FRACTURE MECHANICS APPLIED TO THE STRUCTURAL DESIGN
PART I: TRADITIONAL METHODOLOGIES

Carlos Tasso E. DeAquino
Universidade Estadual de Campinas, Faculdade de Engenharia Mecânica
Departamento de Engenharia de Materiais, Cx. P. 6122–13083-970–Campinas, SP, Brazil
John D. Landes
University of Tennessee–MAES Department
310 Perkins Hall, Knoxville, TN 37996, USA

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. The first part, scope of this very paper, concentrates on the presentation of Fracture Mechanics traditional methodologies applied to the design of structures. In the second part, presented in a companion paper, the new developments obtained in the last 5 years and the research tendencies are detailed.

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 aplicability 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 concentrate 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. The methodologies discussed, as follows, can be classified in two classes: qualitative and quantitative.

2. QUALITATIVE METHODOLOGIES

The oldest approaches used to avoid a fracture failure were qualitative in essence. The idea was to design the structural components in a way to avoid certain behaviors, defined by regions. A typical example would be to limit the interval of operation temperature to avoid the region of fragile fracture occurrence, and to control the loading conditions, to impede the material yielding. If a ductile mode of fracture can be guaranteed, then one can assume that the fracture toughness would be high enough for the possibility of a fracture failure not to be considered. With the load level also controlled, a plastic collapse failure would not also be likely and, therefore, the structure would be safe. Thus, for methodologies of this type, the information related to material fracture behavior needes only to be qualitative. Tests that distinguished the different areas of behavior to the fracture, as the Charpy V-notch impact test, can supply the temperature interval for which the ductile mode of fracture is guaranteed.

The use of purely qualitative methodologies in structural integrity programs seemed not to be sufficiently reliable for most critical applications, such as aerospace and nuclear industries. From this conclusion, researchers and professionals connected to the Fracture Mechanics area started to concentrate their efforts in the development of quantitative approaches.

3. QUANTITATIVE METHODOLOGIES

3.1 Linear Elastic Fracture Mechanics (LEFM) Methodologies

The original methodology, for a quantitative application of fracture testing in the assessment of structural failure, was connected to the use of fracture toughness experimental data in terms of K, whenever available, or in terms of non-linear parameters (J and δ) transformed in their equivalent K value, as computed by Eqs. 1 and 2. The analysis of those results was performed in terms of a linear elastic analysis of the obtained K values (Landes & Begley, 1971)

$$K_{JC} = \sqrt{J_C \, E^{'}} \tag{1}$$

$$K_{\delta C} = \sqrt{\delta_C\, \sigma_{ys}\, E^{'}} \qquad (2)$$

where E' is the effective Young Modulus and σ_{ys} is the yield strength

That approach lead to excellent results because the toughness values measured in small test bodies, even when not fulfilling the linear elastic and plain strain requirements, were applied to much larger components and structures subjected to typically linear-elastic loading conditions. In real life, most structures are designed for never to be carried beyond the linear elasticity limits, causing this approach to be still widely applied to design.

However, for structures of more critical application, such as pressure vessels and industrial piping, the major concern is no longer the load acting in normal service conditions. In this case, what should govern the design criteria are the loads resulting from abnormal service conditions and/or postulated accident conditions, that cause stresses well above the linear elasticity bounds. In order to maintain the initial philosophy of avoiding fracture failure, it becomes mandatory the development of new technologies, that incorporate non-linear parameters in the fracture characterization. That line of thought is endorsed by the current trend of extending the useful life initially defined for structures of larger responsibility and which replacement can cause technical and economical drawbacks, such as the case of nuclear components.

The use of handbooks. The use of the K parameter in the assessment of cracked structures with different geometries and loading conditions, was extremely simplified by the development of solutions' manuals (handbooks), as those compiled by Tada et al. (1985) and by Murakami (1987). The idea behind the handbooks was to replace the geometries of real components by solutions or combinations of existing solutions in the handbooks, referring to simple geometries and load cases.

The ASME Code. The Boiler and Pressure Vessel Code (ASME, 1998), prepared by the American Society of Mechanical Engineers (ASME) to serve as guide for designers, constructors and operators of industrial vessels, piping and related components, is a good example of a group of methodologies and procedures for the application of FM to engineering projects. In its section VIII, the code defines rules for the design of conventional pressure vessels, while in section III it considers the special case of the nuclear industry. This particular industry was responsible for introducing FM philosophy in an industrial design, having prepared section XI, entitled "Rules for Inservice Inspection Nuclear of Power Plant Components". In this latter code section, guidelines are presented for the determination of acceptable crack sizes, based on FM methology. In its appendix G (later included in section III under the same denomination), fracture toughness reference curves are presented. Toughness data from testing performed on steels used in nuclear pressure vessels in operation or being designed in the 70's were compiled and consolidated in the preparation of those curves, also known as the "million-dollar curves". Those data were then divided in two groups: the first including plain-strain fracture toughness values obtained under low loading rates, K_{IC}, and the other containing values of K_{Id} and K_{Ia}, respectively, the dynamic and the crack arrest fracture toughness. The curves represent a plot of fracture toughness versus a reference transition temperature named RT_{NDT}. For each group of values a curve, defined by the lower-bound of the available data, was constructed, being denominated K_{IC} and K_{IR} curves. (Fig.1). Those curves can be defined by the following expressions (Anderson, 1995):

$$K_{IC} = 36{,}5 + 3{,}084\exp[0{,}036\cdot(T - RT_{NDT} + 56)] \qquad (3)$$

$$K_{IR} = 29{,}5 + 1{,}344\exp[0{,}026\cdot(T - RT_{NDT} + 89)] \qquad (4)$$

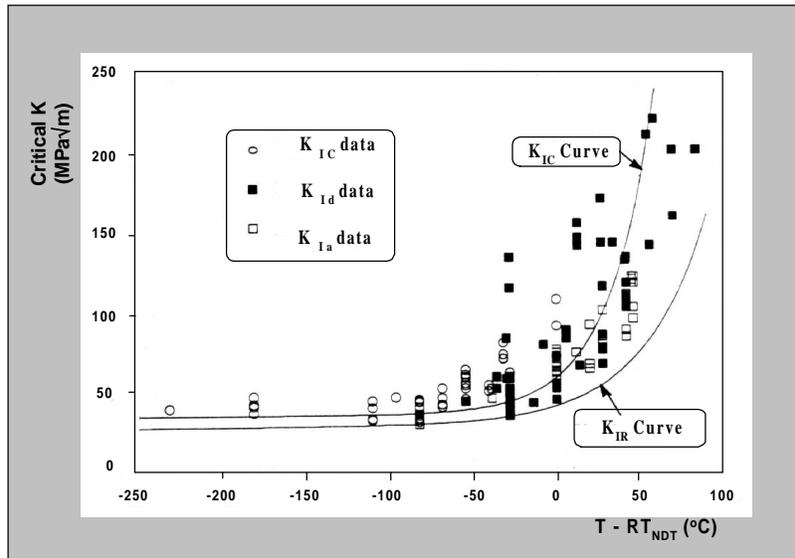where the temperatures are in ^{o}C and K values are in MPa√m.

Figure 1–ASME B&PV Code Section XI Reference Curves

In a real pressure vessel project, the design criteria usually demands fracture tests to be performed at a few different temperatures for obtaining fracture toughness values. If these data are conservative, when compared to the ASME lower-bound references curves, the material is then considered to be adequate for the application and the toughness values adopted in the designed are those provided by the curves. Since, during service operation, it is not possible to guarantee that dynamic loading will not occur, it is advisable to consider the most critical situation, i.e., the K_{IR} reference curve. These considerations and procedures usually lead to a ultra-conservative design.

In order to reduce unnecessary conservatism and to try to extend, in a safe way, the useful life of the structures, a revision of Code procedures is underway, including among proposals a new approach to the reference curves, suggesting a new set that is specific for the heat and material used in a particular design. This is the basis of the new ASTM 1921 standard (ASTM, 1998).

3.2 Elastic-Plastic Fracture Mechanics methodologies based on J_{IC}

Handbooks. The first step for applying non-linear fracture parameters in the assessment of structural components, was the development of the EPRI-GE Handbook of J Solutions (Kumar et al., 1981), as a response to the needs of General Electric in the design of BWR nuclear reactors. This is another example of the very close relationship between FM and the nuclear industry. This manual also contained CTOD solutions.

In using the manual, it became possible the computation of J, as function of the applied load for several types of structural components, that could be loaded beyond the limits of linear elasticity. Furthermore, the load versus displacement (P - v) curve could be determined for a stationary crack. The original version of this manual included only solutions of J for simple cases, such as bars and rectangular plates, containing center or edge cracks, subjected to tension or pure bending loads. The solutions of J and δ for more complex geometries and

loads, such as tubes with axial and longitudinal cracks, knees and T-piping, were only included later in an additional volume, published by Zahoor (1989). The solutions found in manuals can be used, in a direct way, in simple applications, such as in the determination of the load corresponding to the J_{IC} value.

The use of J_{IC} as fracture limit criterium in design is not always satisfactory, for not considering the stable portion of crack growth. Usually, when considering the entire J-R curve, the value of J characterizing the fracture condition can be several times greater than the crack growth initiation value, defined by J_{IC}. Because of that, subsequent approaches developed for FM applications involved the consideration of the portion of the J-Rcurve corresponding to the stable crack growth. The big question, at that time, was related to how incorporate the growing crack effects in the methodologies of fracture behavior prediction of the structures.

3.3 Elastic-Plastic Fracture Mechanics methodologies based on instability assessment

When considering the contribution of the stable crack growth to the definition of a toughness value characterizing the structural failure, the main question that should be answered is "how can one define when the stable growth ends and the unstable propagation begin?" In the development of approaches of this kind, it becomes necessary to determine the point of the ductile instability from the knowledge of the geometry and of the loads acting on the structural component of interest and of the fracture resistance R curve. Due to that, this class of fracture methodologies is often referred to as crack instability prediction or assessment methods.

The tearing modulus T. The first of those methods was developed by Paris and collaborators (1979) and involved the determination of the tearing modulus T, a non-dimensional value corresponding to the J-R curve slope. The method relies on a comparison between tearing modulus values corresponding to the material J-R curve, T_R, and to the applied load, T_{app}. The condition $T_{app} \geq T_R$ corresponds to a situation of unstable crack propagation. This approach was the basis for another instability methodology, the J-T diagram (Paris, 1983), as shown in Fig. 2, and for the analogies of springs in series and springs in parallel of Ernst (1983).
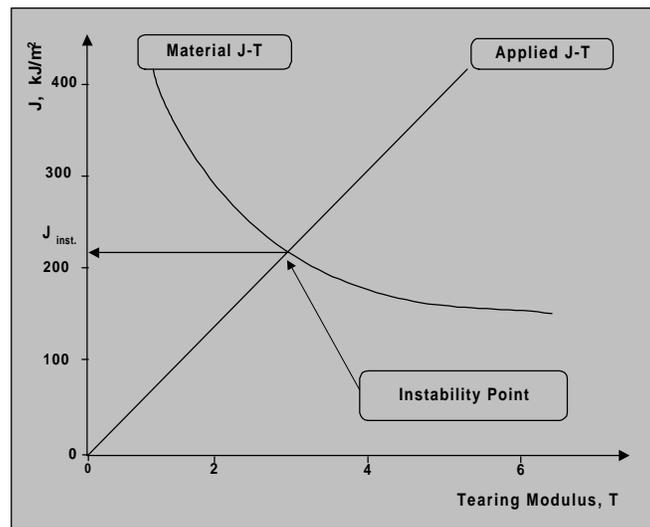

Figure 2–J-T diagram showing the instability point

The R6 document and the FAD diagram. The methods of predicting the maximum load for ductile fracture, when the load is within a non-linear deformation region, need an analysis model that incorporates both the deformation and the fracture behavior of the structure. One important methodology developed with this concern was the R6 method (Harrison et al., 1976), published in United Kingdom by CEGB (Central Electricity Generating Board). This method uses a failure analysis diagram approach, or failure assessment diagram (FAD), to determine "safe areas" of load for a cracked structure, based on a combined fracture toughness and yielding analysis. In the original version, the R6 did not use in its formulation any non-linear fracture parameters (Fig.3), following the of Strip Yield Model formulation, as defined by Dugdale (1960). More current revisions of the document, as the one published in 1986 (Milne et al., 1986), allowed the fracture analysis to be accomplished in three different categories, depending on the degree of conservatism that one wants to have. The first category corresponds to a failure associated with the crack growth initiation, J_{IC}. The second considers a limited stable crack growth, while in the third, the failure analysis is formulated in terms of the ductile tearing instability.
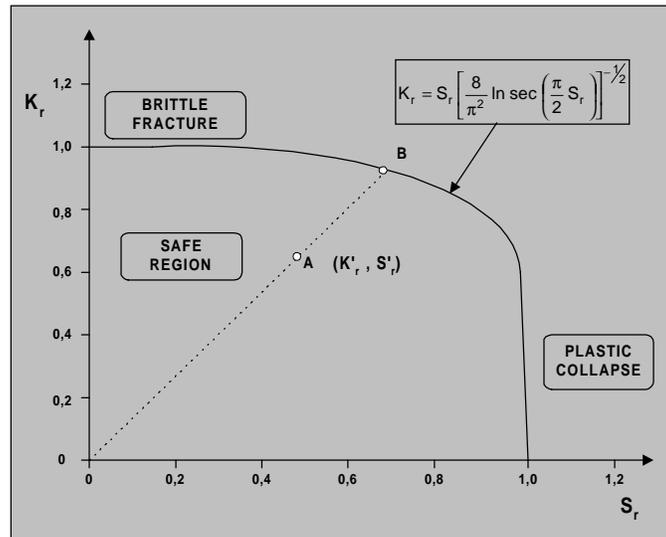

The diagram shows axis K_r (vertical) and S_r (horizontal). Equation:
$$K_r = S_r \left[\frac{8}{\pi^2} \ln \sec \left(\frac{\pi}{2} S_r \right) \right]^{-\frac{1}{2}}$$
Regions labeled BRITTLE FRACTURE, SAFE REGION, PLASTIC COLLAPSE, points B and A (K'_r, S'_r).

Figure 3–FAD diagram (R6–original formulation)

The DPFAD diagram. The FAD approach was taken as the basis for another instabilidade methodology, developed in the USA by Bloom (1980, 1983), denominated DPFAD (Deformation Plasticity Failure Analysis Diagram). In this methodology, Bloom uses J solutions, found in the EPRI-GE Handbook (Kumar et al., 1981), to define the areas for failure analysis. The DPFAD diagram relates a normalized stress or load parameter, represented in the axis of the abscissas, with a normalized fracture toughness parameter, in the axis of the ordinates. The analysis, as defined by this methodology, compares fracture toughness values obtained from the material J-R curve with the boundaries of the DPFAD diagram. This analysis can be accomplished in terms of a single toughness value, such as J_{IC}, as well as for the whole portion of the J-R curve corresponding to the crack stable growth. Figure 4 presents an example of a DPFAD diagram, built for a CCT geometry, with a/W = 0,5. The different curves in the diagram refer to different strain-hardening coefficients.
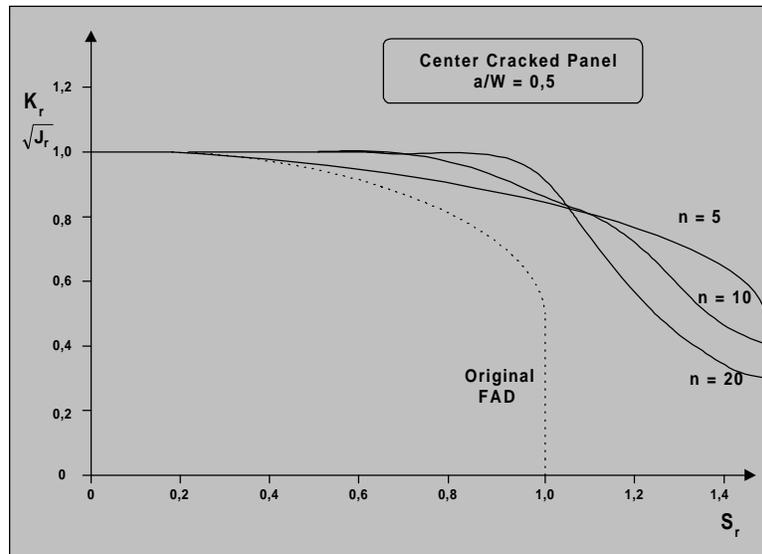
Figure 4–DPFAD diagram

PD6493. The concept of a failure assessment, FAD, initially defined in the R6 method, was developed into a fracture and fatigue assessment general application approach. The document that contemplates this methodology is the PD6493 (BSI, 1980), published by British Standards Institute. PD6493 is adopted worldwide for failure assessments, but mostly in welded structures applications. A revised version, published in 1991, promoted considerable changes to the original version of the document, defining three different analysis levels: the first, based on the CTOD design curve methodology (Kamath, 1978); the second, using the original R6 formulation, and the last, based on the Ainsworth reference stress approach(1984).

In the US there is no equivalent document for general application, existing a tendency of developing fracture assessment procedures that are specific to each project area or to sections of the industry.

The German methodology ETM. Another analysis method that incorporates deformation and fracture properties is ETM, Engineering Treatment Model, developed in Germany (Schwalbe and Cornec, 1991), which example of instability load computation is shown in Fig.5. ETM uses a non-growing crack solution to define the deformation pattern, and a R-Curve fracture characterization, to determine the crack ductile extension.

The DFM method. In the US, the group of Prof. John Landes, from the University of Tennessee, developed a methodology named DFM, Ductile Fracture Methodology (Landes and Zhou, 1991 & Landes et al, 1993), that uses a separation process in the load function, to incorporate the deformation properties and crack growth separately. By using this methodology it becomes possible, from the knowledge of a tested test body load versus displacement curve, to predict the corresponding curve in a component, through a series of analyses, if the scheme shown in Fig. 6 is followed.
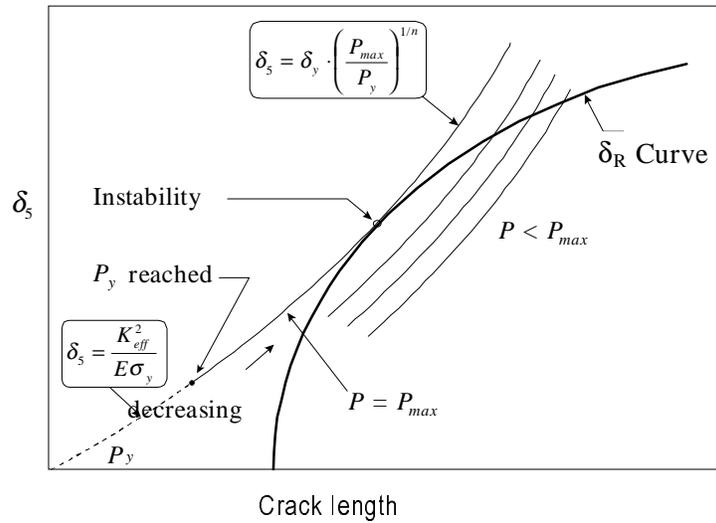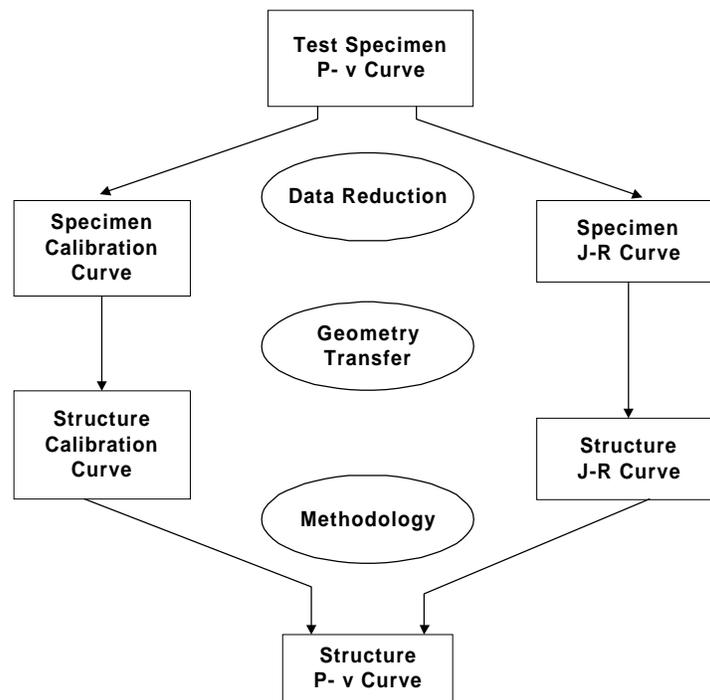
Figure 5–Example of the ETM methodology

Figure 6 - DFM methodology

A fracture behavior prediction example using DFM is shown in Fig. 7 for a pipe containing a surface crack and subjected to bending. The input data for the analysis came from the P- v curve obtained in J-R curve tests, performed in compact specimens C(T). The predicted results were also compared with real experimental data that were available, in order to evaluate the quality of the methodology.
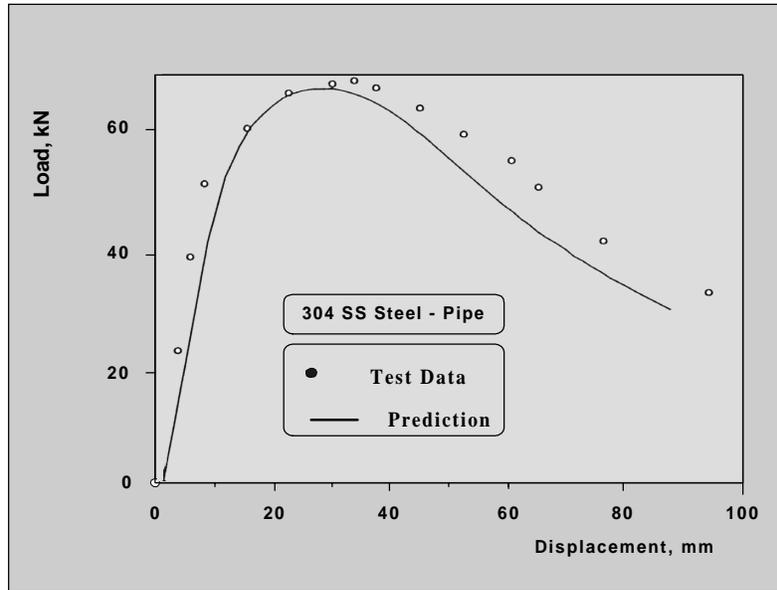
Figure 7–Fracture behavior prediction using DFM–Tube (Landes and Zhou, 1991)

Other Methodologies. There exist other fracture methodologies, developed for applications to engineering problems, that however are not detailed here. Among those, are worth of mention the CTOD design curve approach (Kamath, 1978) and the Ainsworth reference stress approach (1984), both used in the formulation of PD 6493:1991. Many of those methodologies have been used with success in the prediction of the fracture behavior of components and structures.

4. CONCLUSIONS

The purpose of this work is to focus along its two parts, of which the first was here presented, technologies already established and recently 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 those 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.

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