolution of this problem, because the ductile fracture is more controlled by the crack-tip strain than by stress. (O'Dowd and Shih, 1991,1992).

Another frequent problem in ductile fracture refers to the thickness effects on the behavior of the R curve. Typically, fracture toughness values tend to present higher values with a decreasing specimen thickness (Link et al., 1991), when the planar geometry is mantained constant. This toughness variation is attributed to the loss-of-constraint effect due to a change from a plane-strain to a plane stress condition, as the thickness decreases. However, certain materials, as very tough steels and alloys, present an inverse tendency in the toughness variation with the thickness. Nevertheless, the ability to predict the occurrence of such cases is not still developed, making necessary the accomplishment of further work focused on the problem.

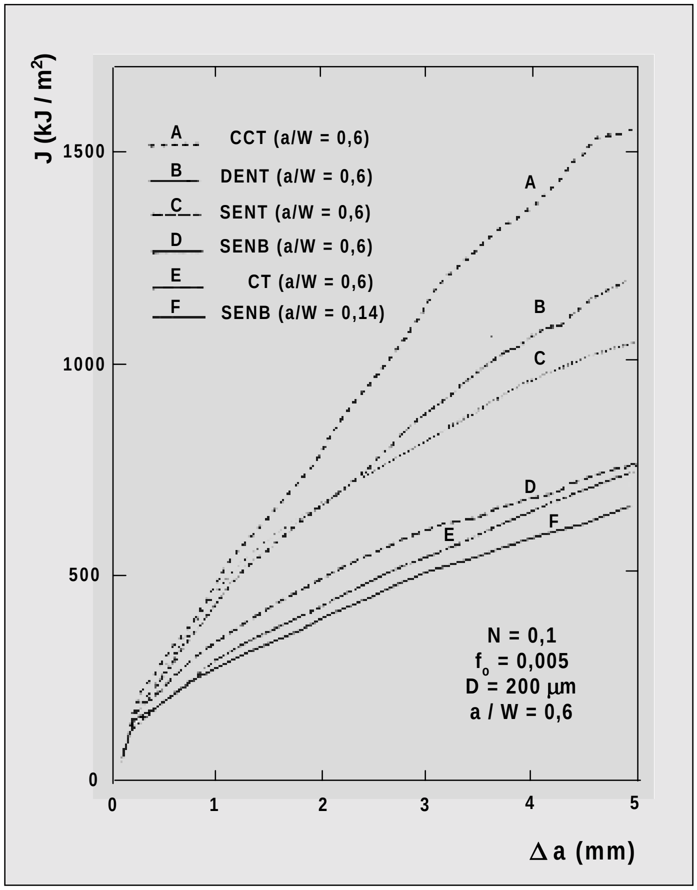

Figure 3 – Geometry Effects in J-R curve predictions using a micromechanical damage numerical model (Xia and Shih, 1994)

Another area needing new studies and developments is the analysis of the fracture behavior in bodied containing surface flaws (three-dimensional), that are the most frequently found in structures and components. The approach traditionally used in this analysis type is numerical modelling. Recently, Sharobeam and Landes (1995) developed a methodology based on load separation principles (Landes and Herrera, 1989) that defines a J value that is equivalent to the J values measured at the considered surface flaw. Equivalent J corresponds to an average of the toughness values at the crack front and its adoption creates conditions for treating the 3-D flaw as a 2-D through-the-thickness crack. The feature that makes this approach attractive for application in tests and analyses is that J can be computed from the area under the load x displacement curve measured in the load line. This new methodology was also applied, by Sharobeam and Landes (1996), to a bimaterial interface (Fig.4), so it could have applications for cracks in a weldment.

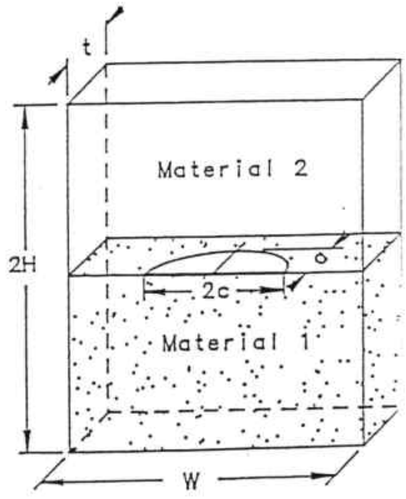

Figure 4 – Application of Equivalent J to bimaterial interface
(Sharobeam & Landes, 1996)

Another area of new developments in ductile fracture is related to the use of load separation techniques in test procedures. A technique denominated normalization allows the determination of the instantaneous crack growth during a toughness test, from the knowledge of the plastic deformation properties of the material (Landes and Herrera, 1989 & Landes et al., 1991). In this case, only the load and displacement values measured during the test are necessary for the development of the R curve. By using this technique, additional instrumentation used to determine the changes in crack length during the test becomes unnecessary. Generalizing, separation principles can be used to develop the R curve of a given material when test conditions limit the instrumentation to be used. In that way, J-R curves can be obtained without displacement measurements, if the load and the crack length are simultaneously measured (Lee and Landes,1993), or without load measurements, if the displacement and the crack length are monitored (Lee and Landes,1994). Therefore, the accomplishment of valid tests in high temperatures, in adverse atmospheres or in hot cell (radioactive environment) conditions can be highly facilitated by applying the normaliztion technique. Test procedures using load separation techniques were also applied for test conditions under dynamic load, as the Charpy impact test (Landes and Lee, 1994). In this particular case the load hammer had to be instrumented to make possible the load measurement during the impact of the test specimen.

Most of FM applications to components and real structures is characterized by the presence of very small or shallow cracks. The fracture toughness values determined in laboratory tests involve deeply cracked specimens. The shallow defects present a difference in planar constraint that can cause great difficulty for applying the experimental results in their fracture behavior assessment. The two-parameter approach has been of special use for the prediction of fracture behavior for shallow flaws. Furthermore, the use of cruciform specimens (Fig.5), subjected to biaxial loading, has been demonstrating its usefulness for obtaining toughness results that can be transferred for the analyses of components with shallow surface flaws, as studied by (Bass et al., 1994) in the Oak Ridge National Laboratory, USA.

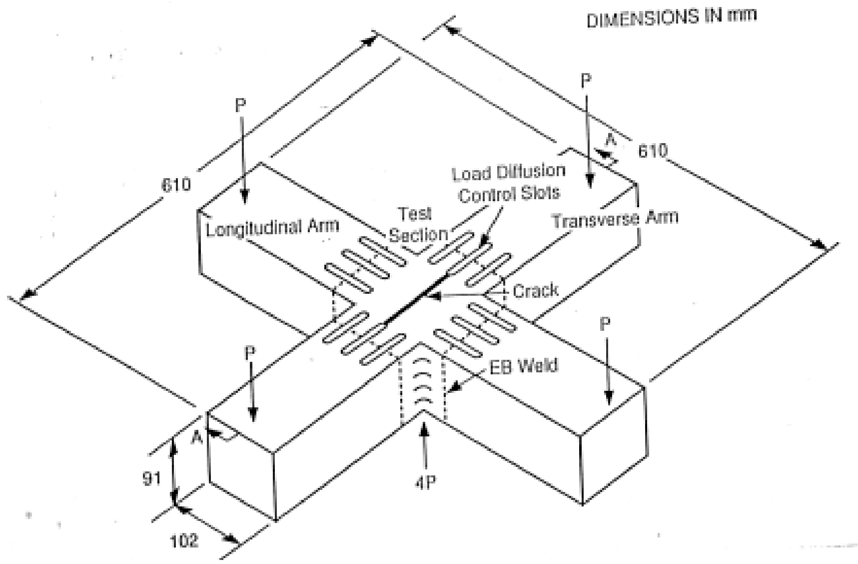

Figure 5 – Cruciform specimen for the fracture characterization of surface flaws

4. CONCLUSION

The research in the area of Fracture Mechanics is part of an extremely dynamic process, always seeking to improve the already existent technologies and to present new developments, in order to achieve a better performance and to guarantee the integrity of the structures and components being designed or in service.

The purpose of this work is to focus along its two parts, of which the second was here presented, technologies already established and newly proposed under development, in order to demonstrate the importance of FM in the design and in the operation of structures and industrial components. The work concentrates on the analysis of steel structures, due to the authors' previous experience. It should be noticed, however, that the applicability of FM methodologies encompass a much broader universe of materials than that considered in this study, allowing to be extended to most of the structural materials, as long as revised the inherent particularities of each one of them.

Ackowledgements

The authors would like to thank FAPESP, Fundação de Amparo à Pesquisa do Estado de São Paulo, for funding part of this research through Project 97/13023-4.

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