



Task 5

Development and Validation of Procedures

Subtask 5.1

Review of Existing Procedures



UNIVERSITY OF CANTABRIA

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I. INTRODUCTION

This Report contains the results of the analysis performed by the *Grupo de Ciencia de los Materiales* of the University of Cantabria on the available procedures for the structural assessment of cracked components. This work represents their contribution to the SINTAP project -Structural Integrity Assessment Procedures for European Industry- relative to Task 5, subtask 5.1 (Critical Review of Existing Procedures).

The work carried out can be divided into three parts:

- Critical review of procedures.
- Performance and calculation of specific examples.
- Proposal of working framework for the final procedure.

The first two tasks have been performed simultaneously and were mutually supportive. The methods were initially analysed in the order they were received. After this first analysis which consisted of thoroughly reading the procedures, a series of practical examples were performed in order to continue the process of familiarisation with the different methodologies and to detect possible difficulties in their interpretation and application for the potential user. In turn, this extensive knowledge of the procedures enriched the later revisions, paying special attention to an ample series of variables which characterise each method and, therefore, distinguish it from the others.

Similarly, this improved knowledge of the methods enabled their better evaluation, offered the possibility of analysing and optimising the calculations and results of the examples solved, permitting the option of comparing and also criticising them from an analytical point of view.

Once these tasks were finished and having studied the characteristics, advantages and disadvantages of nine different codes, in the third part of this report the University of Cantabria makes a proposal for the principal guidelines which will define the future procedure, the final objective of the SINTAP project. Within this framework, the proposal combines the different existing methodologies trying to find the most apt for the situations which could occur during the evaluation of structures or components with defects.

II. PROCEDURES REVIEW

INITIAL CONSIDERATIONS

The University of Cantabria sent a fax on 26th April, 1996, to all the Consortium Members detailing the available procedures, and also asked for the collaboration of the other members to obtain as many methods as possible in their most up-to-date versions.

The result of this was that the University of Cantabria received and later studied the following procedures, methods, codes, documents, and standards in the order they were obtained:

- *GE-EPRI Approach* [1]. *Topical Report* of 1981 published by Electric Power Research Institute. The University of Cantabria had access to this work before the SINTAP project was initiated. During 1996, additional handbooks developed by Zahoor [2] were obtained.
- *R6 Method (Revision 3)*, version July 1995, *Amendment 6*, supplied by Nuclear Electric through Dr. R. A. Ainsworth in April 1996. The information obtained contains the 14 sections of the principal body of the procedure, the corresponding appendices and a complementary document explaining the background and validation of the method. In mid-December, 1996, we received the October 1996 version, *Amendment 7* [3], in which Appendix 9 is revised and Appendix 14 is incorporated.
- *British Standard Institute Published Document 6493 (BSI PD6493)* [4] supplied by The Welding Institute through Dr. R. Phaal in April 1996. The available version dates from November 1995 and corresponds to the draft of the revision made by TWI on Fracture Assessment. Therefore, only sections from 7 to 14, and the appendices are available.
- *A Procedure for Safety Assessment of Components with Cracks - Handbook* [5] supplied by SAQ Inspection through Dr. Björn Brickstad in May 1996. This version dates from December 1991 and is pending revision.
- *Exxon. Fitness-for-Service Guide* (version February 1995) [6] supplied by Exxon Chemical through Dr. Stefan Winnik in May 1996.

- *The Engineering Treatment Model for Assessing the significance of crack-like defects in engineering structures (EFAM ETM 95) [7] and The ETM for assessing the significance of crack-like defects in joints with mechanical heterogeneity (strength mismatch) (EFAM ETM-MM 96) [8]* supplied by GKSS-Forschungszentrum Geesthacht through Dr. Mustafa Koçak and Prof. K.-H. Schwalbe in September 1996. The methods studied correspond to the versions “draft for comments” of August and April 1996, respectively. The first studies on the ETM procedure were performed following the methodology shown in reference [9].
- *ASME XI Boiler & Pressure Vessel Code. Rules for Inservice Inspection of Nuclear Power Plant Components. Division 1 (Subsections and appendices), 1995 [10]* version obtained by the University of Cantabria in November 1996. The first comments and approaches to the code were made through the 1991 version having brought the review up-to-date.
- *Fitness-for-Service Evaluation Procedures for Operating pressure vessels, tanks and piping in refinery and chemical service (FS 26). Draft #5 October 1995* edited by The Materials Properties Council [11] and supplied in December 1996 by Shell Research and Technology Centre, Amsterdam through Dr. Ronald Koers.
- *API 579 Recommended Practice for Fitness-in-Service. Issue 4. Draft Version October 1996 (sections and appendices) [12]* again supplied by Shell Research and Technology Centre, Amsterdam in December 1996.

1. ASSESSMENT METHODOLOGIES

The documents listed above could be classified according to their different assessment methodologies or philosophies to organise the study in a more logical way. All procedures which follow a certain methodology could then be analysed consecutively in order to highlight their differences. These could then be compared with others which follow alternative methodologies.

Therefore, the nine studied documents have been divided into three main groups. These groups have been named as follows:

- Assessment procedures based on Failure Assessment Diagram (FAD) techniques.
 - * Calculation procedures.
 - * Fitness-for-service Guides.
- Assessment procedures based on Crack Driving Force (CDF) techniques.
- Others.

1.1. ASSESSMENT PROCEDURES BASED ON FAD TECHNIQUES

The methodology based on the use of Failure Assessment Diagrams is an integrated graphical representation where fracture failure and plastic collapse are simultaneously evaluated by means of two non-dimensional variables (L_r and K_r).

These two variables represent the ratio between the applied value of either stress or stress intensity factor and the resistance parameter of the corresponding magnitude (yield stress or fracture toughness).

Once the plotting plane is determined by the variables L_r and K_r , each procedure defines a critical failure line which establishes the safe or acceptable zone. This zone is the area bounded by the mentioned line and the axes.

Thus, these methods represent a different philosophy from classic structure calculations because they do not directly compare the applied variable versus the corresponding resistance value, which complicates their interpretation from a physical point of view. Nevertheless, the simplicity and swiftness of this kind of calculation recommend these diagrams for Structural Integrity Assessment.

The procedures which use Failure Assessment Diagrams have been divided into two different sections according to structural and objectives differences.

1.1.1. Calculation Procedures

The following documents that can be considered as an overall assessment procedure are included in this group:

- R6 Method.
- BSI PD6493.
- SAQ.

1.1.2. Fitness-for-service Guides

The following documents in addition to having an assessment procedure (founded in the ones mentioned above), contain a number of recommendations for inspection, maintenance or repair of in-service components. These documents are:

- EXXON.
- MPC.
- API 579.

1.2. ASSESSMENT PROCEDURES BASED ON CDF TECHNIQUES

The assessment methodology of the procedures based on the use of Crack Driving Force Diagrams is different from the philosophy of FAD based documents. The evaluation of fracture failure and plastic collapse are not simultaneously calculated. Therefore, two independent steps are needed. On the one hand, a direct comparison between applied stress or load and flow stress or limit load; and on the other hand, a diagram should be plotted where the applied stress intensity factor, J-integral or CTOD is compared with the corresponding toughness values.

The Crack Driving Force Diagrams are easier to interpret in a physical sense than the Failure Assessment Diagrams. Moreover, if the CDFD is used together with the J_R curve, the full crack propagation history is described.

The studied procedures that follow the Crack Driving Force philosophy are:

- GE-EPRI.
- ETM.

1.3. OTHERS

Only the ASME Section XI code is included here as it does not rigorously follow any mentioned methodology.

The ASME code is similar to the fitness-for-service guides but, concerning the assessment procedure, it does not use FADs, rather, it uses figures and tables which the real situations can be compared to.

2. R6 METHOD

2.1. GENERAL

The R6 Method, as is reflected in the Foreword on page vii¹ and in Section 2.1, is a general procedure for establishing the integrity of a structure containing defects.

Apparently, it is directed towards the power generation industry, both in its origin and development (Nuclear Electric) and in the examples mentioned in the Validation document (pressure vessels and pipes).

2.2. MATERIALS LIMITATION

There are no limitations in terms of materials that can be covered by this type of analysis and it is assumed to be valid for any material. However, as the method has a certain orientation towards the power generation industry, it seems logical that the procedure has been developed principally for the materials used in this sector. In fact, in Section 6 it is affirmed that the Failure Assessment Diagrams have been amply validated for metallic materials.

2.3. STRUCTURAL ANALYSIS METHODOLOGY

The calculation methodology is based on the use of the Failure Assessment Diagram (Section 2.2) in which failure by fracture and by plastic collapse are simultaneously evaluated.

The R6 Method makes use of three different FAD lines depending upon the accuracy required of the analysis and the information available to generate such diagram:

- Option 1: General curve (Section 6.1.1). Suitable for all materials except those which exhibit a yield plateau. Only the engineering yield stress and the flow stress values need to be known in order to obtain the cut-off value.

¹ Referenced pages and sections belong to the corresponding procedures analysed.

- Option 2: Material Specific curve (Section 6.1.2). Available for any material when the detailed true stress-true strain data are known.
- Option 3: Curve obtained using a J-integral analysis (Section 6.1.3). A curve specific to a particular material and geometry is obtained using this option. The method requires the J-integral to be evaluated using both elastic and elastic-plastic analysis of the flawed structure under the corresponding loads.

2.4. CRITICAL CONDITIONS ANALYSED

Fracture

There are three categories of analysis (Section 7):

- Category 1: Crack initiation. Appropriate when the fracture is through brittle mechanisms or if there is no important benefit from taking into account the possibility of ductile tearing propagation. Only one point is assessed.
- Category 2: It is appropriate for situations where failure may be preceded by a small amount of ductile tearing. A Category 2 analysis is not as simple as a Category 1 analysis, but it does allow benefit to be taken for the increase in toughness due to ductile tearing without the complications inherent in the full ductile tearing crack growth analysis of Category 3. Thus, one additional point is evaluated (that which considers the fracture toughness increment owing to ductile tearing once the conditions for J-controlled crack growth are justified) apart from the initial situation.
- Category 3: This category of analysis is appropriate to situations where failure is preceded by ductile tearing. The analysis is evaluated by reference to the detailed ductile tearing resistance curve so a locus is obtained which may be compared with the FAD line. Although it would normally be applied only up to the limits of J-controlled crack growth, it may be extended beyond these limits where necessary.

Plastic collapse

Plastic collapse is intrinsically considered in the definition of the cut-off (variable L_r) as corresponds to the philosophy of the FAD.

The concept of limit load (yielding) is defined in Section 10 and in Appendix 2 (Section A2.2). For part-through cracks, the yield load considered is called “local”, i.e. the load needed to cause plasticity to spread across the remaining ligament, calculated for an elastic-perfectly plastic material with a yield stress equal to σ_y . If a crack is through-thickness or requires to be recharacterised as through crack, the yield load is the so-called “global”, that is, the rigid-plastic limit load of the structure, calculated for a rigid-plastic material with a yield stress equal to σ_y .

The structural collapse is considered to be governed by failure of the ligament at the flaw and the possibility of premature collapse elsewhere in the structure should be separately investigated.

2.5. FRACTURE MECHANICS VARIABLES USED

Any variable is reduced to K_I , except if Option 3 of FAD is used whereby knowledge of the applied J-integral is needed.

2.6. SAFETY FACTORS AND RISK ASSESSMENT

The R6 Method does not use safety factors in the input data as is normally the case in structural calculations. However, the procedure mentions in Section 8 that the material characteristic data must be sufficiently conservative and in Section 5 that the stresses to be considered have to be those which produce the worst situation for the structure.

Appendix 1 mentions the steps to follow to conservatively determine the toughness value (statistical analysis).

The method defines the existing reserve factors in each analysis and proposes, in Section 12, the evaluation of these factors with the aim of estimating the sensitivity of the results.

A specific procedure also exists for structural evaluation using probabilistic techniques (Appendix 10).

2.7. FRACTURE MODE

The R6 Method, in Section 3.1, states that the procedure has been developed for Mode I loading. Appendix 7 mentions the guidelines for structural evaluation under a combination of modes (I, II, and III).

2.8. STRESS DEFINITION

Section 5.1, dedicated to the analysis of stresses, states that the user must ensure that all relevant loadings are included and that the analysis should produce upper bound values of stress.

In Section 5.2 the stresses are categorised between primary and secondary and are conveniently defined. Throughout the procedure they are treated in different ways, the presence of secondary stresses only affecting the calculation of K_r (ρ parameter). If in doubt about the stress category, primary stresses should be assumed.

Residual stresses (secondary) are named in Section 5.2. The index mentions an appendix (12) which refers to a residual stress compendium. Although it has not been included in UC's information, it has been covered in the SINTAP Task 4 review.

The stresses due to tests or pre-stresses are mentioned in Section 3.6 where there is a warning about the precaution which needs to be taken when they are being considered. The version Amendment 7 presents Appendix 13 which takes into account the effects of Load-History.

2.9. FORMULATION CATALOGUE

As such, no handbook is available. Nevertheless, Appendix 2 and 3 include information and a collection of important references according to which numerous limit loads and stress intensity factors may be determined, but there is no explicit solutions catalogue.

The validation of the method uses specific software programs which are not described in spite of the existence of Appendix 5: Computing Aids.

2.10. DEFINITION OF MATERIAL MECHANICAL BEHAVIOUR

Both the yield stress, σ_y , and the ultimate tensile strength, σ_u or UTS, are defined in Section 8.2 and refer to British Standards. The flow stress is defined as the average between σ_y and σ_u , although greater values may be taken when they can be justified.

For determining the mechanical parameters of the material, indirect methods may be used when they are demonstrated to be applicable (Section 8.2.3).

No modelling of the stress-strain curve is required.

2.11. FRACTURE TOUGHNESS DEFINITION

Fracture toughness is perfectly defined in Section 8.1.1 and is referred to British and ASTM Standards.

Appendix 1 presents statistical recommendations for determining the toughness value in a sufficiently conservative way.

Indirect methods as Charpy type tests may also be used if they have been widely validated. Section 8.1.3 directs the user to Appendix 1 which offers a list of references in which different correlations appear.

2.12. CRACK CHARACTERISATION

The method references the characterisation of the procedures PD6493 and ASME XI. If these procedures do not present acceptable safety factors, it is recommended that the crack be characterised following other rules (Section 9).

Three types of planar cracks are considered: embedded, surface and through-thickness. They are geometrically defined in the figures in Section 9.

The characterisation of the cracks also considers the possible influence of other nearby defects.

2.13. CRACK EVOLUTION AND RECHARACTERISATION

Appendix 6 develops the study of possible sub-critical crack growth, i.e. fatigue and environmentally assisted.

Section 9.3.2 defines the possible recharacterisation of cracks due to growth: embedded to surface, surface to through-thickness.

Appendix 9 represents an overall procedure of Leak Before Break.

2.14. WELDING

Although Section 8.2.2 states that the weakest material tensile characteristics around the crack will be used in all cases, a new appendix (16) has been presented which deals specifically with mis-match effects and its treatment.

Other aspects in welding have been covered through the development of Appendix 12 (residual stresses) as mentioned in a previous section.

2.15. STRESS FIELD CONDITIONS

The only comment referring to the different conditions of the stress field (plane strain, plane stress) is found in Appendix 2. There, it is mentioned that, in the case of needing to choose a limit load, plane stress is conservative and therefore recommendable. Mention is also made of the care that should be taken when bidimensional situations are analysed because uniaxial solutions may be non-conservative.

R6 is the unique code which analyses the influence of constraint effects on the structural analysis (Appendix 14).

2.16. OTHERS

Throughout the procedure, reference is made to dynamic effects (dynamic loads, strain rates, non-static material characteristics...) which do not appear in other methods.

3. BSI PD6493

3.1. GENERAL

The procedure described in British Standard Institute Published Document 6493 is a general procedure applicable to any engineering construction (Section 7) although it apparently specialises in questions of welding as it contains many appendices dedicated to welding effects.

In spite of its generality, it also contains special appendices for certain applications such as: offshore structures (Appendix L), pressure vessels and pipes (Appendix M).

3.2. MATERIALS LIMITATION

Although there are no explicit limitations in terms of materials, a certain preference exists for metallic materials. Section 12.2 establishes that the FAD curves have been validated for a wide range of metallic materials.

3.3. STRUCTURAL ANALYSIS METHODOLOGY

The calculation methodology is based on the use of the Failure Assessment Diagram (Section 7) which combines consideration of fracture failure and plastic collapse.

The PD6493 fracture assessment Procedure considers three types of FAD lines (Sections 11.2 and 12.2):

- Option 1. Generalised curve. The procedure presents two different default curves depending on the material's hardening behaviour. Only the yield stress and the flow stress are needed to be known in order to perform this kind of diagram.
- Option 2. Material Specific curve. This curve is derived from the specific material stress-strain curve. Therefore, all the tensile data need to be known.
- Option 3. Curve obtained using a J-integral analysis. A curve specific to a particular material and geometry is obtained using this option. The method

requires the J-integral to be evaluated using both elastic and elastic-plastic analyses of the flawed structure under the corresponding loads.

3.4. CRITICAL CONDITIONS ANALYSED

Fracture

There are three levels of analysis:

- Level 1. Preliminary assessment (Section 10). Simplified evaluation for a given crack, without the possibility of ductile tearing. The simplicity of the analysis implies the use of “inherent” safety factors, i.e. included in the evaluation and not introduced by the user. The evaluation of a structure using Level 1 is complemented in Appendix O. Literally speaking, it does not make use of a Failure Assessment Diagram as it is usually understood. It only checks that neither fracture failure nor plastic collapse can occur.
- Level 2. Normal assessment (Section 11). Typical analysis category. Only one point is evaluated, but the possibility of ductile tearing may be considered. The use of inherent safety factors is not necessary for this method as it is more precise.
- Level 3. Advanced assessment for ductile tearing (Section 12). The same as Category 3 of the R6 Method, it analyses the complete tearing process.

Plastic collapse

The method considers plastic collapse through the cut-off.

All three levels of assessment consider local plastic collapse (Section 7). Appendix 7 extends this approach to consider global plastic collapse, where relevant. There, the different definitions of collapse are presented:

- Local collapse. Collapse of the remaining ligament adjacent to the defect being assessed.
- Net section collapse. Collapse of the structural section containing the defect.

- Gross section collapse. Collapse of the structure by gross straining. This occurs when collapse takes place away from the cracked section or is unaffected by the presence of the cracks.

Both two last options could be considered as global collapse.

3.5. FRACTURE MECHANICS VARIABLES USED

The analysis may be developed by using techniques based both on the stress intensity factor and the CTOD (Section 7). However, the user is recommended not to transform values from one to the other because of constraint effects when Levels 1 and 2 are used.

When option 3 of FAD is used, the expression of the applied J-integral needs to be known.

3.6. SAFETY FACTORS AND RISK ASSESSMENT

Appendix A defines safety factors for stress, flaw size and toughness as a function of the extent of damage in case of failure.

As was previously mentioned, the Level of analysis 1 has “inherent” safety factors due to the simplicity of the method.

Appendix Q describes the safety margins obtained when analysis Levels 2 and 3 are used (identical to those of R6). There (Section Q3), the method’s sensitivity studies are also defined.

3.7. FRACTURE MODE

The general method only considers Mode I (Section 7). However, Appendix I explains the steps to be taken when there is a combination of modes (I, II, and III).

3.8. STRESS DEFINITION

The overall stress state is defined in Sections 8.1, 8.2 and 8.3. Recommendations are presented about the stresses to be considered in each case.

The method considers the differentiation between primary and secondary stresses and treats them in a different way. Appendix P deals with the interaction between both types of stresses.

The residual stresses due to welding are mentioned throughout the stress definitions in Sections 8.1 through 8.3. If data are not available, they are quantified in Appendix C.

The stresses owing to proof tests are mentioned and comments are made on the advantages that these tests offer for reducing certain peak stresses under some circumstances. Appendix K should consider the effects of these pre-stresses but it is not available.

3.9. FORMULATION CATALOGUE

The formulation catalogue is presented in two different appendices:

- Appendix E: Stress intensity factors solutions.
- Appendix F: Limit load solutions.

3.10. DEFINITION OF MATERIAL MECHANICAL BEHAVIOUR

Both the yield stress and the UTS are referred to British and European Standards in Section 8.8. The flow stress is defined as the average between σ_y and σ_u in all cases.

The formulation of the method does not require any modelling of the stress-strain curve.

3.11. FRACTURE TOUGHNESS DEFINITION

Fracture toughness is referred to British Standards and work can be done following either K_I or CTOD. Appendix A presents the guidelines for determining the correct toughness value as a function of the number of tests performed.

Appendix B gives certain guidelines in cases where toughness is obtained using Charpy test data.

3.12. CRACK CHARACTERISATION

Three types of cracks are defined: embedded, surface and through-thickness; all are assumed to be planar (Section 8.4). Section 13 presents some indications in the case of non-planar cracks, imperfect shapes, etc.

Also, mention is made of the possibility of interaction between neighbouring cracks and its consideration.

3.13. CRACK EVOLUTION AND RECHARACTERISATION

No comments are made on subcritical crack growth through the available sections except in Appendix L (dedicated exclusively to offshore applications) in which a fatigue assessment is presented for those structures.

When an embedded or a surface flaw cannot be assessed as tolerable according to any level of the procedure, it may be recharacterised as a surface or through-thickness flaw, respectively. Such a situation is mentioned in Section 8.4.3 and is amplified in Appendix G.

Appendix J develops an analysis procedure for Leak Before Break situations.

3.14. WELDING

As was mentioned in the first point, this method presents specific appendices for welding effects (Appendices C, D, H and N) which are:

- Appendix C: Residual stress distribution in as-welded joints.
- Appendix D: Stress due to misalignment.
- Appendix H: The significance of weld strength mismatch on the fracture behaviour of welded joints.
- Appendix N: Fracture assessment for Weld Heat Affected Zones.

3.15. STRESS FIELD CONDITIONS

Special considerations are not made for situations of plane stress or plane strain.

Nor are modifications presented relative to constraint effects.

3.16. OTHERS

A comment is made in Appendix F which covers the case of redundant structures. It establishes that the consideration of the plastic collapse of the remaining ligament as an upper limit could turn out to be extremely conservative. Therefore, the use of a greater limit load could be convenient after the corresponding validation.

Nevertheless, and even though it is the only procedure which reflects redundancy as a special situation, it does not take into account stress redistribution mechanisms nor their effects.

4. SAQ

4.1. GENERAL

Initially developed for the nuclear industry, but used in other branches, the SAQ Procedure is based on the R6 Method (Section 1) with the objective of a safe rather than accurate analysis of components (Appendix B).

4.2. MATERIALS LIMITATION

In principal it may be used for any metallic material, although it is most valid for steels (Section 1).

4.3. STRUCTURAL ANALYSIS METHODOLOGY

As stated above, the procedure is based on a simplified version of the R6 Method (Section 1). Therefore, it uses techniques based on the Failure Assessment Diagram.

There is only one option of FAD corresponding to the default curve of the R6 Method (Option 1. General).

4.4. CRITICAL CONDITIONS ANALYSED

Fracture

Only takes into account the initial crack, it does not consider the possibility of ductile tearing and the consequent increase in toughness (Section 2.10).

Plastic collapse

As corresponds to the methods that use FADs, plastic collapse is considered in the definition of the cut-off.

The limit load is defined as the yielding load of a perfectly plastic material with a yield stress σ_y (Section 2.8). Further explanations are found in Section B.3, Appendix B.

4.5. FRACTURE MECHANICS VARIABLES USED

Any variable relative to fracture is reduced to K_I , there are no references to any other variable.

4.6. SAFETY FACTORS AND RISK ASSESSMENT

Appendix P presents a table of safety factors for loads, sizes and characteristics of materials depending on the type of event (normal, upset, emergency and faulted) for ferritic and austenitic steels.

The reserve factors are defined in the same way as in the R6 Method (Section 2.11).

4.7. FRACTURE MODE

It only takes into account Mode I and makes no reference to possible combinations of forces.

4.8. STRESS DEFINITION

In spite of not making recommendations about how to consider a not constant stress distribution through a section, it mentions that the computer aids, developed from the method, do linearise any distribution, thus preserving the equilibrium (Section B.5, Appendix B).

This method differentiates between primary and secondary stresses in a similar way to the R6 Method (Section 2.4), taking into account their interactions in the procedure and clarifying the situation in Appendix B.1.

Appendix E evaluates residual stresses from welding by modelling typical distributions.

4.9. FORMULATION CATALOGUE

The formulation catalogue is presented in three different appendices:

- Appendix G: Geometries of the components considered.

- Appendix K: Stress intensity factors solutions.
- Appendix L: Limit load solutions.

4.10. DEFINITION OF MATERIAL MECHANICAL BEHAVIOUR

The material mechanical parameters are defined in Section 2.5 but there is no mention of Standards. In spite of not mentioning the flow stress in the method, in the definition of cut-off it is assumed to be the average between the yield stress and the ultimate tensile strength.

Appendix M refers to ASME III where information of σ_y and σ_u values for most steels used in nuclear applications can be found.

The procedure's methodology does not require any modelling of the stress-strain curve.

4.11. FRACTURE TOUGHNESS DEFINITION

In Section 2.5 references are made to the ASTM Standards for determining the material's fracture toughness.

Appendix M presents some values for materials used in the nuclear industry based on ASME III data.

4.12. CRACK CHARACTERISATION

Similarly to the R6 Method, the SAQ Method refers to the characterisations of the ASME code and to the PD6493 in Appendix A. Therefore, it considers three types of planar defects: embedded, surface and through-thickness.

It also includes the possibility of neighbouring cracks and their interdependence.

4.13. CRACK EVOLUTION AND RECHARACTERISATION

Section 2.6 briefly comments on fatigue and stress corrosion cracking, referring to Appendix M dedicated to the materials used in the nuclear industry.

No mention is made of any type of crack recharacterisation by propagation although it does take into account the possibility of recharacterising some defects when they go beyond the applicability of their typology (Section 2.7), e.g.:

- A semi-elliptical surface crack with a length/depth ratio which is larger than the applicability limit can instead be treated as a long crack.
- A semi-elliptical surface crack with a depth that exceeds the applicability limit can instead be treated as a through-thickness crack with the same length as the original crack.
- A cylinder with a ratio between wall thickness and inner radius which is below the applicability limit can instead be treated as a plate with a corresponding stress state.

4.14. WELDING

This method recommends using the mechanical values of the base material when there is a crack in a weld as it considers that the load limit supported by a structure is not a local property nor it is only dependent on nearness to the cracked zone (Section 2.5).

As mentioned above, Appendix E quantifies the residual stresses due to welds.

This method does not present any type of comment on the problems relating to mis-match situations.

4.15. STRESS FIELD CONDITIONS

There is no consideration of stress field and possible simplifications (plane stress/plane strain). Plane strain is only considered specifically when K values are obtained from J-integral.

5. EXXON

5.1. GENERAL

The Guide published by Exxon titled Fitness-for-Service represents a group of sections and appendices which go beyond a calculation procedure because also includes sections dedicated to direct component inspection (Section 1.0).

Referring to the specific calculation procedure (Section 8), the guide's introduction states that this method is directly based on the BSI PD6493 and will be only applicable for the structural evaluation of pressure vessels, storage tanks and pipelines.

5.2. MATERIALS LIMITATION

Even though no explicit limitation exists, it seems clear that it is valid for all metallic materials. In the section on material characterisation (Section 5) reference is made to the ASTM Standards which regulate the determination of the characteristics for such materials.

5.3. STRUCTURAL ANALYSIS METHODOLOGY

This procedure uses methodology founded on Failure Assessment Diagrams and is totally based on the BSI PD6493 Procedure.

It only considers two assessment categories: the preliminary assessment of the PD6493 Procedure which, rigorously speaking, does not make use of a FAD, and the normal assessment by means of the default curve.

For evaluating real defects found during inspections there are figures and graphs which are analogous to those used by ASME and others.

5.4. CRITICAL CONDITIONS ANALYSED

Fracture

References PD6493.

Plastic collapse

References PD6493.

Section 8.1 adds in that special care must be taken when a crack passes the PD6493 assessment and afterwards it is ground out, because it could then fail the local thin area assessment detailed in Section 7.

5.5. FRACTURE MECHANICS VARIABLES USED

Uses the same parameters and considerations as PD6493.

5.6. SAFETY FACTORS AND RISK ASSESSMENT

References PD6493.

5.7. FRACTURE MODE

References PD6493.

5.8. STRESS DEFINITION

Two sections refer to stress calculations. Section 6 in a general way and on application of fitness-for-service, including methods of fracture analysis. For more specific points reference is made to Section 8 in which crack analysis is also dealt with.

In principal it recommends (Section 6.0) that stress calculation is made following ASME VIII, Division 2, Appendix 4.

The overall stress state is defined in the two previously mentioned sections. Section 6.1 defines which loads have to be considered and specifies which types of stress may exist. Section 8 covers the recommendations that have to be taken into account for the correct use of the stresses following the ASME code.

On categorising the different stresses: primary and secondary, it must be said that Section 6 distinguishes them semantically but considers them in the same way in terms of calculation (Section 8.1.2).

The residual stresses are specifically mentioned in Section 8.2, stating that they must be considered in the analysis. For the residual stresses produced by welding a distinction is made between equipment with or without Post Welding Heat Treatment (PWHT). The values which must be considered are specified for both cases.

5.9. FORMULATION CATALOGUE

The Guide does not include a handbook of typical typologies and solutions. As reference is continually made to the PD6493 procedure, the formulation catalogue of said procedure could be considered as valid for this one.

5.10. DEFINITION OF MATERIAL MECHANICAL BEHAVIOUR

Section 5.1.1 states that the values which appear in the material certifications should be taken for σ_y and σ_u .

Flow stress is defined as the average between the yield stress and the UTS. The maximum value is limited to that which exceeds the yield stress by 20%.

There is no reference to any kind of mathematical fit of the stress-strain curve throughout the guide.

5.11. FRACTURE TOUGHNESS DEFINITION

Section 5 deals extensively with the definition of fracture toughness in terms of K, CTOD and J. It always refers to the ASTM Standards.

Sections 5.4 and 5.5 consider the possibility of obtaining toughness values by indirect methods. Section 5.4 specifies how to obtain resistance parameters from Charpy impact test correlations, while Section 5.5 develops how to estimate them when these are not available.

5.12. CRACK CHARACTERISATION

An incomplete modelling appears in Figure 8.2 on crack characterisation. Given that the guide refers to the PD6493 document concerning structural analysis, it seems clear that the characterisation defined in said document is also valid for this fitness-for-service.

As stated in the initial point, this document goes beyond what can normally be considered as a calculation procedure because it contains sections and chapters oriented towards the inspection of real plant situations. Therefore, there is a specific Section (4.2) dedicated to the detection and measurement of real cracks.

5.13. CRACK EVOLUTION AND RECHARACTERISATION

No comments are made with respect to cracking evolution except that they have to be monitored if not repaired. In fact, the clear recommendation of the manual is that any crack should be removed (Section 4.3).

5.14. WELDING

No special mention is made on welding and associated problems except that of the already mentioned quantification of residual stresses.

5.15. STRESS FIELD CONDITIONS

No mention is made of stress field given that anything related to stress is referred to the ASME code and the PD6493 document.

6. MPC

6.1. GENERAL

Similarly to the guide published by Exxon, the method published by The Materials Properties Council represents a fitness-for-service procedure evaluation. In this case, the applicability of the document extends to operating pressure vessels, tanks and piping in refinery and chemical service. It can also be used for variations in these geometries when they are adapted to what is said in the ASME codes and the API standards (Sections 1.1 and 1.2).

Therefore, once again, fitness-for-service must be taken in two parts:

- The totality of the recommendations for inspecting and maintaining the mentioned structures.
- The procedure for the assessment of the structural integrity of such components.

6.2. MATERIALS LIMITATION

Section 1.2 limits the method's applicability to low-alloy, austenitic and carbon steels.

6.3. STRUCTURAL ANALYSIS METHODOLOGY

Based on the use of Failure Assessment Diagrams. The PD6493 Procedure and the R6 Method are referred to as the basis for the document.

The guide contains two options of FAD (Section 8.5):

- Lower-Bound FAD. Identical to FAD Option 1 of R6 Method (General curve).
- Elastic-Plastic J-integral analysis. Identical to FAD Option 3 of R6 Method.

6.4. CRITICAL CONDITIONS ANALYSED

Fracture

Crack initiation is only considered through the evaluation of one point in the FAD (Section 8.4).

Plastic collapse

Considered in the cut-off like all the procedures which use FAD techniques. The document does not definitively specify which load is taken as the limit (relative to the local or global plastic collapse). Section 8.3 states that the local solution would be the more conservative approach.

6.5. FRACTURE MECHANICS VARIABLES USED

Section 8.4 establishes the stress intensity factor as the normal analysis parameter used, but also permits the use of CTOD and J.

6.6. SAFETY FACTORS AND RISK ASSESSMENT

The reserve factors are analogous to those of R6, PD6493 and others. A later study of sensitivity to such reserve factors is recommended (Section 8.6).

6.7. FRACTURE MODE

Section 5.2.1 states that Mode I load is assumed for fracture calculations. However, the possibility of mixed loads (I and II) is covered in Appendix F.

6.8. STRESS DEFINITION

The stress state is defined in Section 8.2.1 and recommends the use of Finite Elements Analysis for calculating the exact stress distribution.

In Section 8.2.1 a clear and precise distinction is made between primary and secondary stresses. They are treated in different procedures using the parameter ρ which already exists in other methods.

Similarly to the R6 Method, when stress classification is not known, it is preferable to consider it as primary.

Residual welding stresses are considered in the calculation guide (Section 8.2.1), differentiating between components which have or have not received a post welding heat treatment (PWHT). In both cases, residual stress values are recommended for performing the analysis.

6.9. FORMULATION CATALOGUE

There are two appendices which cover different solutions:

- Appendix B: Solutions for K_I .
- Appendix C: Solutions for limit load.

6.10. DEFINITION OF MATERIAL MECHANICAL BEHAVIOUR

The yield stress and the ultimate tensile strength are only mentioned in the list of symbols, no reference is made to any Standard.

Flow stress is defined in Section 8.3 as the average between σ_y and σ_u . It may also be considered as the yield stress plus 10 ksi (for most medium strength steels similar values are obtained for both definitions).

No stress-strain curve modelling is needed.

6.11. FRACTURE TOUGHNESS DEFINITION

Reference is made to the ASTM Standards which permit the determination of fracture toughness both in terms of K and CTOD or J (Section 8.2.3).

6.12. CRACK CHARACTERISATION

Classic modelled planar cracks of almost all the procedures are considered in Section 5.2: surface, embedded and through-thickness, along with the possible interaction of neighbouring defects.

Recommendations are also provided for idealising a real crack for its treatment by the procedure.

The following defects are also dealt with in the part on in-service plant inspections: slag inclusions (Section 5.3), pitting corrosion (Section 5.4), local thin areas (Section 5.5) and blisters (Section 5.6).

6.13. CRACK EVOLUTION AND RECHARACTERISATION

Subcritical crack growth as well as the Leak Before Break situation are treated in-depth in Chapter 9 “Assessment of Growing Cracks”.

Section 5.2.3 covers a series of recommendations for the conservative recharacterisation of difficult-to-measure cracks.

6.14. WELDING

Apart from what is mentioned in the point on residual stresses, K_I solutions are given for cracks close to fillet welds in Appendix B (Section B.6).

About the material to be taken in the analysis when there is a defect in a weld, this method only states that the worst mechanical characteristics should be considered, either the base or the weld material.

6.15. STRESS FIELD CONDITIONS

The only mention of the stress field appears in Section 8.4 in the definition of the K_r ratio, and simply states that plane stress and plane strain have little importance if both the applied values and the resistant parameters are considered coherently, that is, under the same stress state.

7. API 579

7.1. GENERAL

Paraphrasing Section 1.2 of the API 579 standard, "The fitness-for-service assessment procedures in this recommended practice cover situations involving flaws commonly encountered in the refining and petrochemical industry in pressure vessels, piping and tankage".

7.2. MATERIALS LIMITATION

No explicit limitation is made on the materials covered by the standard. However, it may be assumed that it is mainly dedicated to metallic materials because of both the content of the guidelines (for example, metallic corrosion) and the scope of the procedure (vessels, piping and tankage).

7.3. STRUCTURAL ANALYSIS METHODOLOGY

Section 9.4.1.1 clearly states that the evaluation procedures are based on the Failure Assessment Diagram methodology.

There are three levels of assessment (Section 9.4.1.2) which could be summarised as follows:

- Level 1 assessment (Section 9.4.2). It is a screening criterion, i.e. it is only valid for certain components, with certain crack-like flaw geometries, under certain loads and made of certain materials. It does not need the representation of a Failure Assessment Diagram.
- Level 2 assessment (Section 9.4.3). Analogous to the analysis in Level 1 of PD6493 (preliminary assessment) with a different inherent safety factor for K_I -axis.
- Level 3 assessment (Section 9.4.4). Analogous to the analysis in Level 2 of PD6493 (normal assessment) or Categories 1 or 2 of the R6 Method. It uses the General curve of the R6 Method.

7.4. CRITICAL CONDITIONS ANALYSED

Fracture

No benefit on toughness due to ductile tearing is considered. So, only simple situations are covered by the three levels of analysis. Level 1 does not even use the FAD as such because the analysis is reduced to checking that the stress intensity factor is lower than the fracture toughness value.

Plastic collapse

The following are taken into account according to the level of study chosen:

- Level 1: The plastic collapse of the damaged section is not considered as such, but it is implicit in the requirements (Section 9.4.2.1.b.h).
- Level 2: There are no recommendations taking plastic collapse into account. No explanation is made about which section the limit load refers to. Appendix D should describe this item but it is not available at the moment.
- Level 3: In addition to the explanation for Level 2 applying here, plastic collapse is considered through the cut-off of the FAD.

7.5. FRACTURE MECHANICS VARIABLES USED

K_I is used in all levels of analysis irrespectively of their complexity.

7.6. SAFETY FACTORS AND RISK ASSESSMENT

In Levels 1 and 2 no indication is made on how to obtain the existing safety margins.

For Level 3 the reserve factors are defined in a similar way to the procedures based on the FAD. Also, Section 9.4.4.8 requires the performance of a sensitivity study.

7.7. FRACTURE MODE

Only Mode I load is mentioned through the standard. No reference is made to the study of load mode combinations.

7.8. STRESS DEFINITION

Stresses are defined in-depth in Appendix B and recommendations are made for taking the correct values. Table B-2 summarises the information given throughout the appendix.

Primary and secondary stresses are well differentiated, stating that, when in doubt any stress is considered as primary.

For residual welding stresses, Section 9.3.5.5 refers to Appendix E where a series of guidelines are provided for estimating the value of such stresses.

7.9. FORMULATION CATALOGUE

The formulation catalogue is covered in the following appendices:

- Appendix C: Solutions for K_I .
- Appendix D: Solutions for limit load (in preparation).

7.10. DEFINITION OF MATERIAL MECHANICAL BEHAVIOUR

The material properties are defined in Appendix F, describing how to correctly obtain the yield stress and the ultimate strength (refers to ASTM Standards).

Section F.2.2 indicates how to obtain the value of the most adequate flow stress in each case.

7.11. FRACTURE TOUGHNESS DEFINITION

Covered in Appendix F and referenced to the ASTM Standards. The appendix also covers the relations necessary for transforming any toughness variable into K.

Correlations are available for obtaining toughness values from Charpy tests.

7.12. CRACK CHARACTERISATION

Section 9.1.5 covers the modelling of planar cracks, classifying them as surface, embedded and through-thickness. Subsection 3 of this point also establishes the possibility of the interaction between nearby cracks.

Other sections of the Standard cover different types of defects: general metal loss (Section 4), local thin areas (Section 5), pitting corrosion (Section 6), blisters and laminations (Section 7) and groove-like flaws (Section 8).

7.13. CRACK EVOLUTION AND RECHARACTERISATION

Section 9.5 clearly states that documents such as PD6493, R6, EPRI and ASTM are focused on other needs. Therefore, the subject of subcritical crack growth is especially dealt with in these API Standards: Section 9.5.1. Subcritical crack growth - Assessment for permissible crack growth and remaining life.

Section 9.5.2 analyses the problem of Leak before Break.

7.14. WELDING

There are only two specific sections on welding effects. First, as it has been mentioned, the residual stresses due to welding are estimated (Appendix E). Second, the evaluation of misalignments in welds are covered in Section 10.

7.15. STRESS FIELD CONDITIONS

No special considerations appear relative to stress field and its consequences.

8. GE-EPRI

8.1. GENERAL

The EPRI Report of 1981 rather than representing a calculation procedure is a working methodology which, at first sight, is applicable to any cracked structure if the necessary solutions for its analysis are available (Section 1.1).

Therefore, the EPRI Approach should not be understood as a procedure lacking appendices and specific situations. Instead, it should be considered as the basis of a useful philosophy which needs new complementary developments.

8.2. MATERIALS LIMITATION

There are no limitations in terms of materials that can be covered by this type of analysis. The material should normally be adjusted as correctly as possible to a Ramberg-Osgood law because most of the solutions developed from the theoretical formulae described through the report are based on this kind of modelling (Sections 2.2.1 and 3.2.2). Nevertheless, there are other estimation formulae for several different stress-strain laws in Appendix A.

As is common to most procedures, the examples presented in the report are two steels which leads to the belief that there is a certain preference for metallic materials.

8.3. STRUCTURAL ANALYSIS METHODOLOGY

The philosophy of the method consists of comparing the applied J-integral (or also the CTOD) as a function of crack length, with the analogous resistance curve. This analysis can be made using three possible representations (Section 2.5):

- Crack Driving Force Diagram (Section 6). It is basically a plot of the J-integral or the CTOD versus crack length and applied load (or displacement). If it is used together with the material J-resistance curve (J_R), a complete history of deformation and crack growth behaviour is predicted.
- Stability Assessment Diagram (Section 7). It is a plot of the tearing modulus as a function of the relevant flaw and structure parameters (e.g. J-integral). This kind

of diagram could be considered as a compression of the information contained in the Crack Driving Force Diagram.

- Failure Assessment Diagram (Section 8). Paraphrasing Section 8.1, “in essence, a Failure Assessment Diagram represents a transition curve or interpolation between two distinctly separate mechanisms of failure: brittle fracture governed by the LEFM defined fracture toughness and plastic collapse governed by the limit load. The region bounded by the axes and the failure line is the safe regime”.

8.4. CRITICAL CONDITIONS ANALYSED

Fracture

Referring to the critical conditions that the method considers, it must be said that both initiation (for simple situations) and propagation are analysed and, as has just been said, the CDF represents the complete history of the ductile tearing process.

Plastic collapse

In the case of using the CDF representation, we are dealing with a non-integrated method. Hence, the plastic collapse of the remaining section has to be considered separately and as another critical conditioner. However, the method does not categorically reflect this although the existing formulation quantifies it.

8.5. FRACTURE MECHANICS VARIABLES USED

The J-integral is generally used. However, in some of the simpler situations it is possible to use techniques based on CTOD and K_I .

8.6. SAFETY FACTORS AND RISK ASSESSMENT

The EPRI Report does not make any reference to safety factors as they are classically understood, that is, maximisation of forces and minimisation of characteristics. Neither does it present the possibility of performing statistical or sensitivity studies.

8.7. FRACTURE MODE

Throughout the method there are no comments about the fracture mode. The calculation philosophy is not necessarily linked in with Mode I loading (even when it is the most common) but rather it is also valid for loading combinations. In fact, in reference [2], solutions which combine Modes I and II appear.

8.8. STRESS DEFINITION

Neither are there specific sections or appendices relating how to characterise the different stresses produced by the different loads. There is no absolute difference in the treatment of primary and secondary stresses nor are there any details on how to consider residual or preload stresses throughout the original report.

However, further publications [13] have developed the incorporation of secondary stresses in the EPRI Approach.

8.9. FORMULATION CATALOGUE

The original EPRI Report includes an extensive series of solutions for laboratory specimens and cracked cylinders. Later, publications [2] have been developed which complement the handbook of the first report.

8.10. DEFINITION OF MATERIAL MECHANICAL BEHAVIOUR

There is no specific point which defines the mechanical characteristics of the material, nor are the Standards referred to. For most of the solutions developed from the theoretical background of the approach, it is assumed that the material's tensile behaviour fits a Ramberg-Osgood law.

The handbooks produced after the original report explicitly mention the material's mechanical parameters, and thus, the yield stress is considered to be equal to the reference stress (σ_0) of the Ramberg-Osgood law, and the flow stress is considered as the average between the yield stress and the ultimate tensile strength except if there are experimental results which justify another value.

8.11. FRACTURE TOUGHNESS DEFINITION

Section 2.2.2 defines the J_R curve as the fracture resistant parameter, but it does not make any reference on how it is obtained nor to any Standard.

8.12. CRACK CHARACTERISATION

There is no specific section where a classification of flaws is described. All the solutions analysed through the Procedures Review has been part-through or through cracks. The University of Cantabria has not worked with any embedded defect.

8.13. CRACK EVOLUTION AND RECHARACTERISATION

There are no comments relative to any subcritical crack growth, therefore, fatigue, stress corrosion cracking, or any other mechanical or environmentally induced cracking processes, are not considered.

The method does not take into account the possibility of recharacterising a crack that changes its physical characteristics during its propagation, for example, passing from embedded to surface or from surface to through-thickness.

Leak Before Break situations are not evaluated in any specific way.

8.14. WELDING

The EPRI Approach does not contemplate the particularities associated to welding processes and, therefore, does not consider, in any section, specific procedures which analyse, for example, residual stresses or effects caused by the heterogeneity of the materials (mis-match).

8.15. STRESS FIELD CONDITIONS

The formulation derived from the EPRI Approach only considers plane strain and plane stress situations. There are different variables ("h" functions and " β " parameter) which take into account these two stress field conditions. These variables have different values whether plane strain or plane stress conditions are satisfied.

There are no references to constraint effects through the method.

9. ETM

9.1. GENERAL

In this section no analysis is made of only one assessment procedure, rather two are studied together.

- EFAM ETM 95: The Engineering Treatment Model Method for assessing the significance of crack-like defects in engineering structures. General procedure.
- EFAM ETM MM 96: The Engineering Treatment Model Method for assessing the significance of crack-like defects in joints with mechanical heterogeneity (strength mis-match). Specific procedure.

9.2. MATERIALS LIMITATION

In Section 1 of EFAM ETM 95, the applicability of the method is limited to homogenous metallic materials and welds, logically recommending, that in cases of mis-match, the evaluation be made through the above mentioned specific procedure.

9.3. STRUCTURAL ANALYSIS METHODOLOGY

Based on the use of Crack Driving Force Diagrams (Section 3.1.1).

9.4. CRITICAL CONDITIONS ANALYSED

Fracture

The general procedure distinguishes different critical conditions for the end-of-life of a component (Section 2.2):

- Initiation of unstable crack extension without substantial prior crack growth.
- Initiation of unstable crack extension without taking into account of possible prior stable crack growth.
- Initiation of stable ductile crack growth.

- Unstable ductile crack growth.
Plastic collapse

There are many references throughout the method relative to plastic collapse consideration. These comments sometimes are a little confusing because it is not clear whether they are related to the net section or to the gross section.

9.5. FRACTURE MECHANICS VARIABLES USED

Initially, the variable to use is K_I , from which δ_5 (crack measurement based on an initial size of 5 mm), classical CTOD or J can also be obtained.

9.6. SAFETY FACTORS AND RISK ASSESSMENT

There is no specific point in the method which studies and defines safety factors. Section 3.1.3 states that the use of safety factors is at the user's discretion.

Reserve factors are mentioned but not defined throughout the method although Figures 3.22 and 3.25 explain how to graphically obtain them. However, there are no factors which could guarantee conservativeness nor are there associated sensitivity studies.

9.7. FRACTURE MODE

In Section 3.2.2.4 the general procedure mentions the considered load modes. It permits the combination of Modes I and II but never mentions Mode III.

9.8. STRESS DEFINITION

No special recommendations are made on the overall stress state except in Section 3.2.1.2.1 in which three types of stresses are mentioned (mechanical, thermal and residual) which are assumed to be linear and are added together.

As seems logical after what has just been said, no distinction is made between how to treat primary and secondary stresses.

Residual welding stresses are considered in Section 3.2.1.2.2, defining recommendable values for the user in the case of not knowing the real values and establishing the fundamental guidelines for their inclusion in the structural evaluation.

9.9. FORMULATION CATALOGUE

The solutions catalogue for K_I and the limit load for different configurations are covered in Appendix 2. Section 3.2.1.4 mentions that, for cases not considered in the Appendix, other handbooks (referenced in the method) may be consulted.

9.10. DEFINITION OF MATERIAL MECHANICAL BEHAVIOUR

The material mechanical parameters (σ_y and σ_u) are referred to ESIS and the ASTM Standards (Section 1). Flow stress is not used in this method.

The stress-strain curve is modelled through a piece-wise power law (Section 3.1.2). For some materials it may not be appropriate to fit a single power law for describing the hardening behaviour. In such cases, a double power law fit may be used as described in Appendix 3.

9.11. FRACTURE TOUGHNESS DEFINITION

The user is referred to ESIS and ASTM Standards.

Section 3.2.4.1 states that guidelines are provided in Appendix 5 (not available) for transferring the toughness values obtained in the laboratory to their corresponding values in the structural components.

9.12. CRACK CHARACTERISATION

The three classic typologies are covered: embedded, surface and through-thickness, all of which are planar. The cases of non-planar cracks may be analysed after their projection onto the plane where the maximum normal stress acts (Section 3.2.1).

The possible interaction of neighbouring cracks is also mentioned.

9.13. CRACK EVOLUTION AND RECHARACTERISATION

No mention is made about possible forms of subcritical crack growth and their evaluation.

9.14. WELDING

Apart from what relates to the study of residual stresses and their quantification in the general procedure, the effect of welding and associated problems (mis-match) are dealt with in-depth in the procedure developed specifically for this purpose (EFAM ETM MM 96).

9.15. STRESS FIELD CONDITIONS

The cracked component is assumed to deform under prevailing plane stress conditions. This assumption may tend to overestimating the driving force if non-plane strain conditions are present.

If, however, it can be demonstrated that plane strain appropriately characterises the component, then guidance is provided on how to take advantage of its effects on δ_5 or J (Section 3.1.2).

10. ASME XI

10.1. GENERAL

Literally, "Section XI, Rules for Inservice Inspection of Nuclear Power Plant Components, of the ASME Boiler and Pressure Code provides requirements for examination, testing and inspection of components and systems, and repair/replacement activities in a nuclear power plant" (Section A95: Introduction).

10.2. MATERIALS LIMITATION

Firstly, it must be mentioned here that the exhaustive treatment of materials is dealt with in the ASME II.

The only noteworthy point in ASME XI about this item is that it has several appendices dealing with different materials, for example:

- Appendix H: Ferritic piping.
- Appendix C: Austenitic piping.
- Subsection IWL: Concrete components.

10.3. STRUCTURAL ANALYSIS METHODOLOGY

Rigorously speaking none exists. It uses tables and limit curves which can be contrasted with the real situations.

10.4. CRITICAL CONDITIONS ANALYSED

Fracture

The analysis is generally based on linear elastic fracture mechanics -LEFM- (Appendix A) although for certain materials and structures there are also other types of analysis based on elastoplastic fracture mechanics -EPFM- (Appendices C and H).

Plastic collapse

There are recommendations on the evaluation of the plastic collapse, but it is not clear on the type of limit load to be considered.

10.5. FRACTURE MECHANICS VARIABLES USED

K_I is always used except in cases where elastoplastic analysis can be made.

10.6. SAFETY FACTORS AND RISK ASSESSMENT

The safety factors maximise loads and minimise resistance parameters, covering four different events: normal, upset, emergency and faulted.

10.7. FRACTURE MODE

It only refers to mode I, but modes may be combined if justified.

10.8. STRESS DEFINITION

The stresses are studied in-depth in the ASME Section III. The following observations can be pointed out:

- The code clearly defines how to calculate the different stresses. In fact, this code is referenced in other methods, e.g. Exxon fitness-for-service.
- It differentiates between primary and secondary stresses.
- It does not evaluate residual stresses.
- It does not take into account the effects of prior overloads or proof tests.

10.9. FORMULATION CATALOGUE

Solutions appear throughout the method for the most common cases.

10.10. DEFINITION OF MATERIAL MECHANICAL BEHAVIOUR

The material's mechanical characteristics are clearly defined but no references are made to official Standards throughout ASME XI code.

Given the methodology of the analysis (comparison with critical table or figures), it is not necessary to use any type of fitting function for the stress-strain curve.

10.11. FRACTURE TOUGHNESS DEFINITION

The parameters K_{Ia} and K_{Ic} , obtained from an experimental approach dependent on RT_{NDT} (Section A-4200), are used.

10.12. CRACK CHARACTERISATION

The ASME code presents the crack characterisation that all the other procedures use (IWA-3300) and that has already been widely mentioned. It also includes guidelines for considering the interaction of neighbouring defects.

Offers the possibility of analysing non-planar defects.

10.13. CRACK EVOLUTION AND RECHARACTERISATION

Fatigue propagation is considered as a general material property. For certain structures and materials, fatigue, stress corrosion cracking and fatigue-corrosion are evaluated.

It does not consider the recharacterisation of cracks due to growth and changes in geometric properties nor does it have procedures for assessing Leak Before Break situations.

10.14. WELDING

No special mention is made about welding and associated problems except in Appendix D, where welded joints in pipes are mentioned but not analysed in any detail.

10.15. STRESS FIELD CONDITIONS

The code does not make any reference to different stress field conditions nor their consequences.

It neither refers to any kind of constraint effects.

11. SUMMARY TABLES

This section presents a compendium of tables which summarises the main characteristics of the procedures described throughout this second chapter.

The items that have been summarised here are:

- I. General.
- II. Materials limitation.
- III. Structural analysis methodology.
- IV. Critical conditions analysed.
- V. Fracture mechanics variables used.
- VI. Safety factors and risk assessment.
- VII. Fracture mode.
- VIII. Stress definition.
- IX. Formulation catalogue.
- X. Definition of material mechanical behaviour.
- XI. Fracture toughness definition.
- XII. Crack characterisation.
- XIII. Crack evolution and recharacterisation.
- XIV. Welding.
- XV. Stress field conditions.

I. GENERAL

PROCEDURE	COMMENTS
R6	• General (Foreword and Section 2.1). • But apparently directed towards the power generation industry.
PD6493	• General (Section 7). • But apparently specializes in welding (numerous appendices). • Special appendices for certain applications: * Offshore structures (Appendix L). * Pressure Vessels and Pipelines (Appendix M).
SAQ	• Initially developed for the nuclear industry. • But used in other branches. • Based on the R6 Method (Section 1). • Objective: Safe rather than accurate analysis (Appendix B).
EXXON	• Besides being a calculation procedure, also for inspection (Section 1.0). • Based on the BSI PD6493 (Section 8). • Only applicable for pressure vessels, storage tanks and piping.
MPC	• Besides being a calculation procedure, also for inspection (Section 1.1). • Only applicable for pressure vessels, tanks and piping.
API 579	• Besides being a calculation procedure, also for inspection (Section 1.2). • Only applicable for pressure vessels, piping and tankage.
GE-EPRI	• Rather than a calculation procedure is a working methodology. • At first sight, applicable to any cracked structure (Section 1.1).
ETM	• Procedure 1: General. • Procedure 2: Specific applications for mis-match problems.
ASME XI	• Directed to activities in a nuclear power plant (Section A95).

II. MATERIALS LIMITATION

PROCEDURE	COMMENTS
R6	• No specified limitations. • Although apparently valid for any material, there is certain preference for metallic materials (Section 6).
PD6493	• No specified limitations. • Although apparently valid for any material, there is certain preference for metallic materials (Section 12.2).
SAQ	• For any metallic material, although most valid for steel alloys (Section 1).
EXXON	• No specified limitations, but oriented to metallic materials.
MPC	• Limited to low-alloy, austenitic and carbon steels (Section 1.2).
API579	• No specified limitations. • Although apparently valid for any material, there is certain preference for metallic materials (Section 6).
GE-EPRI	• No specified limitations. • The stress-strain curve should be modelled as correctly as possible.
ETM	• Limited to homogeneous metallic materials and welds.
ASME XI	• Treatment of materials: Section II (not available). • Special appendices for certain materials: ferritic, austenitic and concrete.

III. STRUCTURAL ANALYSIS METHODOLOGY

PROCEDURE	COMMENTS
R6	- Based on FAD. 3 different FAD lines (Section 6). * General. * Specific. * Based on J.
PD6493	- Based on FAD. 3 different FAD lines (Sections 11.2 and 12.2). * General. * Specific. * Based on J.
SAQ	- Based on FAD. 1 FAD line: Default curve of the R6 Method.
EXXON	- Based on FAD. - Uses default curves of the PD6493 procedure.
MPC	- Based on FAD. 2 different FAD lines (Section 8.5). * General. * Based on J.
API 579	- Based on FAD. - Uses general curves or preliminary assessments analogous to PD6493.
GE-EPRI	- Directed at using Crack Driving Force Diagrams (Section 6). - FAD and SAD (Stability Assessm. Diagr.) also available (Sections 7 and 8).
ETM	Based on the use of Crack Driving Force Diagrams (Section 3.1.1).
ASME XI	- Rigorously none exists. - Uses tables and limit curves which can be contrasted with the real situation.

IV. CRITICAL CONDITIONS ANALYSED

Fracture and Plastic Collapse

PROCEDURE	COMMENTS
R6	3 categories (Section 7): * Category 1: Initiation. * Category 2: Ductile tearing (discrete). * Category 3: Ductile tearing (continuous). - Plastic collapse is considered in the definition of the cut-off. - Limit load is defined (Section 2 and Appendix 2) as “local” for part-through cracks and “global” for through-thickness cracks.
PD6493	3 levels: * Level 1: Preliminary assessment (Section 10). Initiation. * Level 2: Normal assessm. (Sect. 11). Initiation or limited ductile tearing. * Level 3: Advanced assessment (Section 12). Full ductile tearing. - Plastic collapse is considered in the definition of the cut-off. - Collapse is defined (Section 7) and extended in Appendix 7 where it differentiates between local and global collapse.
SAQ	- Only considers crack initiation. - Plastic collapse is considered in the definition of the cut-off. - Limit load is defined in Section 2.8 and explained in Appendix B.
EXXON	References PD6493.
MPC	- Only considers crack initiation. - Plastic collapse is considered in the definition of the cut-off.
API 579	- Only considers crack initiation. - Plastic collapse is considered in the definition of the cut-off.
GE-EPRI	- CDFD can be used to address initiation and ductile tearing up to instability. - Plastic collapse must be calculated independently of the method.
ETM	- Considers different critical conditions: * Initiation of unstable crack extension without prior crack growth. * Identical but without taking into account prior stable crack growth. * Initiation of stable ductile crack growth. * Unstable ductile crack growth. - There are many references to plastic collapse consideration related to both the net section and the gross section.
ASME XI	- Analysis based on LEFM, although for certain situations EPFM can be used. - Recommendations are given for the evaluation of plastic collapse, but it is not clear on the type of limit load to be considered.

V. FRACTURE MECHANICS VARIABLES USED

PROCEDURE	COMMENTS
R6	• K_I. • Except for FAD3, needs to be known the applied J-integral.
PD6493	• K_I or CTOD. • Except for FAD3, needs to be known the applied J-integral.
SAQ	• K_I.
EXXON	• References PD6493.
MPC	• K_I is the normal analysis parameter. • Also permits the use of CTOD and J-integral.
API 579	• K_I.
GE-EPRI	• J-integral. • Possible to use techniques based on CTOD and K_I for simpler situations.
ETM	• Initially K_I, from which, δ_5 or J can be obtained.
ASME XI	• K_I.

VI. SAFETY FACTORS AND RISK ASSESSMENT

PROCEDURE	COMMENTS
R6	• Does not use safety factors for input data. • Reserve factors are defined for all the categories of analysis. • Sensitivity analysis proposed (Section 12). • Probability studies are possible (Appendix 10).
PD6493	• Safety factors for materials characteristics (Appendix A). • Inherent safety factors for the first level analysis. • For the rest, recommendations are made in Appendix Q. • Sensitivity analysis defined.
SAQ	• Safety factors referring to ASME codes (Appendix P). • Reserve factors identical to R6 Method (Section 2.11).
EXXON	• References PD6493.
MPC	• Reserve factors are defined, analogous to R6, PD6493 and others. • Sensitivity analysis recommended (Section 8.6).
API579	• There are no indications for levels 1 and 2. • For level 3, reserve factors are defined. • Section 9.4.4.8 details the sensitivity studies for such factors.
GE-EPRI	• No observations on safety factors nor reliability and sensitivity study. • No probability studies.
ETM	• Use of safety factors is at the user's discretion. • Reserve factors are mentioned but not defined.
ASME XI	• Different safety factors depending on the type of event.

VII. FRACTURE MODE

PROCEDURE	COMMENTS
R6	- Developed preferably for Mode I (Section 3.1). - Permits combination of Modes (I, II and III) (Appendix 7).
PD6493	- Developed preferably for Mode I (Section 7). - Permits combination of Modes (I, II and III) (Appendix I).
SAQ	Only mentions Mode I loading.
EXXON	References PD6493.
MPC	- Mode I loading is assumed (Section 5.2.1). - Permits combination of Modes I and II (Appendix F).
API 579	Only mentions Mode I loading.
GE-EPRI	Although the calculation philosophy is also valid for the combination of modes, there are very limited solutions for those other than mode I.
ETM	- The considered load modes are mentioned in Section 3.2.2.4. - Permits the combination of Modes I and II.
ASME XI	Only mentions Mode I loading.

VIII. STRESS DEFINITION

Global state / Primary-Secondary stresses / Residual stresses / Prestresses

PROCEDURE	COMMENTS
R6	- The analysis should produce upper bound values of stress (Section 5.1). - Considers different categorisation of stresses (Section 5.2). - Considered and quantified in Appendix 12. - Appendix 13 takes into account the effects of Load-History effects.
PD6493	- Overall stress state defined in Sections 8.1-8.3. - Considers different categorisation of stresses. - Evaluated and extra appendix (C) for as-welded joints. - Appendix K should consider these effects but it is not available.
SAQ	- Software available to calculate distribution of stresses (Appendix B). - Considers different categorisation of stresses (Section 2.4). - Guidance about residual stresses for welded joints: Appendix E. - No observations.
EXXON	- Defined in Sections 6 and 8. - Differentiated semantically but not in the calculation (Section 8.1.2). - Mentioned in Section 8.2. - No observations.
MPC	- Defined in Section 8.2.1, recommends the use of Finite Elements Analysis. - Considers different categorisation of stresses (Section 8.2.1). - Considered in the calculation guide (Section 8.2.1). - No observations.
API 579	- Defined in Appendix B. - Considers different categorisation of stresses. - Appendix E provides guidelines for estimating such stresses. - No observations.
GE-EPRI	- Does not present any recommendation. - Does not differentiate between stress categories. Further publications do it. - No observations. - No observations.
ETM	- Does not present any recommendation. - Does not differentiate between stress categories. - Are considered and estimated in Section 3.2.1.2.2. - No observations.
ASME XI	- Clearly defines how to calculate the stresses. - Differentiates primary and secondary stresses. - Residual stresses are not evaluated. - No observations.

IX. FORMULATION CATALOGUE

PROCEDURE	COMMENTS
R6	• As such, no handbook available. • Numerous references of limit load solutions are given in Appendix 2. • Numerous references of SIF solutions are given in Appendix 3. • Software exists but it is not included in UC's information.
PD6493	• Appendix E: Stress Intensity Factor Solutions. • Appendix F: Limit Load Solutions.
SAQ	• Appendix G: Geometries. • Appendix K: Stress Intensity Factor Solutions. • Appendix L: Limit Load Solutions.
EXXON	• Reference PD6493.
MPC	• Appendix B: Stress Intensity Factor Solutions. • Appendix C: Limit Load Solutions.
API 579	• Appendix C: Stress Intensity Factor Solutions. • Appendix D: Limit Load Solutions (in preparation).
GE-EPRI	• Original report: Solutions for laboratory specimens and cracked cylinders. • Further publications have complemented the handbook.
ETM	• Handbook: Appendix 2. • Other handbooks may be consulted (Section 3.2.1.4).
ASME XI	• Provides solutions for the most common cases throughout the method.

X. DEFINITION OF MATERIAL MECHANICAL BEHAVIOUR

PROCEDURE	COMMENTS
R6	• Defines σ_y and σ_u and refers to Standards (Section 8.2). • Flow Stress: average except when a higher value is justified. • Indirect methods may be used if applicable (Section 8.2.3).
PD6493	• σ_y and σ_u are referenced to Standards. • Flow Stress: average.
SAQ	• σ_y and σ_u are defined (Section 2.5) but not referenced to Standards. • Flow Stress: not used in this method but assumed to be the average. • Information of values for most steels used are given in Appendix M.
EXXON	• The values which appear in the certifications should be taken as σ_y and σ_u. • Flow Stress: average but limited to $1.2 \sigma_y$.
MPC	• σ_y and σ_u are only mentioned in the list of symbols. • Flow stress: average or σ_y plus 10 ksi.
API 579	• Material properties defined in Appendix F and referred to Standards. • Section F.2.2 indicates how to obtain the most adequate flow stress value.
GE-EPRI	• σ_y and σ_u not referenced to Standards. • Flow Stress: average except when another value is justified experimentally. • R-O: obligatory because most of the formulae are based on this modelling.
ETM	• σ_y and σ_u are referenced to Standards (Section 1). • Flow Stress: not used in this method. • Stress-strain curve modelled through a piece-wise power law (Section 3.1.2). • Possibility of double power law fit (Appendix 3).
ASME XI	• σ_y, σ_u and σ_f are clearly defined but not referenced to Standards.

XI. FRACTURE TOUGHNESS DEFINITION

PROCEDURE	COMMENTS
R6	- Defined and referenced to Standards (Section 8.1.1). - Recommendations for determining the toughness value are given in App. 1. - Appendix 1 also references some correlations with Charpy.
PD6493	- Referred to Standards. - Guidelines for determining the correct toughness value are given in App. A. - Appendix B details some correlations with Charpy test data.
SAQ	- References Standards (Section 2.5). - Appendix M presents some values for different materials.
EXXON	- Defined and referenced to Standards (Section 5). - Sections 5.4 and 5.5 detail different indirect methods.
MPC	Referred to Standards (Section 8.2.3).
API 579	- Referred to Standards (Appendix F). - Correlation from Charpy tests are available.
GE-EPRI	Section 2.2.2 defines the J_R curve, but it does not refer to Standards.
ETM	References Standards.
ASME XI	K_{IC} obtained from experimental approaches.

XII. CRACK CHARACTERISATION

PROCEDURE	COMMENTS
R6	• 3 types: embedded, surface and through-thickness (Section 9). • Only mentions planar flaws. • Considers the interaction of neighbouring cracks.
PD6493	• 3 types: embedded, surface and through-thickness (Section 8.4). • Section 13 presents indications for non-planar flaws and imperfect shapes. • Mentions the interaction of neighbouring cracks.
SAQ	• 3 types: embedded, surface and through-thickness (Appendix A). • Only mentions planar flaws. • Mentions the interaction of neighbouring cracks.
EXXON	• References PD6493. • Special assessment for real cracks (Section 4.3).
MPC	• 3 types: embedded, surface and through-thickness (Section 5.2). • Only mentions planar flaws. • Mentions the interaction of neighbouring cracks. • Recommendations for real cracks are given (Sections 5.3-5.6).
API 579	• 3 types: embedded, surface and through-thickness (Section 9.1.5). • Only mentions planar flaws. • Mentions the interaction of neighbouring cracks. • Recommendations for real cracks are given (Sections 4-8).
GE-EPRI	• No recommendation for modelling defects.
ETM	• 3 types: embedded, surface and through-thickness. • Non-planar flaws can be analysed (Section 3.2.1). • Mentions the interaction of neighbouring cracks.
ASME XI	• 3 types: embedded, surface and through-thickness (IWA-3300). • Non-planar flaws could be decomposed over principal axes. • Mentions the interaction of neighbouring cracks.

XIII. CRACK EVOLUTION AND RECHARACTERISATION

PROCEDURE	COMMENTS
R6	• Permits recharacterisation of cracks: embedded to surface to through-thickness (Section 9.3.2). • App. 6 contains information relative to other processes of subcritical crack growth (fatigue and environmentally assisted). • Leak Before Break procedure: Appendix 9.
PD6493	• Permits recharacterisation of cracks: embedded to surface to through-thickness (Section 8.4.3 and Appendix G). • No references found in UC's information to other subcritical crack growths except in Appendix L (fatigue in offshore applications). • Leak Before Break procedure: Appendix J.
SAQ	• Does not mention recharacterisation of cracks owing to growth. • Recommendations are given for defects when they go beyond the applicability of their typology (Section 2.7). • Section 2.6 briefly comments on fatigue and SCC and refers to Appendix M. • No LBB procedure.
EXXON	• Does not mention recharacterisation of cracks owing to growth. • No references to other subcritical crack growths. • No LBB procedure.
MPC	• Subcritical crack growth and Leak Before Break situations are covered in-depth in Section 9. • Section 5.2.3: Recommendations for difficult to measure cracks.
API 579	• Subcritical crack growth especially analysed in Section 9.5.1. • Section 9.5.2 analyses Leak Before Break.
GE-EPRI	• Does not mention recharacterisation of cracks owing to growth. • No references to other subcritical crack growths. • No LBB procedure.
ETM	• Does not mention recharacterisation of cracks owing to growth. • No references to other subcritical crack growths. • No LBB procedure.
ASME XI	• Does not mention recharacterisation of cracks owing to growth. • No references to other subcritical crack growths. • No LBB procedure.

XIV. WELDING

PROCEDURE	COMMENTS
R6	- Residual stresses are quantified in Appendix 12. - Appendix 16 presents a specific procedure for mis-match situations.
PD6493	- Special appendices for welding effects. * Appendix C: Residual stresses. * Appendix D: Stress due to misalignment. * Appendix H: Mis-match. * Appendix N: Weld Heat Affected Zones.
SAQ	- Base material to be used when there is a crack in a weld. - Appendix E quantifies the residual stresses due to welds. - No specific procedures for mis-match situations.
EXXON	No special mentions about welding, except residual stress quantification.
MPC	K_I solutions are given for cracks close to fillet welds in Appendix B. - Residual stresses due to welds are considered.
API 579	- Residual stresses due to welds are estimated (Appendix E). - Evaluation of misalignments is covered in Section 10.
GE-EPRI	No mentions to any kind of welding effects.
ETM	Special Report: EFAM ETM-MM 96 (Draft).
ASME XI	No special mentions are made.

XV. STRESS FIELD CONDITIONS

PROCEDURE	COMMENTS
R6	• In the case of needing to choose a limit load, plane stress is recommendable. • Appendix 14 analyses the influence of constraint effects.
PD6493	• Special considerations are not made for situations of plane stress/strain. • No mentions of constraint effects.
SAQ	• Special considerations are not made for situations of plane stress/strain. • No mentions of constraint effects.
EXXON	• Special considerations are not made for situations of plane stress/strain. • No mentions of constraint effects.
MPC	• Section 8.4 states that plane stress or strain have little importance if both applied and resistant values are considered coherently.
API 579	• Special considerations are not made for situations of plane stress/strain. • No mentions of constraint effects.
GE-EPRI	• Formulation depends on stress field conditions through different variables ("h" functions and "β" parameter). • No mentions of constraint effects.
ETM	• The cracked component is assumed to deform under plane stress conditions. • If it can be demonstrated that plane strain characterises the component,
ASME XI	• Special considerations are not made for situations of plane stress/strain. • No mentions of constraint effects.

III. EXAMPLES RUN

INITIAL CONSIDERATIONS

Part of the work done by the University of Cantabria has been to run specific examples using each of the procedures being assessed. These examples are not intended to validate each procedure, rather they are seen as support material for the critical analysis made on the methods which have been provided by the consortium members.

Up until the time of this report five examples have been assessed with the following goals in mind:

- Verify that each method has been correctly interpreted by calculating an example from the bibliography (Example 1).
- Compare the relative conservativeness between the methods (Examples 1 and 5).
- When the methods allow, perform a Leak Before Break analysis using previous work done by the University of Cantabria (Example 2).
- Analyse a welded joint in order to find out how they are treated by each method (Example 3).
- Compare FADs derived from different materials and at different levels of analysis (Example 4).
- Check the absolute conservativeness of each method with respect to real tests (Example 5).

As the examples were proposed sequentially, some of them were elaborated as a consequence of the ones done before.

Both in Example 1 and Example 5, when the relative and absolute conservativeness were compared, no attempt was made to draw general conclusions, rather only to compare the procedures when they were subjected to a type of calculation.

For simplification, from now on, the different types of FAD will be known as:

- Default $\equiv$ FAD 1.
- Specific $\equiv$ FAD 2.
- Based on J $\equiv$ FAD 3.

The running of each example is presented in the following sections including the corresponding results and conclusions which, generally, cannot be extrapolated to other situations.

1. EXAMPLE 1

This example was chosen to check that the methods being studied had been interpreted correctly. It was taken from a European Group of Fracture publication [13].

1.1. DEFINITION

Aluminium pipe with a through-thickness circumferential crack subjected to uniformly distributed axial loading or bending moment. For both types of loading the idea was to find the critical value provoking breakage. The geometrical definition of the tube, shown in Figure 1.1, is completed with the following:

- Geometrical dimensions:
 - Length 10 m
 - Outer diameter 300 mm
 - Thickness 10 mm
 - Crack length, 2c 80 mm
- Mechanical characteristics:
 - 0.2 per cent proof strength 165 MPa
 - Tensile strength 310 MPa
 - Young's modulus 70000 MPa
 - The material's true stress-strain curve is modelled by a Ramberg-Osgood fitted curve with the following mathematical expression:

$$\frac{\varepsilon}{\varepsilon_0} = \frac{\sigma}{\sigma_0} + \alpha \cdot \left(\frac{\sigma}{\sigma_0} \right)^n$$

where:

$$\sigma_0 = 165 \text{ MPa}$$

$$\varepsilon_0 = 0.00236$$

$$\alpha = 1.029$$

$$n = 4.96$$

- Fracture toughness:

$$- \delta = 0.184 (\Delta a)^{0.512}$$

where δ and a are expressed in mm.

1.2. CALCULATIONS AND RESULTS

As shown in the definition of the example, two calculation processes have been performed to determine the maximum critical axial load and the maximum bending which the tube can withstand before breaking.

1.2.1. Calculation of critical axial load

This was calculated using the following methods and options:

- R6 Method: Categories 2 and 3, using all types of FAD.
- BSI PD6493: Level 3, using all types of FAD.
- GE-EPRI.
- EFAM ETM 95.

The numerical results of the critical load for each procedure and the options studied are shown in Table 1.1. The graphic results obtained using R6, Categories 2 and 3, are presented in Figures 1.2 and 1.3, respectively. For Category 2 the resulting point after ductile tearing does not coincide with the FAD because the method itself imposes a partial safety coefficient, due to the simplification of the calculations in this option. The graphic result following PD6493 coincides with that of R6 as can be seen in Figure 1.3, since, in this case, both methods are equivalent at their highest level of analysis. The Crack Driving Force Diagrams corresponding to the EPRI and ETM methods are shown in Figures 1.4 and 1.5, respectively. Finally, all the results obtained for every procedure are graphically compared in Figure 1.6.

1.2.2. Calculation of critical bending moment

This case has been calculated using the following methods and options:

- R6 Method: Category 3, using FAD types Default and Specific.

- BSI PD6493: Level 3, using FAD types Default and Specific.
- GE-EPRI: Crack Driving Force.
- EFAM ETM 95: Crack Driving Force based on K_I .

The critical values predicted by each procedure for the maximum bending moment are shown in Table 1.2. This table also shows that both R6 and PD6493 coincide, as in the previous case, as they are equivalent at these levels of analysis. The graphic results for R6 and PD6493 are presented in Figure 1.7 for FADs 1 and 2. The results for EPRI and ETM are presented in Figures 1.8 and 1.9, respectively. A graphic comparison of the obtained results is presented in Figure 1.10.

1.3. CONCLUSIONS

This example was initially proposed to check that the methods had been correctly interpreted as well as to compare their relative conservativeness. However, apart from fulfilling these objectives, the following series of additional conclusions can be drawn for this example:

- The example was solved separately by two users. The differences in the final results for all the completed methods and options were never greater than 2%. No tendency towards error was noticed.
- In the methods that use FADs, the criteria which only contemplate crack initiation or slight tearing (e.g., R6, Category 2), are more conservative than those which fully consider ductile tearing (e.g., R6, Category 3; PD6493, Level 3).
- Methods based on the same criterion, initiation or ductile tearing in the FAD, or ductile tearing in the CDF, produce similar results because the deviation of the results is less than 10% for any of the mentioned criteria.
- The maximum axial loads obtained from FAD 2 (Specific) by applying both R6 and PD6493, are less conservative than those obtained using FAD 3 (Based on J). This occurs at two levels of analysis, Categories 2 and 3 and, as can be seen in Figure 1.11, is because FAD 3 is more conservative than FAD 2 in the tangential zone "FAD-locus", which goes against what would be expected. A similar situation is found between FADs 1 and 2 in the $0 < L_r < 0.8$ interval that justifies a more precise study, presented in Example 4, on the effect of the differences between FADs.

Critical Load (KN)	R6						PD6493			EPRI	ETM
	C 2.1 *	C 2.2	C 2.3	C 3.1	C 3.2	C 3.3	L 3.1	L 3.2	L 3.3	CDF	CDF
	1085	1135	1105	1239	1375	1331	1239	1375	1331	1260	1386

Table 1.1. Critical axial load. Analytical results.

(*) Analysis Category 2, FAD 1.

Critical bending moment (KN m)	R6		PD 6493		EPRI	ETM
	C 3.1 *	C 3.2	L 3.1	L 3.2	CDF	CDF
	110	117	110	117	111	110.6

Table 1.2. Critical bending moment. Analytical results.

(*) Analysis Category 3, FAD 1.

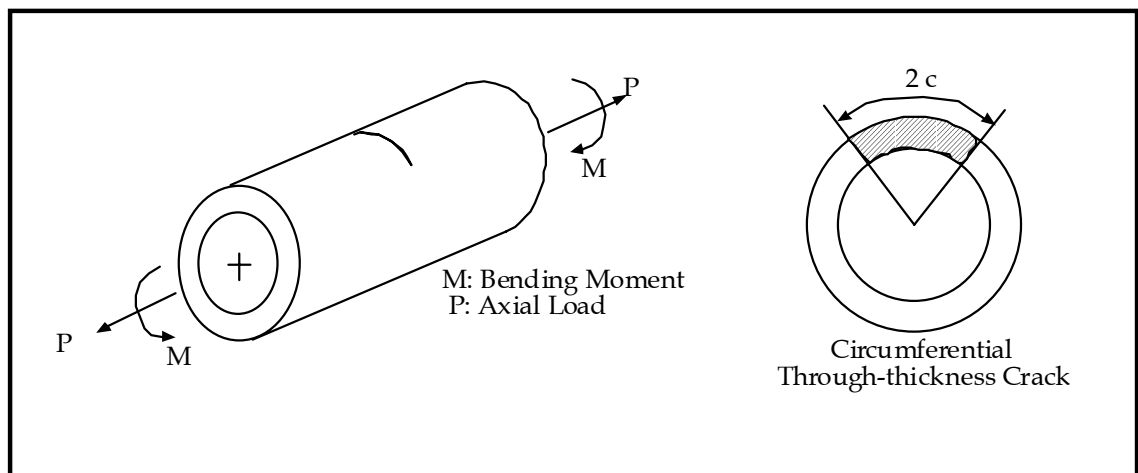


Figure 1.1. Geometrical definition of Example 1.

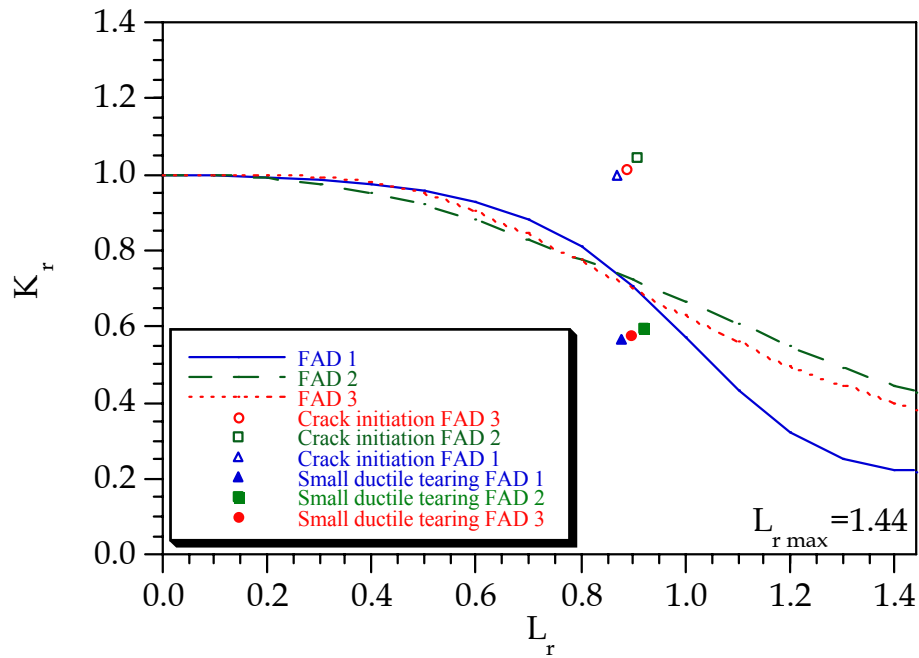


Figure 1.2. Critical axial load. R6 results, Category 2, FADs 1, 2 & 3.

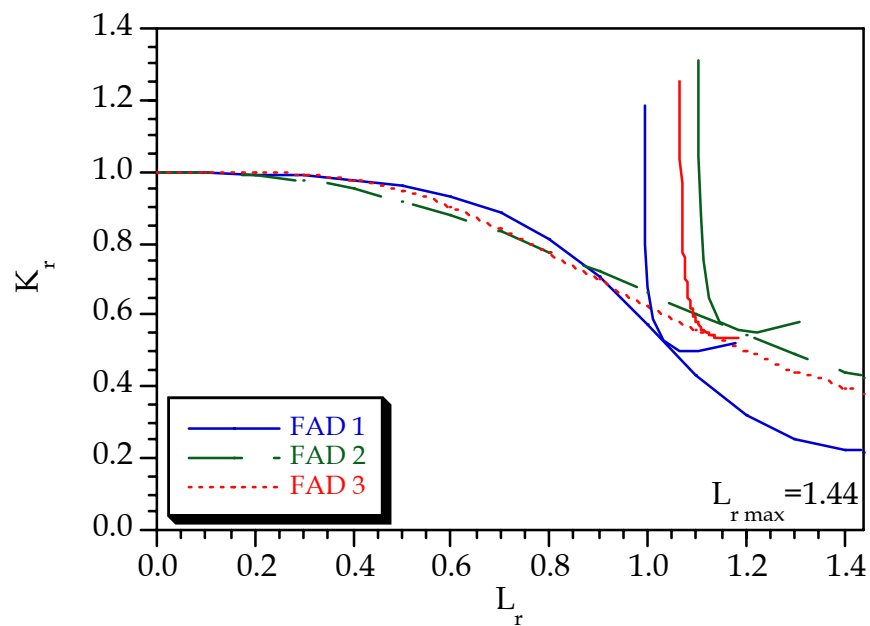


Figure 1.3. Critical axial load. R6 results (Category 3) & PD6493 (Level 3), FADs 1, 2 & 3.

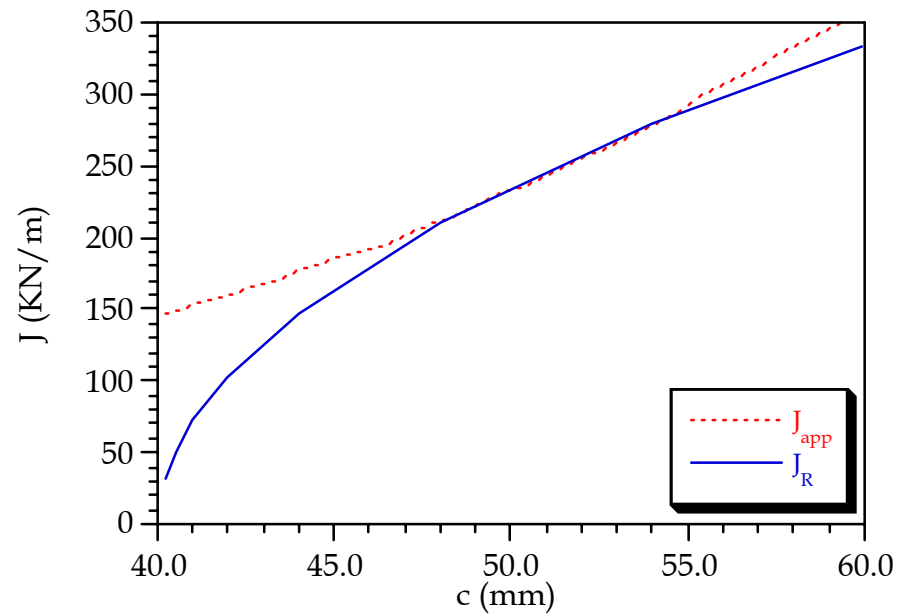


Figure 1.4. Critical axial load. GE-EPRI result.

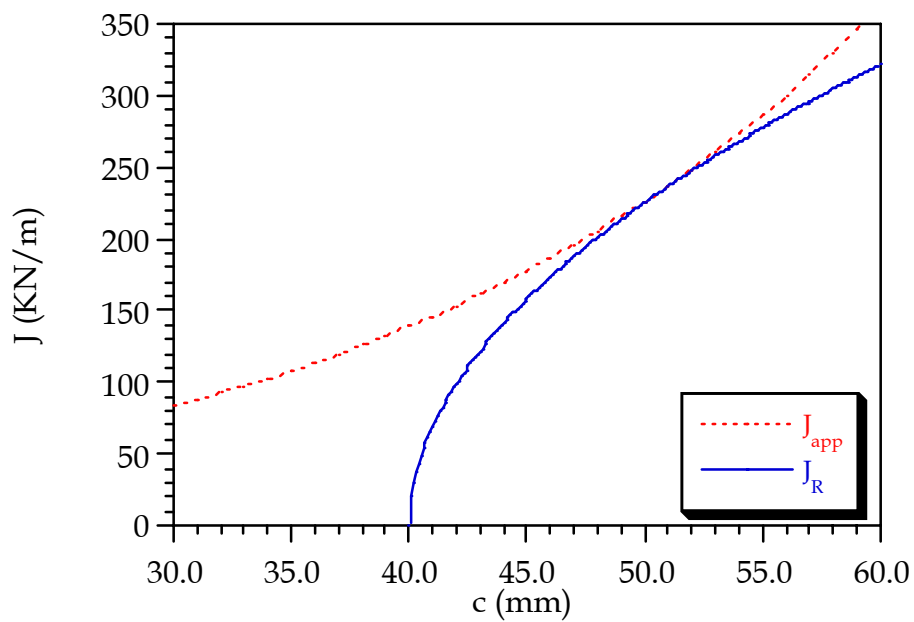


Figure 1.5. Critical axial load. ETM result.

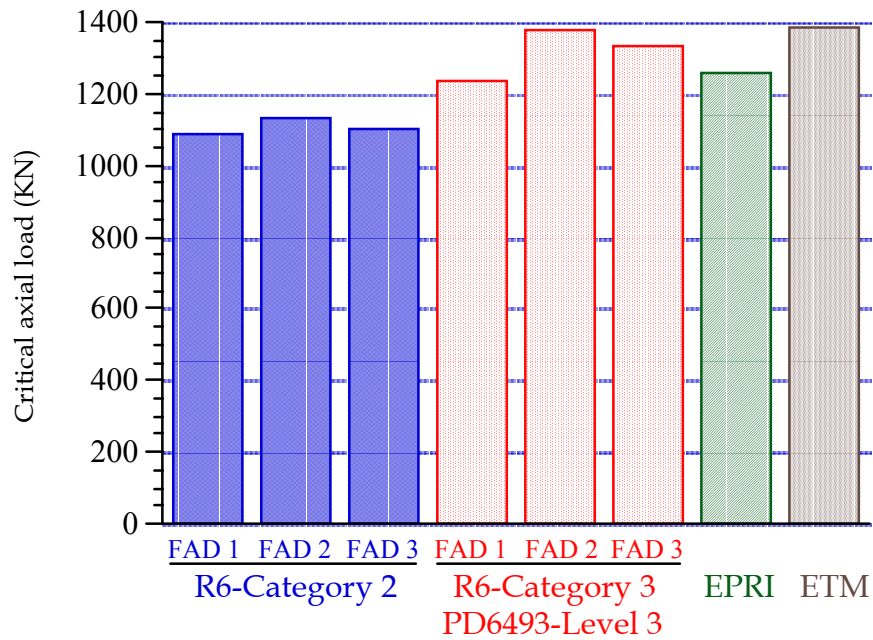


Figure 1.6. Critical axial load. Comparison between methods.

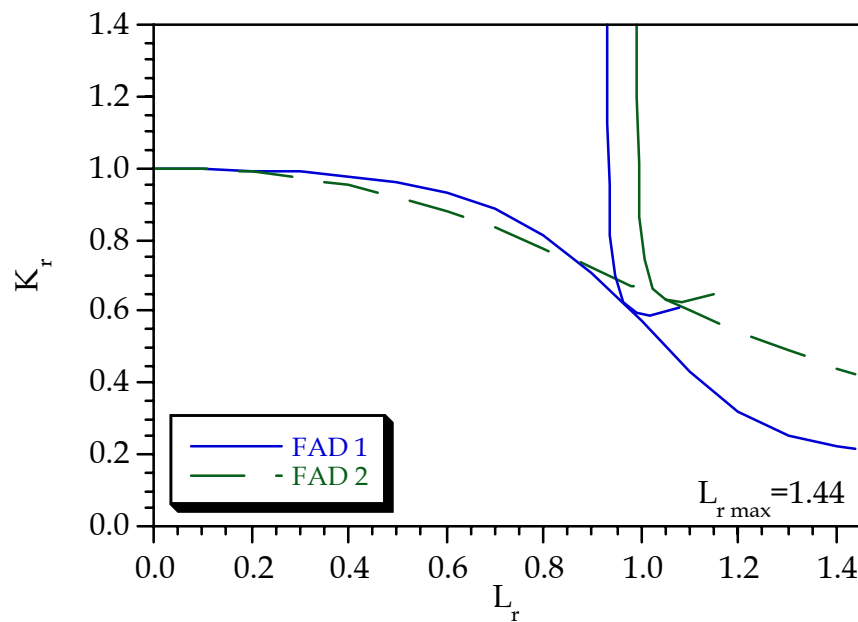


Figure 1.7. Critical bending moment. R6 results (Cat 3) & PD6493 (Lev 3), FADs 1 & 2.

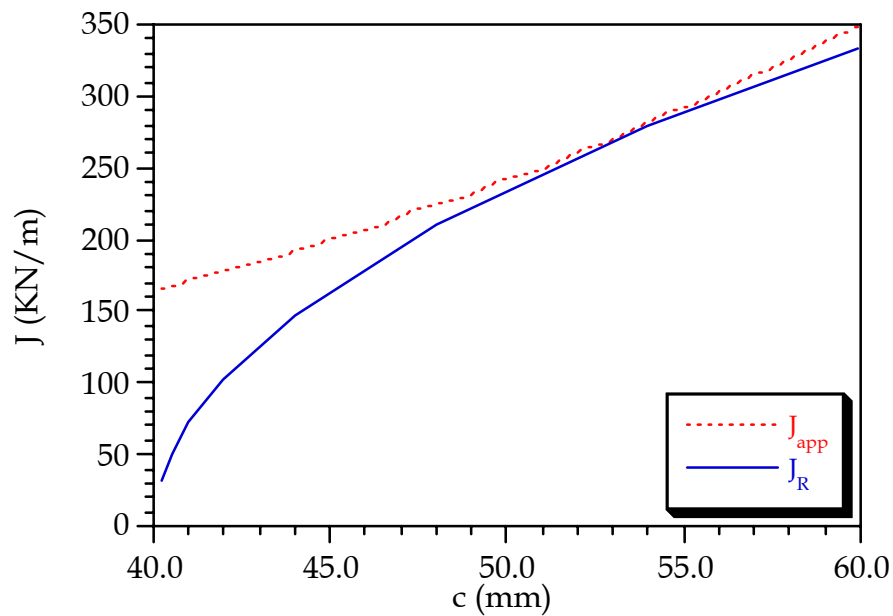


Figure 1.8. Critical bending moment. GE-EPRI result.

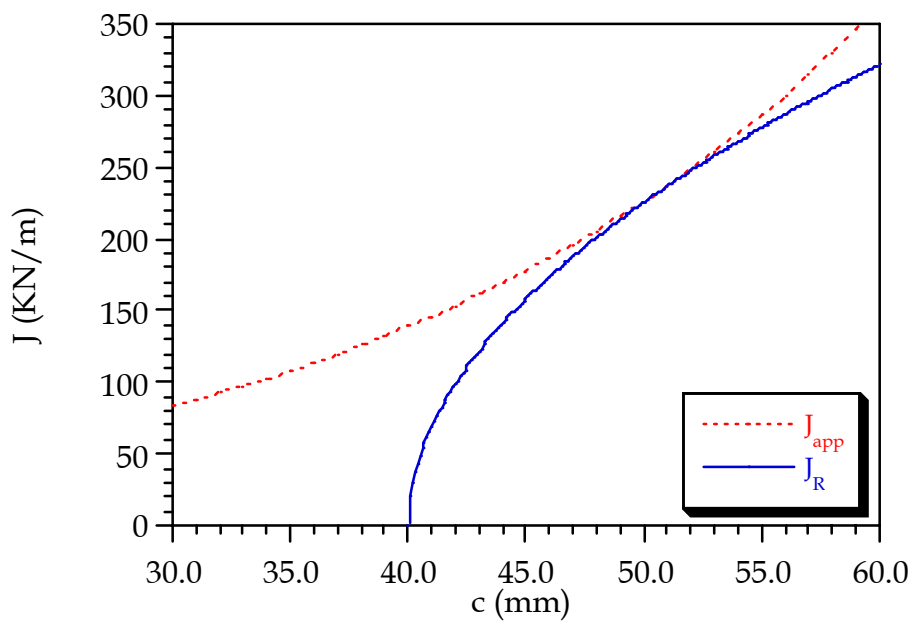


Figure 1.9. Critical bending moment. ETM result.

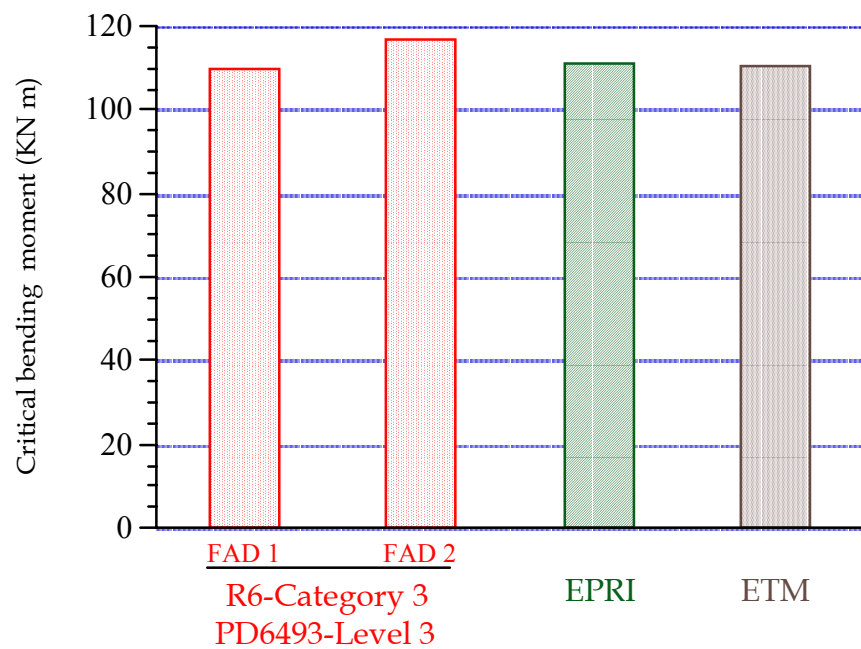


Figure 1.10. Critical bending moment. Comparison between results.

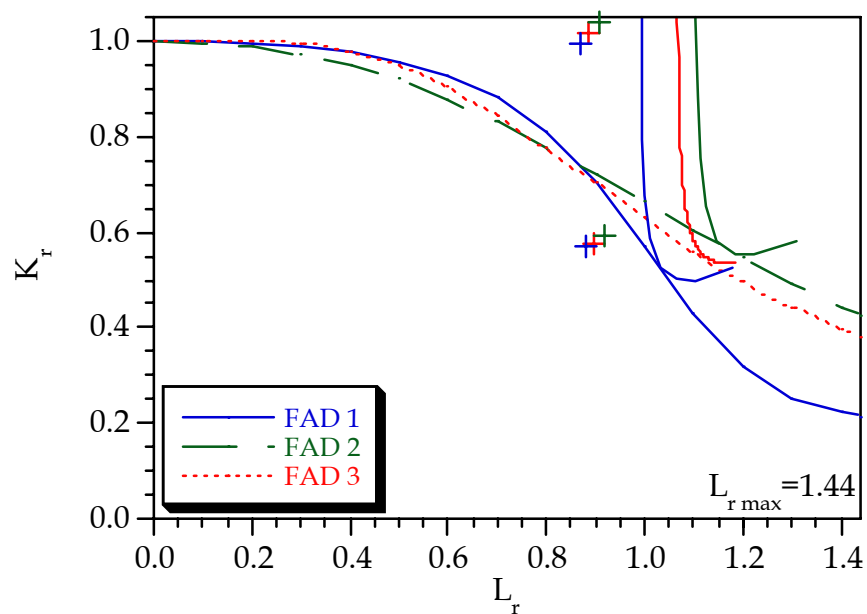


Figure 1.11. Differences between FADs. Critical axial load.

2. EXAMPLE 2

This example has been taken from an extensive work done by the University of Cantabria on the mechanical characterisation and fracture behaviour of steel tubes coming from a nuclear power plant as a basis for the assessment of a Leak Before Break analysis based on EPRI formulation. Given the fact that EPRI is one of the methods to be evaluated in the SINTAP project, it was decided to extend this study to other methods and convert it into a working example. So, the analysis has been proposed as Example 2.

2.1. DEFINITION

The structural element studied is a carbon steel (0.3%C) pipe. In order to study the limits of the Leak Before Break criteria two types of axial cracks have been considered in this tube: through-thickness and internal semielliptical surface. The geometrical definition of this component, shown in Figure 2.1, is completed with the following:

- Geometrical dimensions:
 - Outer diameter 355 mm
 - Thickness 30 mm
 - Shape ratio (part-through crack) $2c/a=12$

The stress-strain curve of the steel for the circumferential orientation is shown in Figure 2.2, defining the following:

- Mechanical characteristics:
 - Yield stress 321.7 MPa
 - Ultimate tensile strength 581 MPa
 - Elastic modulus 198.6 GPa
- Fracture Toughness:

Fracture toughness tests have been performed on compact specimens (CT) made of material coming from the studied tube. The radial and axial crack

propagation directions are considered. Radial propagation corresponds to part-through crack growth, while axial propagation corresponds to through-thickness cracks. The following expressions of J_R were obtained in accordance with the European Standard ESIS P1-92 [14].

- Radial growth	$J_R = 111.56 (\Delta a)^{0.4667}$	$J_{0.2/BI} = 60.21 \text{ KN/m}$
- Axial growth	$J_R = 72.75 (\Delta a)^{0.3457}$	$J_{0.2/BI} = 43.05 \text{ KN/m}$

where J_R is expressed in KN/m and Δa in mm.

- Loading:

The tube is subjected to internal pressure. This pressure is assumed to have values for which the maximum part-through crack size which becomes through-thickness by unstable fracture has been calculated. Also, the maximum through-thickness crack sizes at which the tube suddenly breaks have been calculated. Once the critical crack length has been calculated for the two cases (part-through and through-thickness) the results are compared to verify the Leak Before Break criteria. The internal tube pressure values for which the critical crack size has been calculated are 7, 10, 20, 30, 50, 60, and 69.2 MPa.

2.2. CALCULATIONS AND RESULTS

As has been explained in the definition of the example, the objective is to find the critical crack size in the tube under different pressures. As two types of cracks are being considered, the results of the methods used will be presented in two sections, one corresponding to through-thickness cracks and the other to part-through cracks.

2.2.1. Calculation of the critical size of the axial through-thickness crack

This type of calculation has been performed using the same methods as in Example 1.

The analytical results obtained for each method used in this example are shown in Table 2.1 where R6 and PD6493 results are presented together as they are equivalent at the level of analysis done. Both in R6 and PD6493 the use of the FAD 1 is not permitted for values of $L_r > 1$ if the material presents a yield plateau. As FAD 1

is more conservative than FAD 2 in all the L_r range it was used to calculate the critical crack size. However, it must be pointed out that the results obtained through FAD 1 for $L_r > 1$ are not valid even though they are conservative (that happens for pressures over 50 MPa). The results for R6 and PD6493 for each working pressure used, both the FAD 1 (Default) and the FAD 2 (Specific) are shown in Figures 2.3 through 2.9. The results obtained following the GE-EPRI procedure are presented in Figure 2.10. Finally, Figure 2.11 presents the graphic results obtained following ETM.

Figure 2.12 shows a comparison of the critical crack sizes obtained in the different analysis options used, for the working pressure values considered.

2.2.2. Calculation of the critical size of the part-through axial crack

The critical size of the internal axial crack has been calculated for the different pressures mentioned in the definition of the example. The methods used in this case have been: R6 Method: Category 3, FADs 1 and 2; BSI PD6493: Level 3, FADs 1 and 2 and EFAM ETM 95.

In this case it has not been possible to use GE-EPRI because the corresponding solution for J_{app} was not available to the University of Cantabria. The results found both for R6 and PD6493 once again coincide as the levels of analysis used are equivalent.

As the part-through crack has two geometric parameters, a (depth) and $2c$ (length), it was initially chosen that before ductile tearing the crack fulfills the relationship $a/2c=1/12$. It was also considered that the crack growth was only in a radial direction (direction of the crack depth, a), so crack length stays constant. Only MPC gives an indication of how to vary " a " and " c " in a ductile tearing situation. MPC gives a series of options, from which it was chosen that crack growth was only in the direction of thickness. As the crack is considered to grow radially then the fracture toughness of the material is considered in this direction.

In this case, the lowest working pressure considered was 20 MPa. For lower pressures the solutions for K_I leave the validity range of the solution used.

The critical values of crack depth, a , and crack length, c from the different methods and pressures used are summarised in Table 2.2. The graphic results for

PD6493 and R6 are shown in Figures 2.13 to 2.17. The graphic results of ETM are shown in Figure 2.18. Finally, in Figure 2.19 a comparison is established between the critical part-through axial crack lengths according to the different methods used.

2.3. DISCUSSION

Once the critical lengths have been obtained for the through-thickness and part-through cracks for each working pressure considered, it is possible to verify the fulfillment or non fulfillment of the Leak Before Break criteria. This verification is made for each pressure by comparing the lengths of the through-thickness and part-through cracks. If the former is greater than the latter, then the criterion is satisfied, if the opposite is the case then the criterion is not satisfied. In the present case, the criterion is not satisfied for any of the pressures considered, because in all the cases the critical length of the part-through crack is greater than the through-thickness crack.

Given that each method has a certain degree of conservativeness with respect to the real fracture of the element, this fact may affect the Leak Before Break analysis, if the degree of conservativeness is different when the critical crack lengths are found (whether through-thickness or not) it could make the analysis incorrect. This fact is considered by both PD6493 and R6 in their respective Appendices "Leak Before Break" and, therefore, they recommend a sensitivity analysis based on the variations in the input data.

Figure 2.20 shows a situation in which the difference between the conservativeness in the analysis of the through-thickness and part-through cracks could lead to a non-conservative decision. If the degree of reservation in the determination of the critical part-through crack is sufficiently greater than that of the critical through-thickness crack then it could lead to a situation where a Leak would be predicted when in fact it is a Break. Figure 2.21 shows an analogous example in which the prediction could be, once again, erroneous. Here, a Break would be predicted instead a Leak, nevertheless, this mistake would not be so dangerous because it would lead to a conservative decision.

2.4. CONCLUSIONS

The following conclusions can be drawn from the results of Example 2:

- The analyses, according to all the methods used, lead to the same result: the tube suffers fracture as the crack goes from being part-through to through-thickness and the crack propagates unstably.
- In this case, the relative conservativeness between the predictions, for through- and part-through crack lengths, could lead to an erroneous, but conservative, Leak Before Break analysis. In other cases, the erroneous prediction can be non conservative.
- R6 and PD6493 produce conservative results compared with the rest of the methods used for high working pressures, in other words, close to the tube's plastic collapse.
- No procedure, except MPC, gives any indication about how to validate the part-through crack size in a situation of ductile tearing.

Internal Pressure (MPa)	Through-thickness crack, c (mm)			
	R6 (Cat 3) & PD6493 (Lev 3)		GE-EPRI	ETM
	FAD 1	FAD 2	CDF	CDF
7	325	323	332	324
10	235	235	244	235.5
20	93.9	93.9	125.5	121
30	74	80	84.5	79.5
50	29.3	37.7	44	40.5
60	13.9	13.6	31.3	27
69.2	3.9	5.2	21.3	17.2

Table 2.1. Critical size of through-thickness crack in a pipe. Analytical results.

Internal Pressure (MPa)	Part-through crack					
	R6 (Category 3) & PD6493 (Level 3)				ETM	
	FAD 1		FAD 2		CDF	
	a (mm)	c (mm)	a (mm)	c (mm)	a (mm)	c (mm)
20	21.8	130.8	22	131.7	23.9	143.4
30	17.3	104	17.7	106	20.1	120.6
50	8.6	51.5	8.8	52.5	12.7	76.2
60	4.3	25.5	5	30	9.3	55.8
69.2	1.1	6.7	2.6	15.5	6.4	38.4

Table 2.2. Critical size of part-through crack in a pipe. Analytical results.

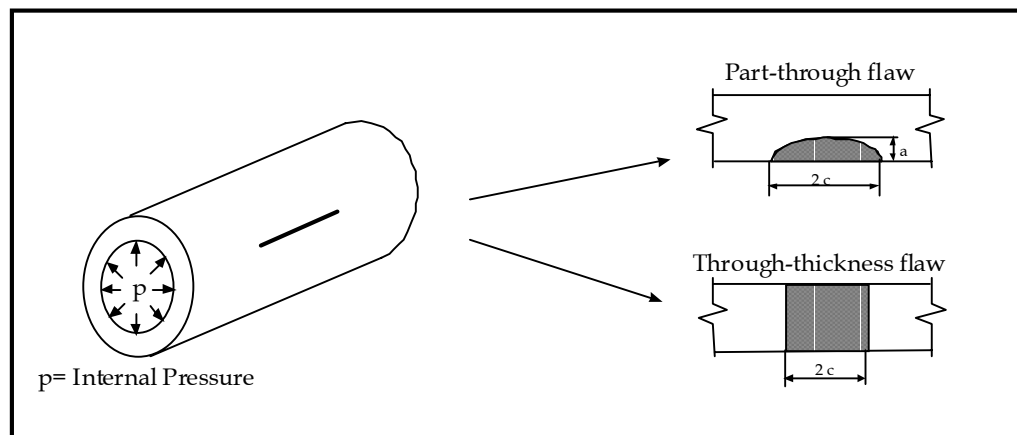


Figure 2.1. Geometrical definition of Example 2.

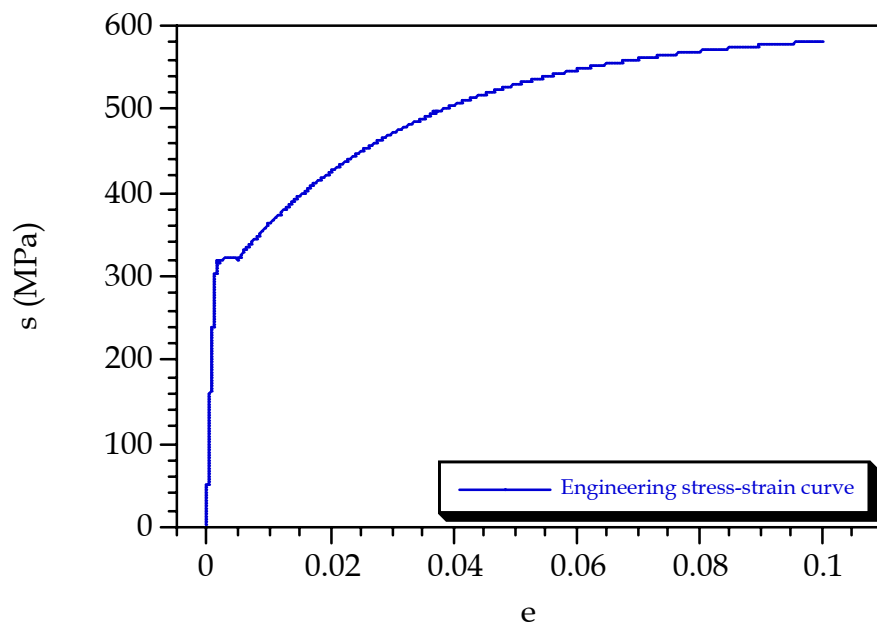


Figure 2.2. Engineering stress-strain curve of steel from Example 2.

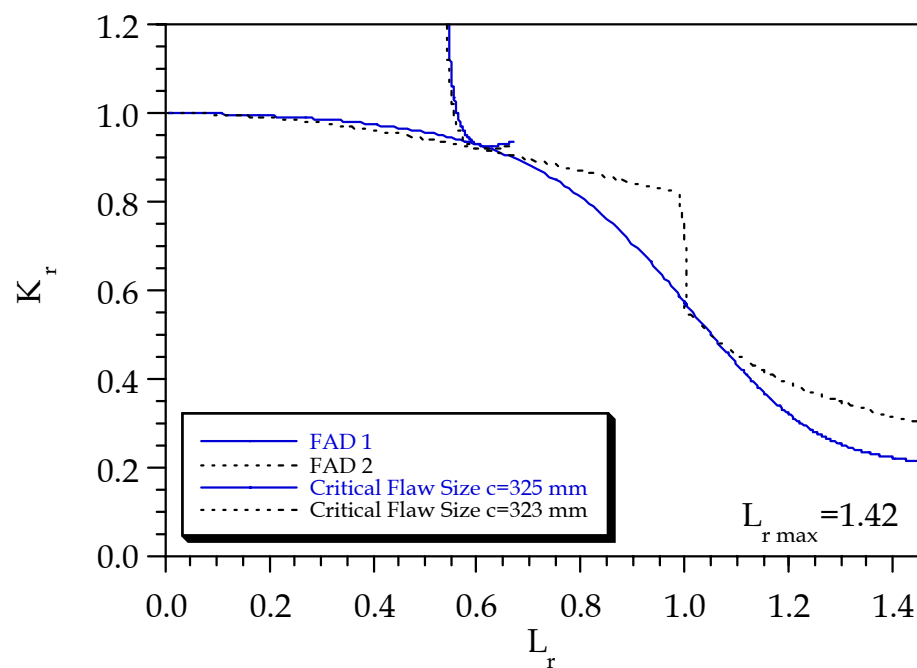


Figure 2.3. Critical size of axial through-thickness crack. Pipe's internal pressure 7 MPa. Methods R6 & PD6493, Category 3 & Level 3, FADs 1 & 2.

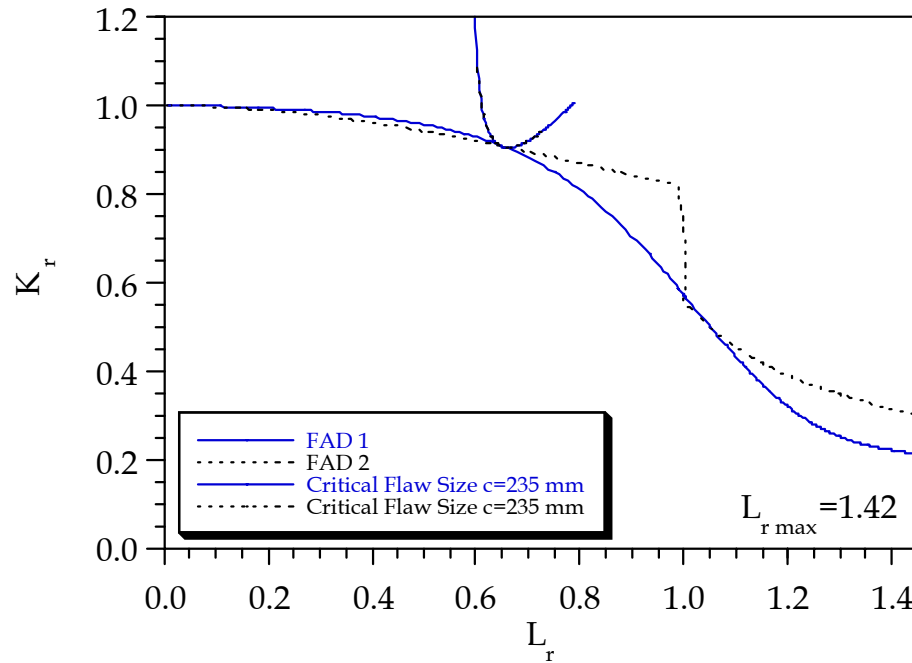


Figure 2.4. Critical size of axial through-thickness crack. Pipe's internal pressure 10 MPa. Methods R6 & PD6493, Category 3 & Level 3, FADs 1 & 2.

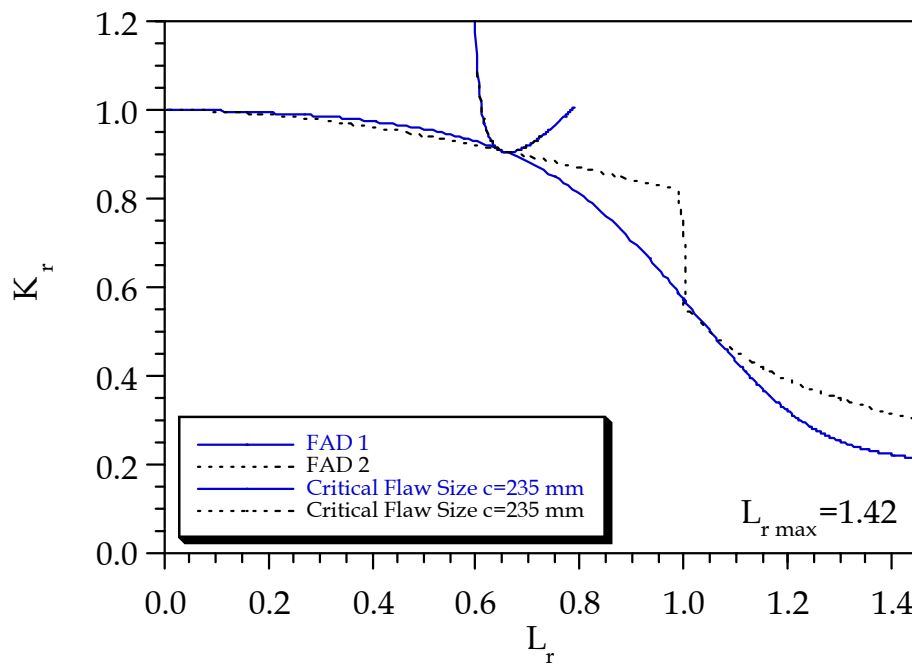


Figure 2.5. Critical size of axial through-thickness crack. Pipe's internal pressure 20 MPa.

Methods R6 & PD6493, Category 3 & Level 3, FADs 1 & 2.

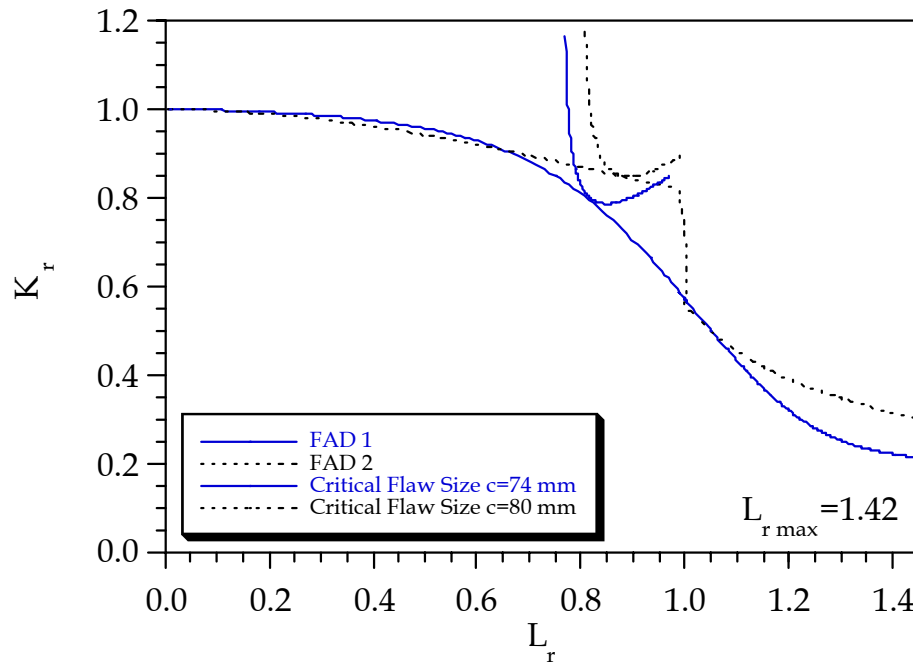


Figure 2.6. Critical size of axial through-thickness crack. Pipe's internal pressure 30 MPa. Methods R6 & PD6493, Category 3 & Level 3, FADs 1 & 2.

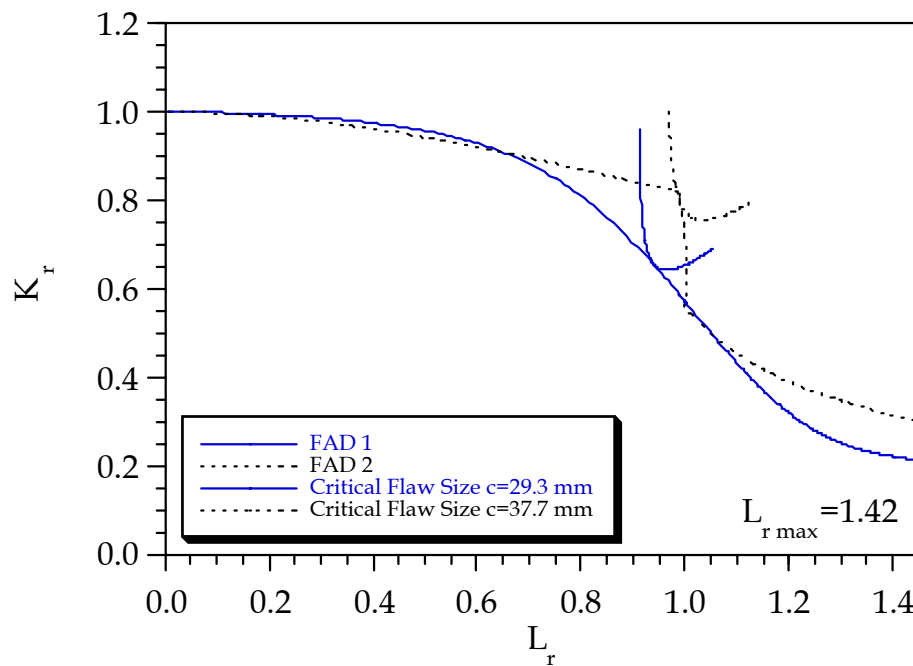


Figure 2.7. Critical size of axial through-thickness crack. Pipe's internal pressure 50 MPa. Methods R6 & PD6493, Category 3 & Level 3, FADs 1 & 2.

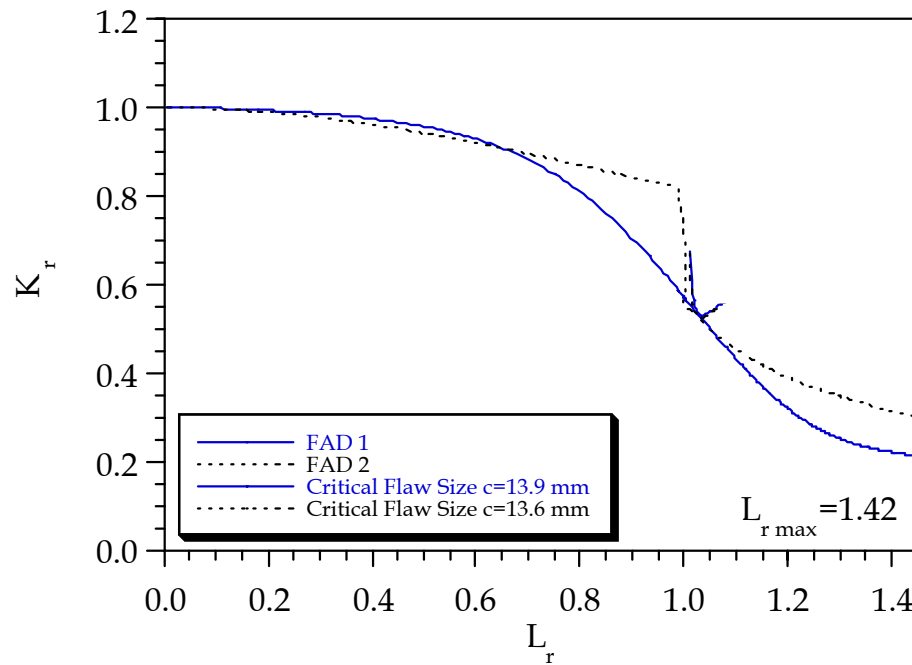


Figure 2.8. Critical size of axial through-thickness crack. Pipe's internal pressure 60 MPa. Methods R6 & PD6493, Category 3 & Level 3, FADs 1 & 2.

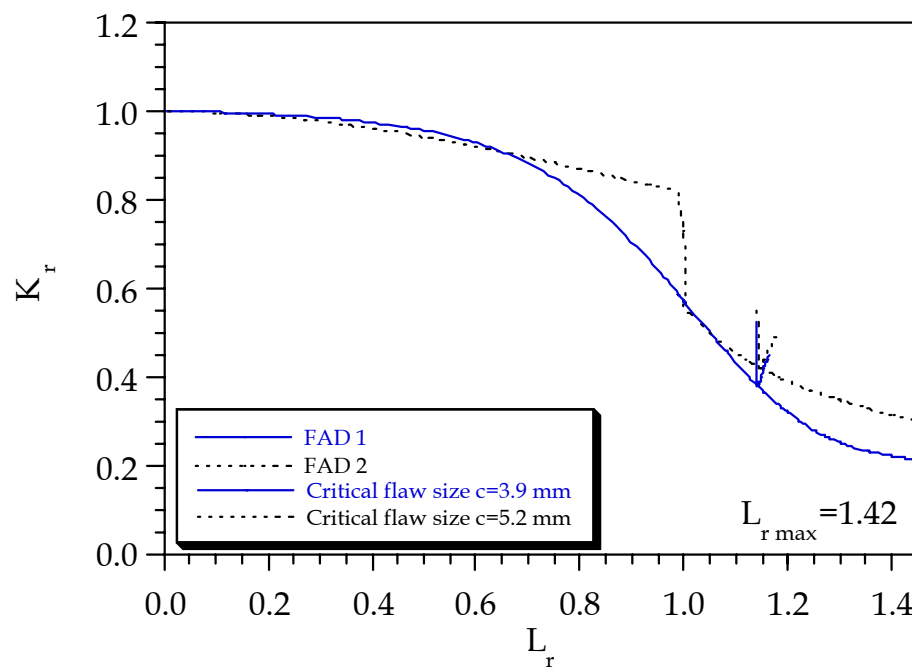


Figure 2.9. Critical size of axial through-thickness crack. Pipe's internal pressure 69.2 MPa. Methods R6 & PD6493, Category 3 & Level 3, FADs 1 & 2.

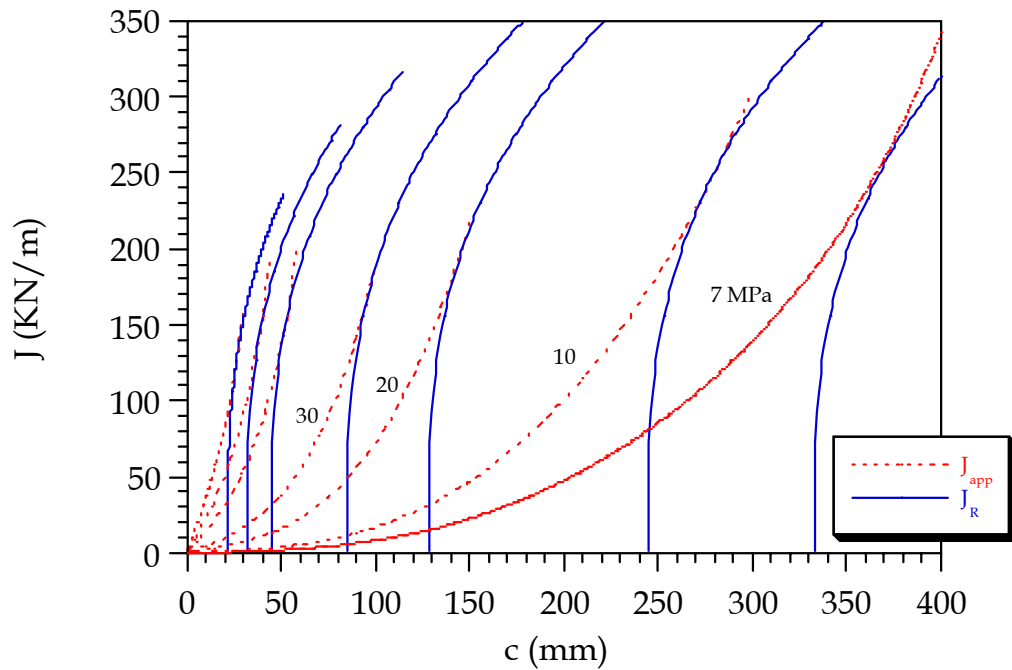


Figure 2.10. Critical size of axial through-thickness crack. Pipe's internal pressures 7, 10, 20, 30, 50, 60 & 69.2 MPa. GE-EPRI Method.

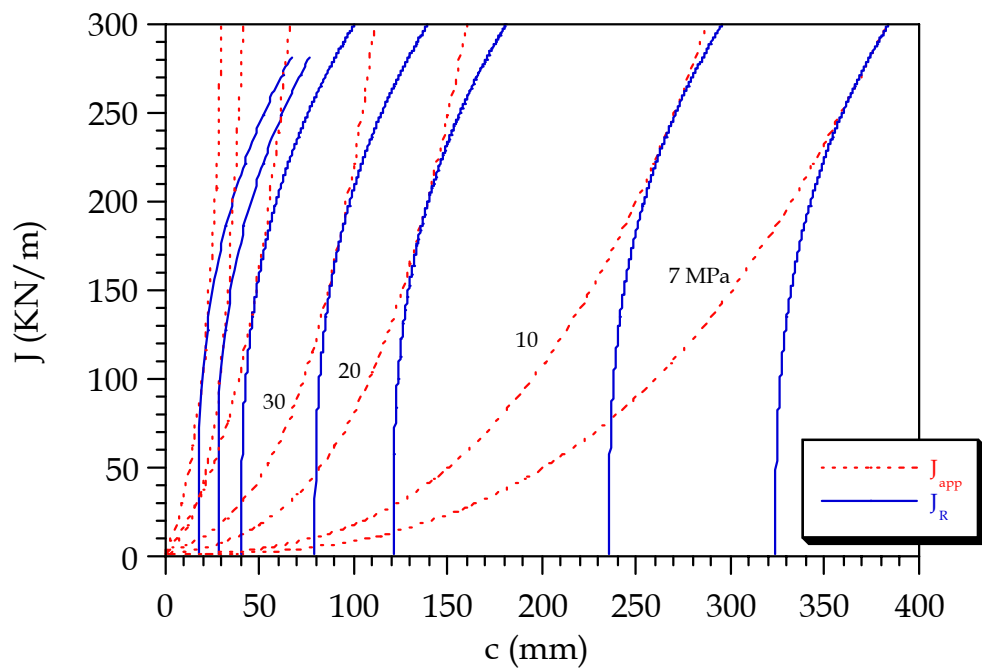


Figure 2.11. Critical size of axial through-thickness crack. Pipe's internal pressures 7, 10, 20, 30, 50, 60 & 69.2 MPa. ETM Method.

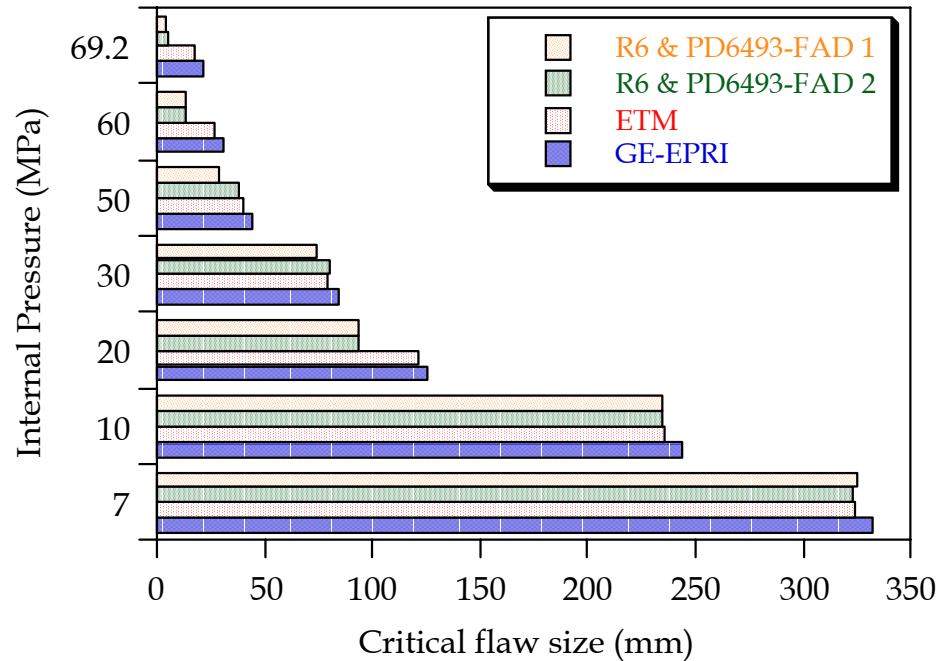


Figure 2.12. Comparison between methods. Critical axial through-thickness crack size for the pressures considered.

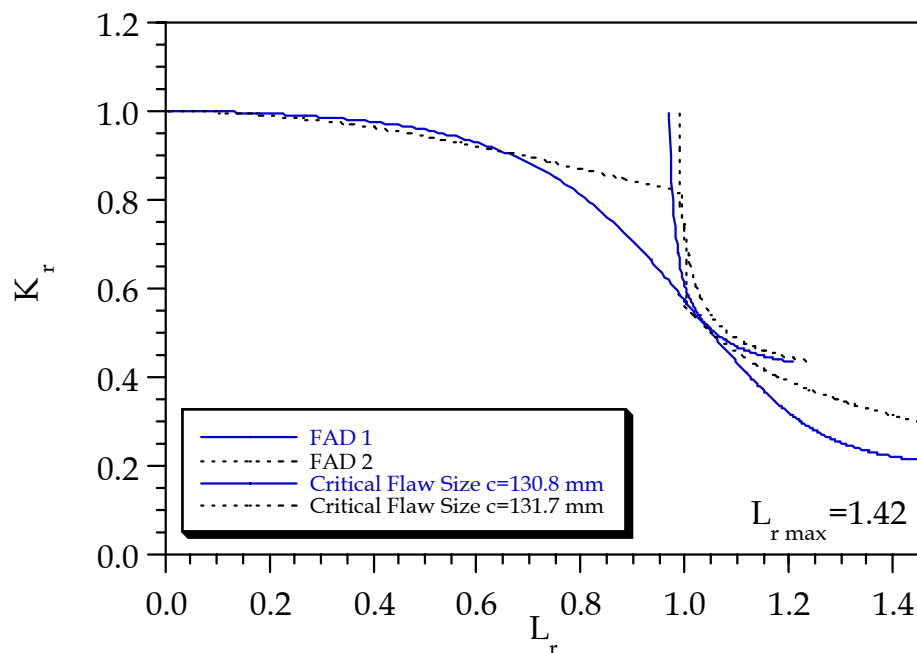


Figure 2.13. Critical size of axial part-through crack. Pipe's internal pressure 20 MPa. Methods R6 & PD6493, Category 3 & Level 3, FADs 1 & 2.

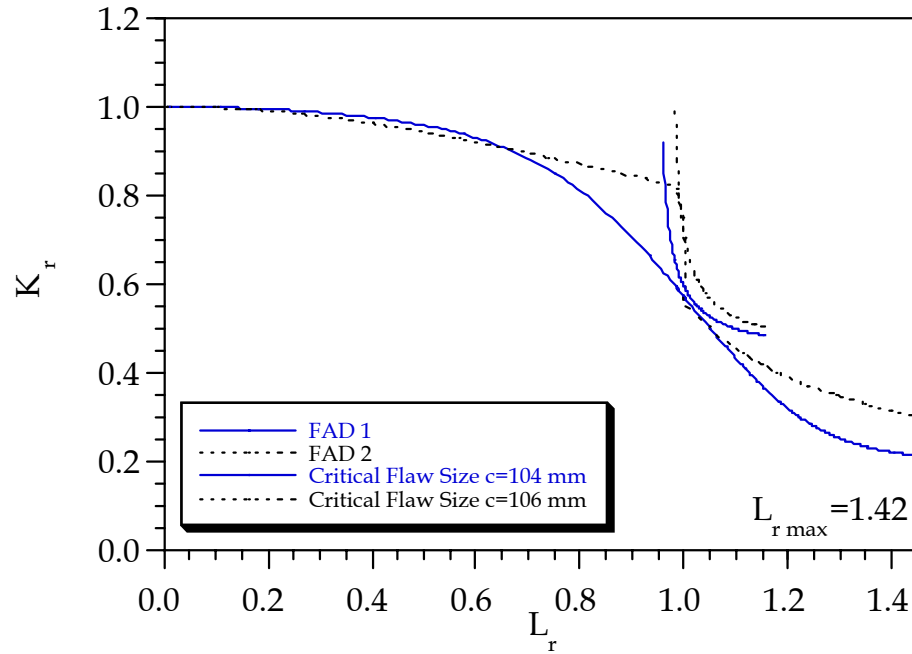


Figure 2.14. Critical size of axial part-through crack. Pipe's internal pressure 30 MPa. Methods R6 & PD6493, Category 3 & Level 3, FADs 1 & 2.

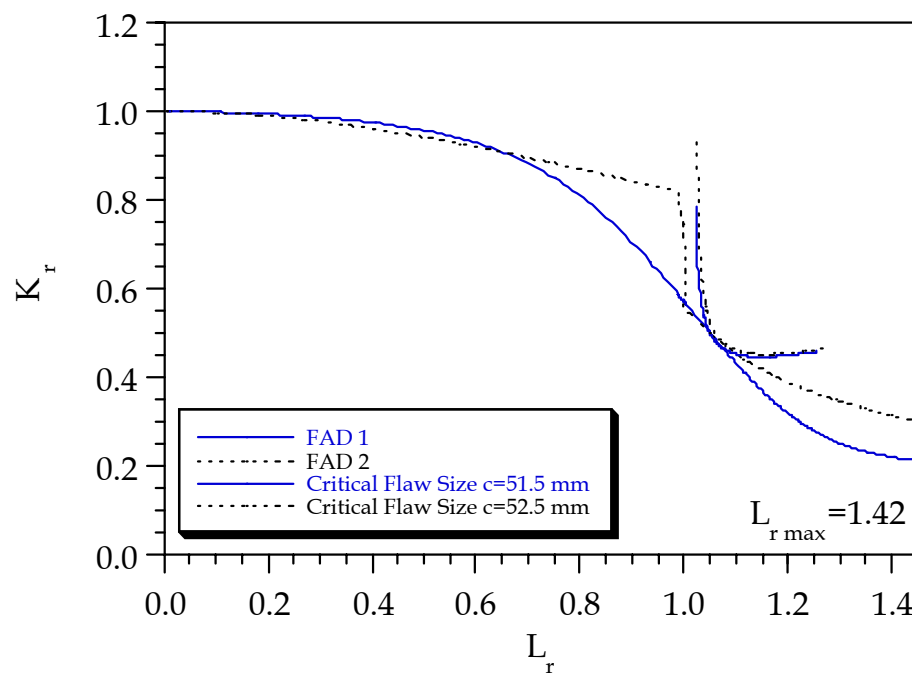


Figure 2.15. Critical size of axial part-through crack. Pipe's internal pressure 50 MPa. Methods R6 & PD6493, Category 3 & Level 3, FADs 1 & 2.

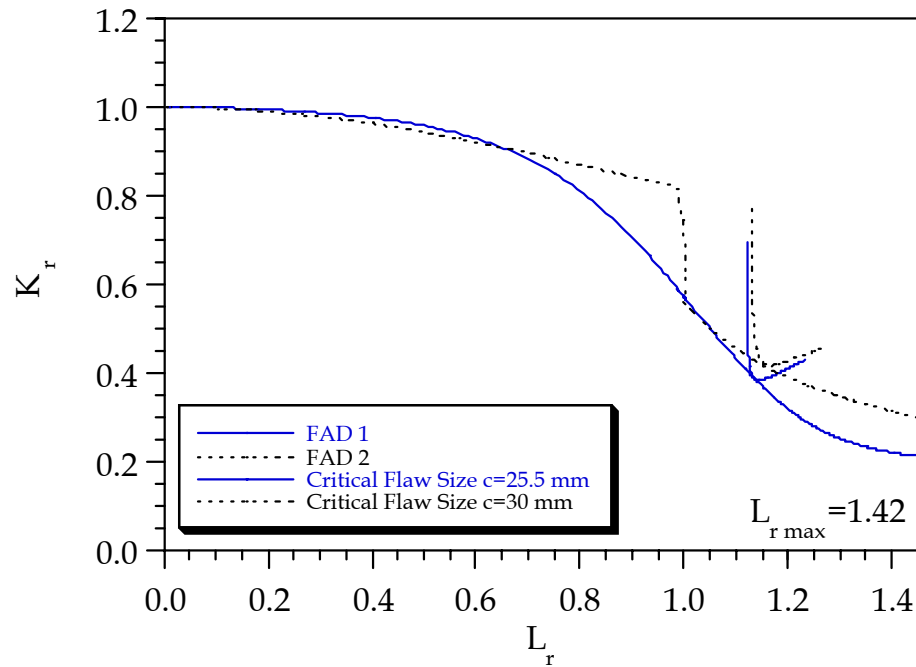


Figure 2.16. Critical size of axial part-through crack. Pipe's internal pressure 60 MPa. Methods R6 & PD6493, Category 3 & Level 3, FADs 1 & 2.

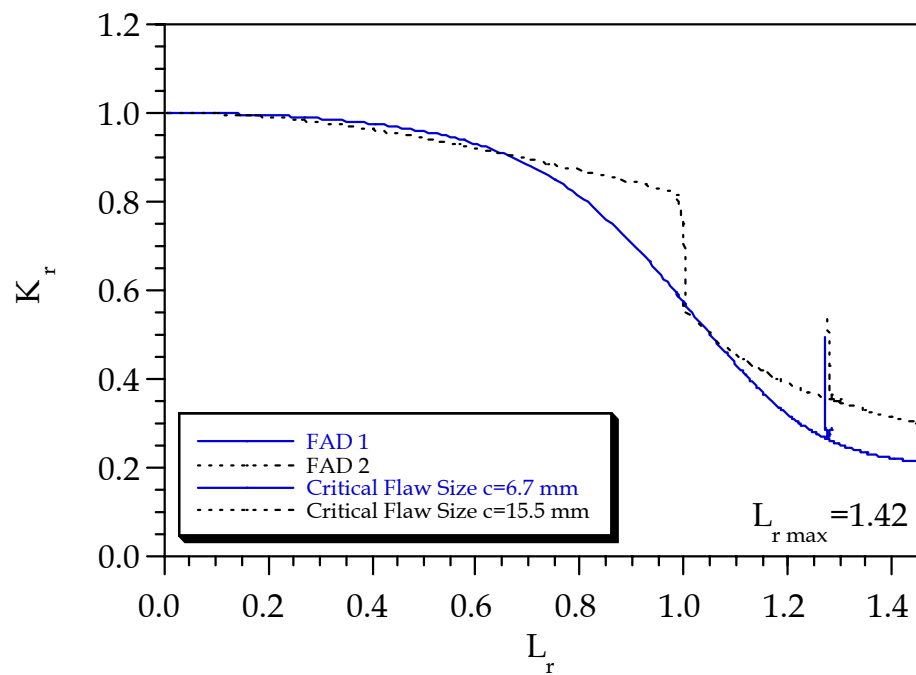


Figure 2.17. Critical size of axial part-through crack. Pipe's internal pressure 69.2 MPa. Methods R6 & PD6493, Category 3 & Level 3, FADs 1 & 2.

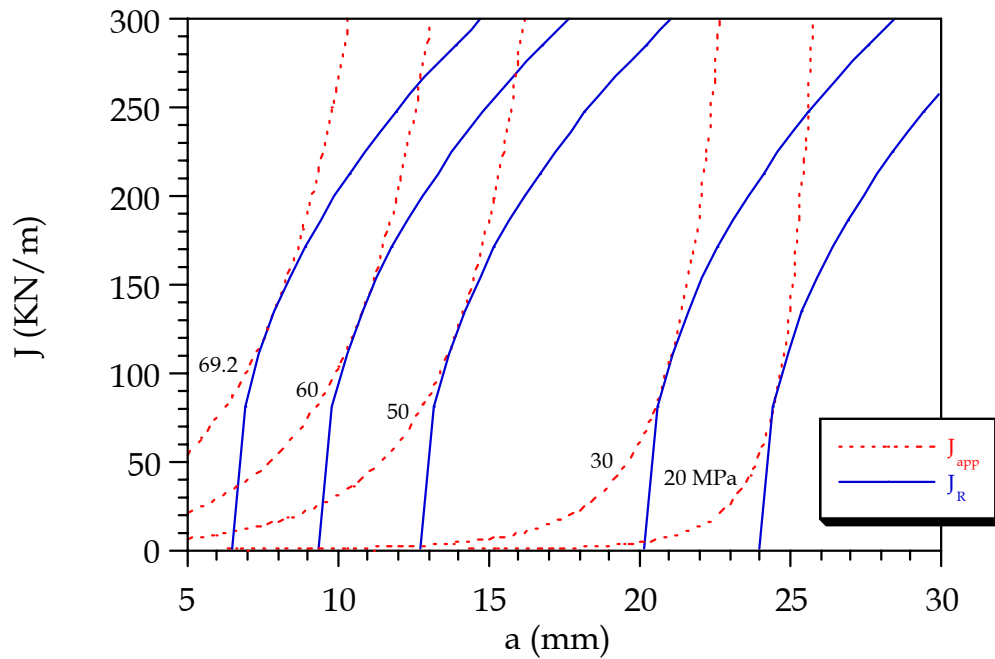


Figure 2.18. Critical size of axial part-through crack. Pipe's internal pressures 7, 10, 20, 30, 50, 60 & 69.2 MPa. ETM Method.

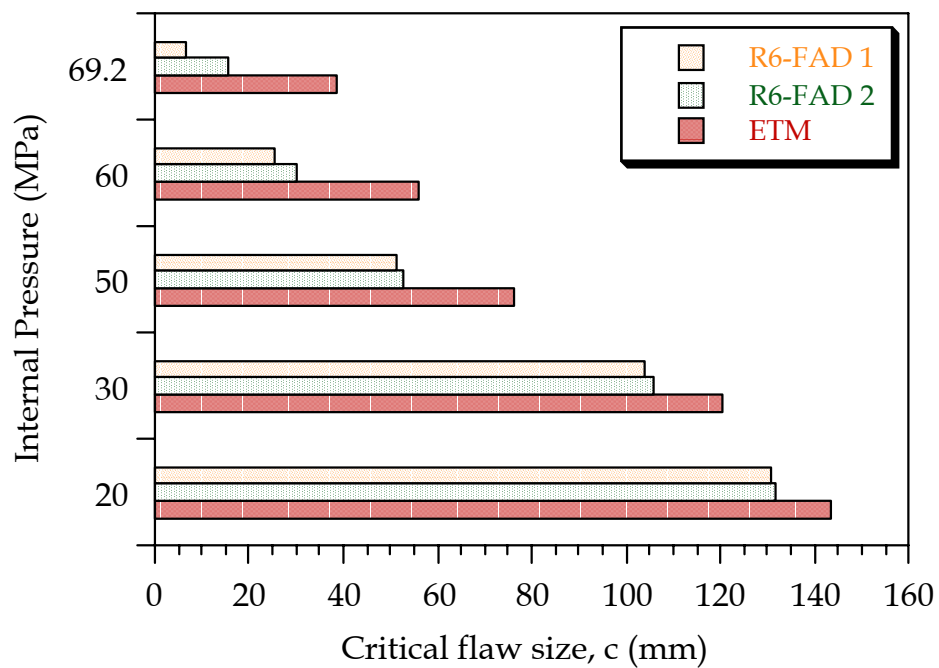


Figure 2.19. Comparison between methods. Critical axial part-through crack size for the pressures considered.

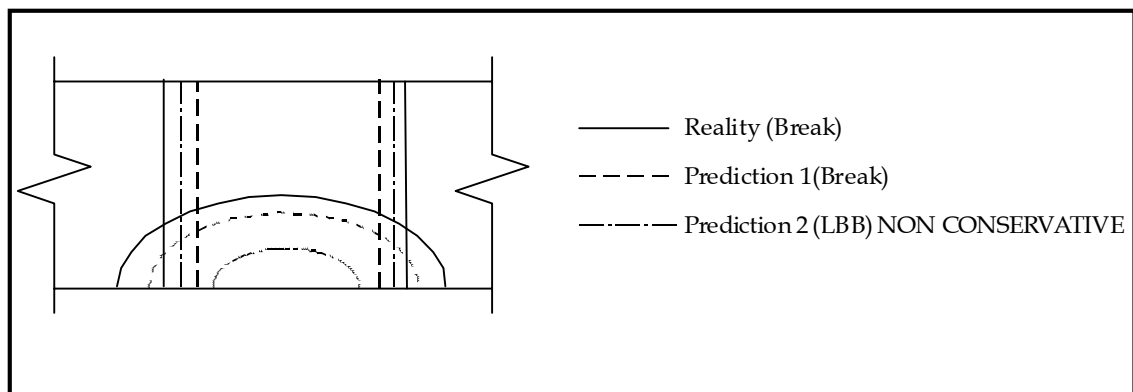


Figure 2.20. Non-conservative prediction in a Leak Before Break analysis.

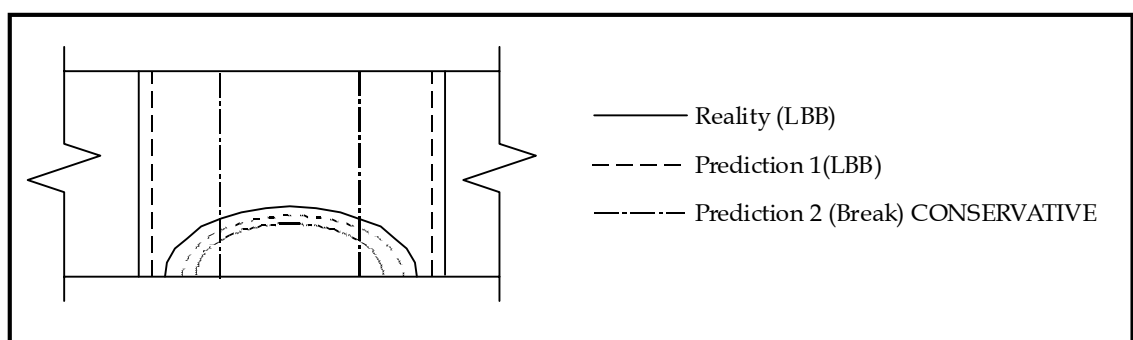


Figure 2.21. Erroneous but conservative prediction in a Leak Before Break analysis.

3. EXAMPLE 3

Once Examples 1 and 2 had been done, it was decided to run a more complex example. The one chosen, a welded joint, brought with it problems of welded joint heterogeneity and the need to understand the stress distributions in and around the weld.

The example was taken from a European Group of Fracture publication [15]. This example addressed the problem of a circumferential crack close to a weld in a pressure vessel (Figure 3.1). The problem was analysed using R6, however, once the calculations had commenced a doubt appeared which was thought to be much more interesting than solving the problem itself. The doubt consisted of which material (parent or weld) should be chosen as the weakest to comply with R6 and other methods recommendations. Depending on the corresponding stress-strain curves for each material, this decision may not be immediately clear. R6 only stated that the weakest material had to be chosen but did not clearly define the material conditions necessary for taking this decision.

3.1. DEFINITION

To try to clarify the above mentioned situation, two materials with available stress-strain curves (Figure 3.2) and tensile strength characteristics which give rise to the doubt can be addressed. The two materials were an aged stainless steel and a weld material, their mechanical characteristics are presented in Table 3.1.

The idea is to analyse the two materials in order to find out which one is the weakest, and then take it as being representative of the mechanical characteristics for the fracture analysis of a defect in the welded zone.

3.2. RESULTS

The FADs (Specific) were plotted for the two materials (Figure 3.3). As can be seen from the figure, the aged stainless steel is the weakest material in the $0 < L_r < 1$ interval. However, the weld material can be considered as weaker under plastic behaviour, because the $L_{r \max}$ value is lower than, and is always below, the stainless

steel curve. In this situation it almost comes down to guessing which of these materials is the weakest. In order to clarify this question, the corresponding material loci were calculated for an axial through-thickness crack in a tube with the following characteristics:

- Outer radius	0.1775 m
- Thickness	30 mm
- Crack length	0.3 m
- Internal pressure	15 MPa

where it was alternately assumed that the tube was made of the two mentioned materials to compare the relative position of the loci in the FAD. The results of these calculations are represented in Figure 3.4 where it now becomes perfectly clear that the stainless steel is the weakest material in the analysis (according to the toughness values for both materials). For the same loading conditions and crack size the locus of the stainless steel is on the unsafe side compared with its corresponding FAD, while that corresponding to the weld material is on the safe side.

3.3. CONCLUSIONS

- The characteristics of weakest material in the analysis of a welded joint cannot be inferred from the area beneath a FAD 2 (Specific) of each of the intervening materials. A complete analysis of the problem addressed must be made, or, observe the relative position of the loci with respect to the corresponding FAD.
- The condition of weak material is associated not only with the material's stress-strain curve, but also to its fracture toughness.
- When the problem was initially assessed by the University of Cantabria, adequate tools were not available for analysing the example. These tools are now available. Both R6 in its Appendix 16 (Allowance for Strength Mis-Match Effects) and ETM in its document EFAM ETM-MM96 (The ETM Method for Assessing the Significance of Crack-like Defects in Joints with Mechanical Heterogeneity), deal with this question. PD6493 also has an appendix (H) (Weld Metal Yield Strength Mis-Match), although here the question is dealt with more superficially. ETM also proposes a series of solutions to treat various geometries

with mis-match which the appendix of R6 references. So, the problem associated with the definition of “weaker” has been solved.

MECHANICAL PROPERTY	AGED STAINLESS STEEL	WELD STAINLESS STEEL
Yield Stress (MPa)	319.15	462.2
Tensile Strength (MPa)	711.7	685.4
Toughness (KN/m)	$J_R=486.7 (\Delta a)^{0.383}$	$J_R=511.39 (\Delta a)^{0.6363}$

Table 3.1. Mechanical characteristics of steels of Example 3.

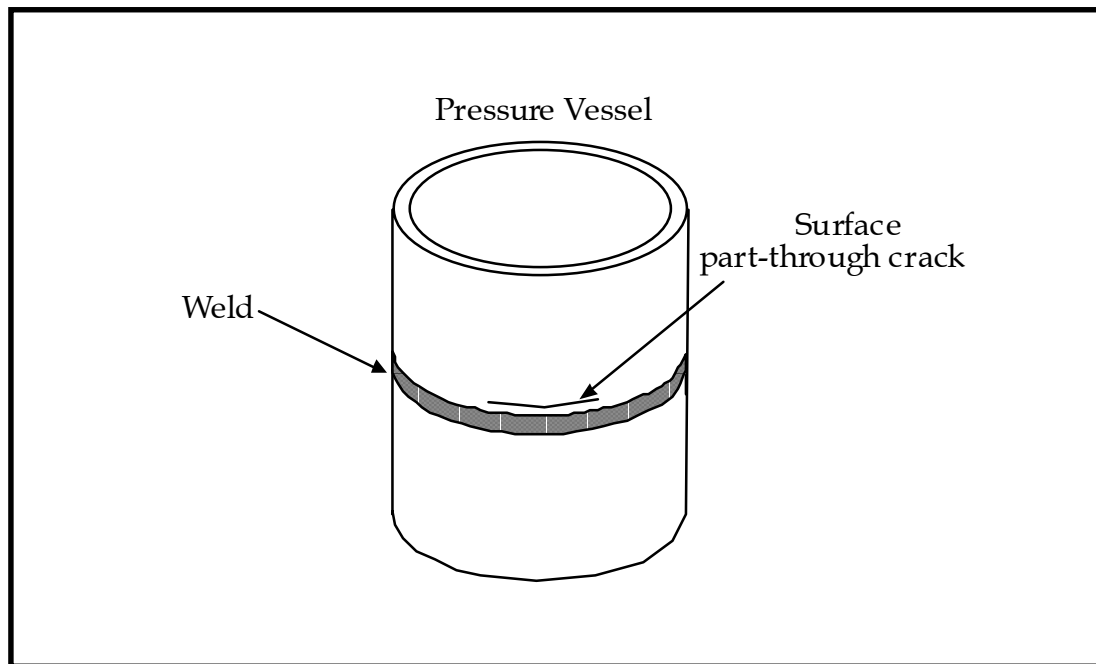


Figure 3.1. Geometrical definition of Example 3.

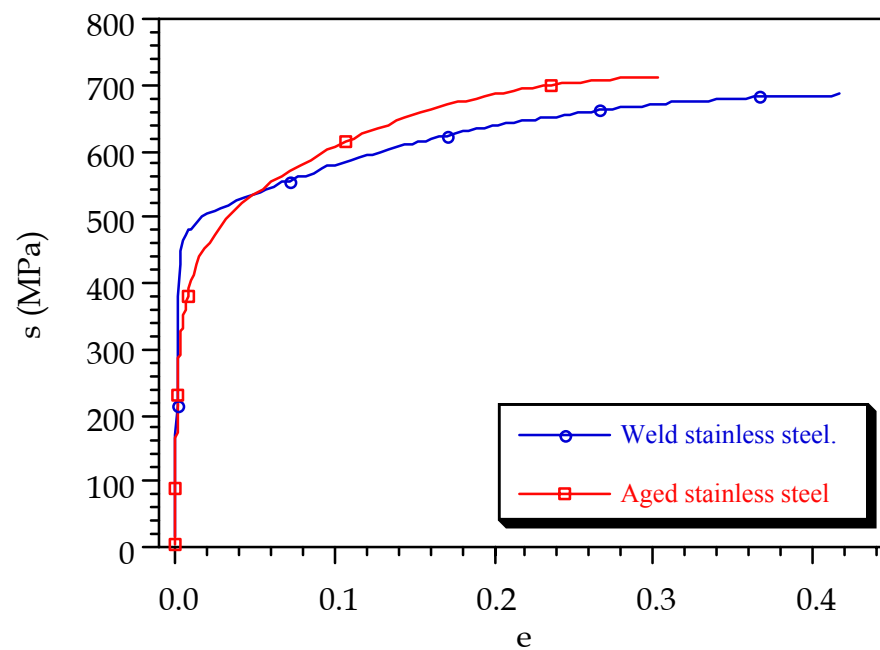


Figure 3.2. Comparison between stress-strain curves.
Weld stainless steel vs. aged stainless steel.

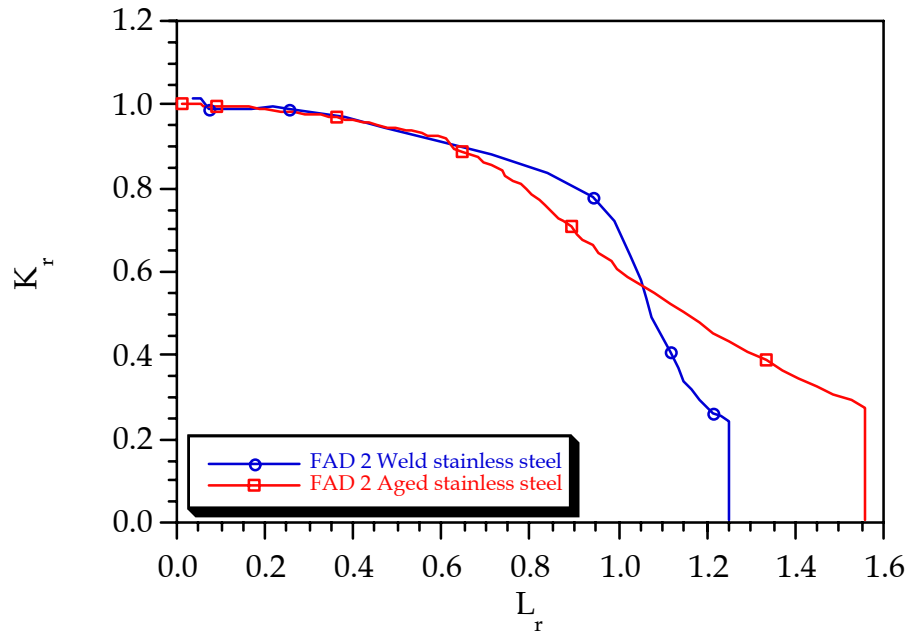


Figure 3.3. Comparison between FADs 2. Weld stainless steel vs. Aged stainless steel.

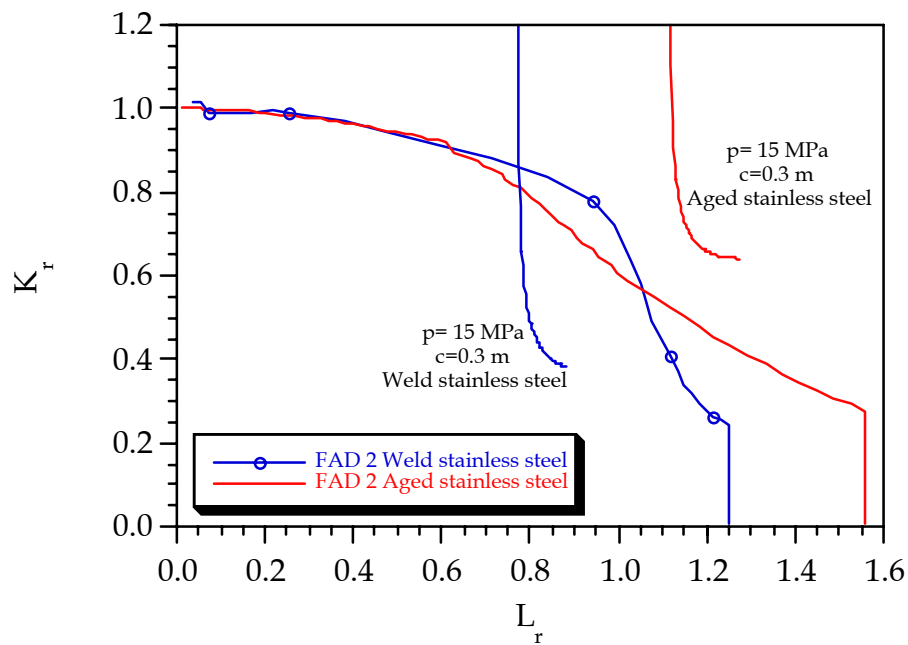


Figure 3.4. Comparison between Aged stainless steel and Weld stainless steel for the same load and crack conditions.

4. EXAMPLE 4

Some of the results from Example 1 were unexpected. These results refer to the relative conservativeness between the different FADs where Default was less conservative than Specific. It was also observed that under certain circumstances FAD Specific could be less conservative than Based on J. Therefore, it was decided to address a new example in which different types of FAD were compared using different materials.

4.1. DEFINITION

Different metallic materials were compared through their corresponding FADs in the different available options (FAD 1, FAD 2, and FAD 3) using both the R6 and the PD6493 methods. The materials were chosen to represent a wide range of commonly used metals.

4.2. RESULTS AND ANALYSIS

4.2.1. Comparison of FADs 1 and 2 for different materials

The following five materials, presenting different stress-strain curves, were chosen to compare their corresponding FADs 2:

- A perfect elastic-plastic material (theoretical).
- A carbon steel.
- A weld stainless steel (same as Example 3).
- A microalloyed steel.
- An aged stainless steel (same as Example 3).

The tensile characteristics of these materials are shown in Table 4.1. The stress-strain curves of the five materials are shown in Figure 4.1. Figure 4.2 presents a comparison between the different FADs 2 of these materials. Although Example 3

makes clear that the FADs 2 are not representative of the material's resistance because their fracture toughness also has to be taken into account, a series of FAD characteristics dependant on the material can still be observed. One of these is that the FAD has an L_r definition range which increases with strain hardening. If the materials possess a yield plateau, this appears in the FAD 2 as a sudden drop around $L_r=1$. This sudden drop decreases and smoothens as the plateau extension decreases.

FADs 1 and 2 originally come from R6 or PD6493 and are analysed as such. However, it should be considered that they are also used in other methods.

The FAD 1 (R6 exponential curve), FAD 1 (PD6493 logarithmic curve), and the FAD 2 (R6 and PD6493) have been drawn for the five materials to check how the FADs differ for the same material. FAD 1 has been differentiated for R6 and PD6493 because even though PD6493 has the same FAD as R6 (exponential curve), if the material does not exceed $L_{r \max} = 1.2$ it also offers a second FAD option (logarithmic curve) which differentiates it from R6. This second option has been taken in all possible cases. Therefore, Figure 4.3 (perfect elastic-plastic material) shows the FAD 1 of R6, the FAD 1 of PD6493 and the FAD 2 corresponding to both methods. A slight lack of conservativeness can be noticed in the FAD 1 of R6 with respect to the FAD 2 in the interval $0.2 < L_r < 0.65$.

The different FADs for the carbon steel are presented in Figure 4.4. In this case, as $L_{r \max} = 1.25$ (now greater than 1.2) the FADs 1 of PD6493 and R6 coincide. The FAD 2 in this case is also less conservative than the FAD 1 in the interval $0.2 < L_r < 0.6$, although the difference is small. In this case, a drop in the FAD 2 is observed at $L_r=1$, due to the yield plateau (see Figure 4.1). As a consequence of this drop, a lack of conservativeness is also observed in the FAD 1 with respect to the FAD 2 in the plastic zone ($L_r > 1$). To avoid this situation all the methods recommend that if the material has a yield plateau then FAD 1 has to be taken with a limit at $L_{r \max}=1$. Figure 4.4 raises the doubt about the size of the yield plateau for a material in which the FAD 1 stops being conservative with respect to the FAD 2. The equation defining this point only depends on the yield stress of the material (σ_y) and its elastic modulus (E). This equation was obtained from the mathematical expressions of the FADs 1 and 2 as well as from the modelling of the stress strain curve for a steel with a yield plateau. The obtained critical size of a yield plateau is $1.88 \sigma_y / E$.

As an example, for a steel with a yield stress of 500 MPa and an elastic modulus of 200 GPa, the critical size of the yield plateau would be around a strain level of 0.5% (Figure 4.5).

Figure 4.6 shows the FADs obtained for a weld stainless steel. Here it can be seen that FAD 1 continues having a small non conservative interval with respect to FAD 2, at $0.25 < L_r < 0.7$. It can also be seen that at the interval close to $L_{r \max}$ the FAD 1 becomes non conservative compared with FAD 2. In this case, as the material does not show a yield plateau (see Figure 4.1, weld stainless steel), the FAD 1 may be drawn for L_r values greater than 1.

Figure 4.7 shows the results for a microalloyed steel for which two types of FAD 1 may be drawn. In this case the FADs 1 of R6 and PD6493 differ more than in the case of the perfect elastic-plastic material (Figure 4.3). A small difference can be seen between the FAD 1 of R6 compared with the FAD 2 in the interval $0.3 < L_r < 0.65$.

Finally, Figure 4.8 shows the FADs 1 and 2 for an aged stainless steel. In this figure the slight non conservativeness of FAD 1 compared with FAD 2 can be observed. In this case the interval is greater than in the previous cases ($0.2 < L_r < 0.9$).

4.2.2. Study of FAD 3 for materials with a stress-strain curve adapted to a Ramberg-Osgood law.

Two materials were chosen to calculate FAD 3. One was taken from Example 1 (aluminium) and the other (Steel A 533-B) from an original EPRI report. The tensile strength characteristics and the Ramberg-Osgood fitting parameters for both materials are shown in Table 4.2

FAD 3 depends on the problem's geometric conditions, including crack size. The corresponding FADs of the two mentioned materials have been calculated under the geometric conditions of Example 1, that defines a pipe with a circumferential through-thickness crack subjected to axial loading. The materials were chosen because they adapt perfectly to the Ramberg-Osgood law. This was necessary because to calculate J_{app} from one of the EPRI Handbooks requires that the material adapt to this type of power law. The results are shown in Figures 4.9 and 4.10. These figures not only show the variation of the FADs 3 with crack size, but also the FADs 1 and 2 of the corresponding material.

Figure 4.9 shows the results for aluminium. Here it can be seen, as for other materials, that FAD 1 is less conservative in the $0.2 < L_r < 0.85$ interval than is FAD 2. Four FADs 3 for different crack sizes can also be seen. Here it can be observed that the area under the corresponding FAD 3 increases as the size of the crack grows. It can also be observed that for a small crack size ($\theta=11.3^\circ$) FAD 3 is more conservative than FAD 2 in the plastic zone ($L_r > 1$). FAD 1 is non conservative in the $0.45 < L_r < 0.9$ interval with respect to the mentioned FAD 3.

For the steel A 533-Grade B (Figure 4.10), contrarily to the previous materials, FAD 2 is always less conservative than FAD 1, which in principal is as would be expected. As in the case of aluminium, FAD 3 corresponding to a small crack ($\theta=11.3^\circ$) is conservative with respect to the FAD 2 for $L_r > 0.6$, and also with respect to the FAD 1 for $L_r > 0.95$.

4.2.3. Study of FAD 3 with materials whose stress-strain curve does not adjust to a Ramberg-Osgood law.

As the formulae provided by the EPRI Handbooks, and others, to calculate J_{app} are only useful for materials which adjust to a Ramberg-Osgood law, until now FADs 3 have been presented for two materials which fit these characteristics. Now, it is interesting to analyse the relative conservativeness of FADs 3 that have been calculated using this method for two materials which do not adjust to Ramberg-Osgood. These materials are the carbon steel and the weld stainless steel analysed in this example. The tensile strength characteristics and their corresponding fits are specified in Table 4.3. The FADs 3 corresponding to these materials have been drawn using the same geometries as for aluminium and the A 533-B steel in the previous section, i.e. for the circumferential through-thickness crack in a pipe subjected to axial loading defined in Example 1. An analysis is also performed on the variation of FAD 3 with crack size, and the FADs 1 and 2 are presented for each material.

The stress-strain curve for the weld stainless steel along with its corresponding Ramberg-Osgood fit are presented in Figure 4.11, where the differences between both curves stand out. The maximum differences are obtained in the zone around the material's yield strength. This fact is directly related to the FADs 3 obtained for the material, which turn out to be extremely conservative in the whole L_r range compared

to the corresponding FADs 1 and 2 of the material for all the crack sizes analysed (Figure 4.12).

The stress-strain curve of the carbon steel is presented in Figure 4.13. The clear yield plateau prevents this material from being correctly modelled by a power law. Figure 4.13 also shows the Ramberg-Osgood fit for this material. In this case, according to the Ramberg-Osgood fit, the resulting FADs are less conservative than in the previous case. For $L_r < 1$, they continue being below FAD 2 (Figure 4.14), but, for $L_r > 1$ and large crack sizes FADs 3 are above FAD 2.

4.2.4. Calculation of FAD 3 using the reference stress method.

As could be seen FAD 3 has a series of disadvantages such as:

- Few solutions available in the bibliography to find J_{app} .
- Complex calculation, because if the FAD line is represented along with the ductile tearing line, the tangential zone between both, once it is obtained, is not representative of the real state of the failure. This is because the FAD line drawn for the initial crack size, after ductile tearing has occurred, is no longer representative of the state of the fracture as this varies with the size of the crack.

Therefore, an attempt was made to construct an alternative FAD 3 following the reference stress method [16]. In this method the J_{app} integral is calculated from the expression of K_I and the stress strain curve of the material for the problem under consideration. The formula provided by the reference for finding J_{app} is:

$$J_{app} = J_{el} + J_{pl}$$

$$J_{el} = \frac{K_I^2}{E'}$$

$$J_{pl} = \frac{\mu \cdot K_I^2}{E} \cdot \left(\frac{E \cdot \epsilon_{ref}}{\sigma_{ref}} - 1 \right)$$

which, when substituted into the expression of FAD 3:

$$K_r = \left(\frac{J_{el}}{J_{tot}} \right)^{-\frac{1}{2}}$$

produces a curve which only depends on the stress-strain curve of the material:

$$K_r = \left[1 + \frac{\mu}{1 - \nu^2} \cdot \left(\frac{E \cdot \epsilon_{ref}}{L_r \cdot \sigma_y} - 1 \right) \right]^{\frac{1}{2}}$$

This expression obtained for the FAD 3 by the reference stress method was already obtained and corrected by Ainsworth, who introduced it as one of the FAD options in the R6 method (FAD 2). The FADs obtained from this expression using different materials are presented for aluminium in Figure 4.15, for steel A 533-B in Figure 4.16, for weld stainless steel in Figure 4.17, and for carbon steel in Figure 4.18 in comparison with FADs 1 and 2. In all these figures it can be seen that the FAD obtained from the reference stress method is always a little less conservative than the FAD 2.

4.3. CONCLUSIONS

The following series of conclusions can be drawn from all the results presented in section 5.2.2.

- The comparison of FADs between two materials is not representative of their resistance as has already been demonstrated in Example 3.
- Although R6 and PD6493 recommend that if the material presents a yield plateau then FAD 1 (Default) should not be used or at least be restricted up to $L_{rmax}=1$, an expression has been found for the maximum size of the yield plateau up to which FAD 1 can be used in the same valid L_r interval as for FADs 2 or 3.
- For values of approximately $L_r < 0.7$ FAD 1 is not conservative compared with FAD 2 in most cases, although this non-conservativeness is small.
- As FAD 3 varies with the size of the crack considered, this means that in some cases it is less conservative than FAD 2.
- Also, owing to the fact that FAD 3 varies with crack size makes it not representative of the real state of the crack after ductile tearing occurs, as the initial crack size has changed.

- If Ramberg-Osgood based formulas are used to calculate FAD 3 (based on J) this type of law has to be perfectly adjusted to the stress-strain curve of the material studied because the FADs are very sensitive to this type of adjustment and to the simplifications they imply. The use of Ramberg-Osgood for obtaining J_{app} in the case of FAD 3 is not mandatory rather there are more ways available for obtaining J_{app} , such as finite elements analysis or the reference stress method.
- The use of formulae based on the reference stress theory are recommended if FADs based on J analysis are used. In fact, the FAD 2 of R6 is a simplification of this theory developed by Ainsworth.

	Perfect elastic-plastic	Carbon steel	Weld stainless steel	Microalloyed steel	Aged stainless steel
s_y (MPa)	260	285	454	840.4	334
s_u (MPa)	260	356.5	684	904	523.6
E (GPa)	210	203	185.9	211.4	188.5

Table 4.1. Mechanical characteristics of steels proposed in Example 4.

	σ_y (MPa)	σ_u (MPa)	ϵ_0	E (GPa)	α	n
Aluminium	165	310	$2.36 \cdot 10^{-3}$	70	1.029	4.96
A 533-B	413.7	689.5	$2 \cdot 10^{-3}$	206.85	1.12	9.71

Table 4.2. Tensile characteristics and Ramberg-Osgood parameters.

	σ_y (MPa)	σ_u (MPa)	ϵ_0	E (GPa)	α	n
Carbon Steel	321.7	636	$1.54 \cdot 10^{-3}$	208.5	3.36	4.2125
Weld stainless steel	453.9	990	$2.44 \cdot 10^{-3}$	185.85	12.96	3.1804

Table 4.3. Tensile characteristics and Ramberg-Osgood parameters.

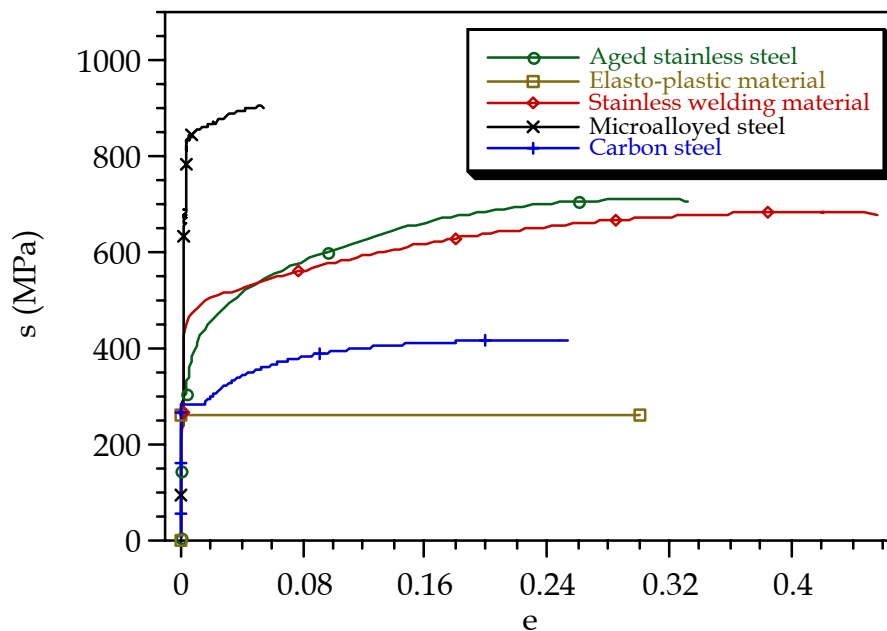


Figure 4.1. Comparison between materials. Engineering stress-strain curves.

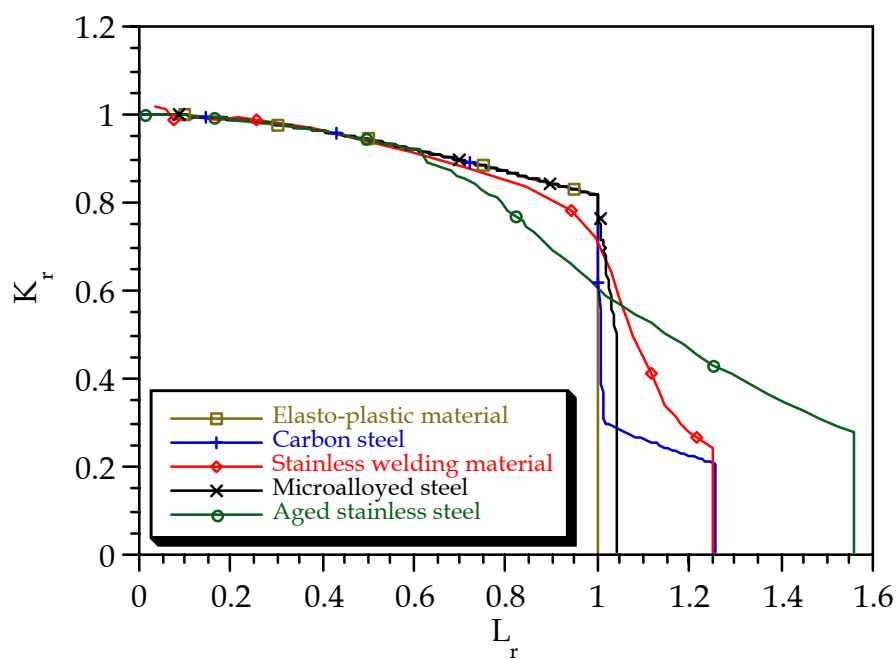


Figure 4.2. Comparison of FADs 2 (Specific) for different materials.

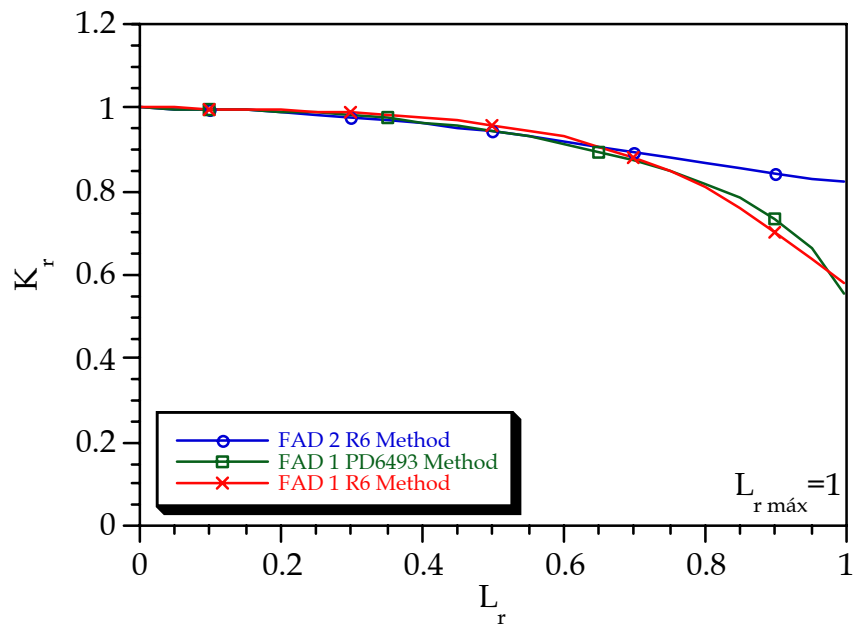


Figure 4.3. Elastic-plastic material. FADs 1 & 2.

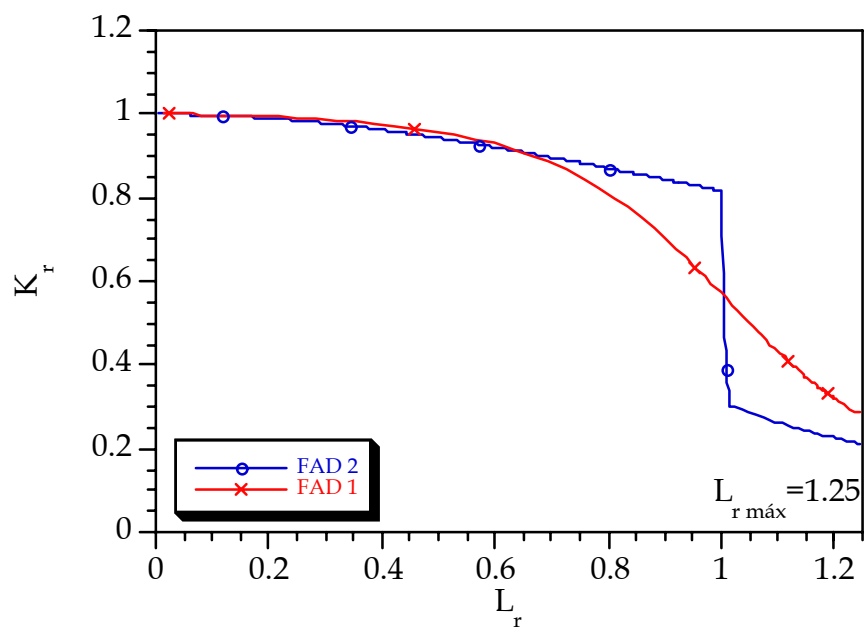


Figure 4.4. Carbon steel. FADs 1 & 2.

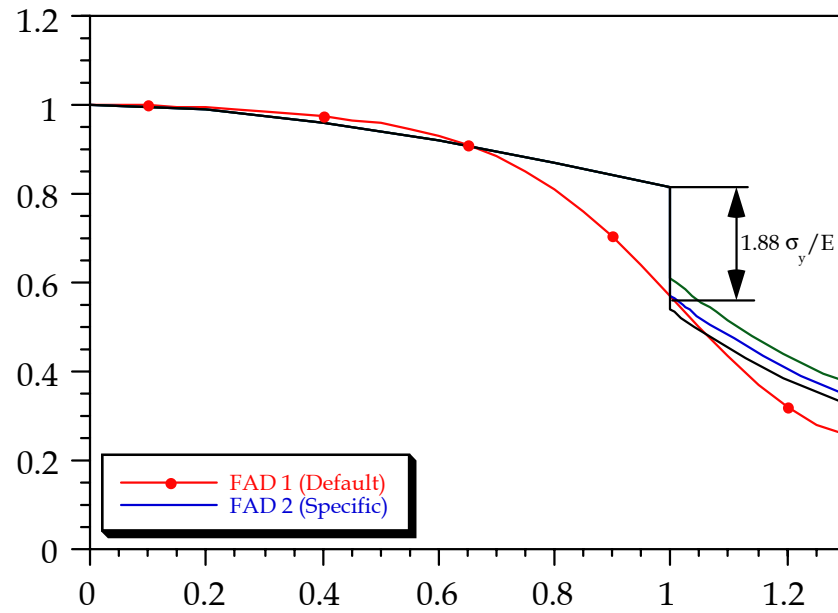


Figure 4.5. Critical size of Yield Plateau.

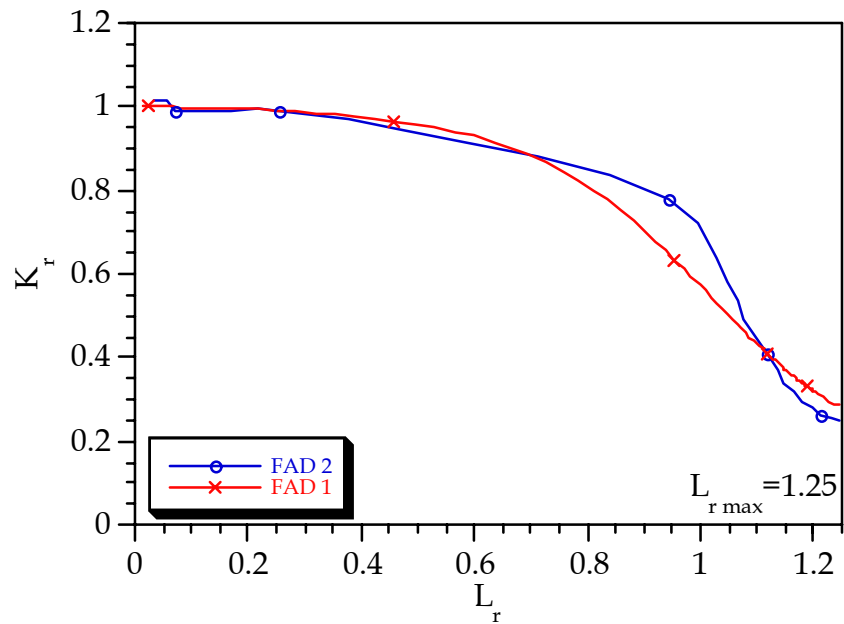


Figure 4.6. Weld stainless steel. FADs 1 & 2.

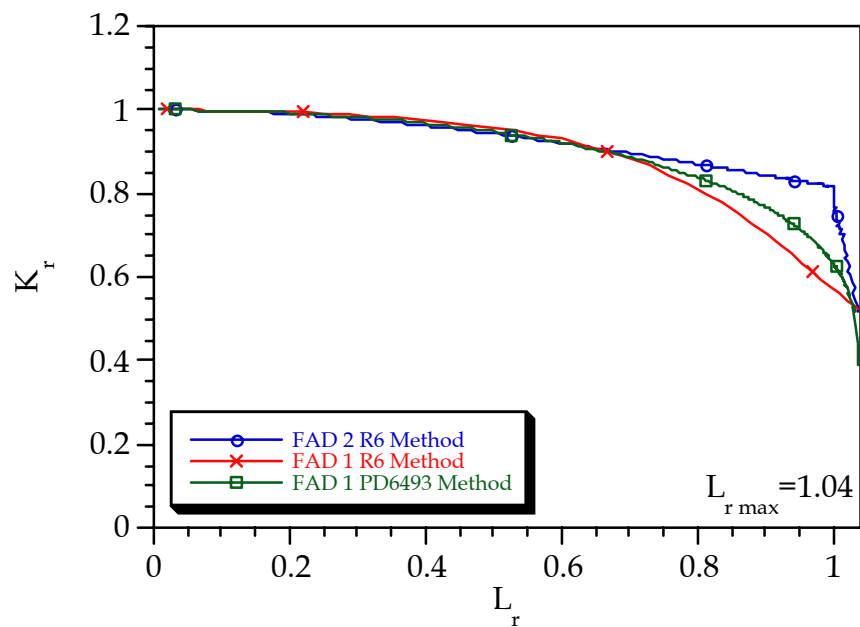


Figure 4.7. Microalloyed steel. FADs 1 & 2.

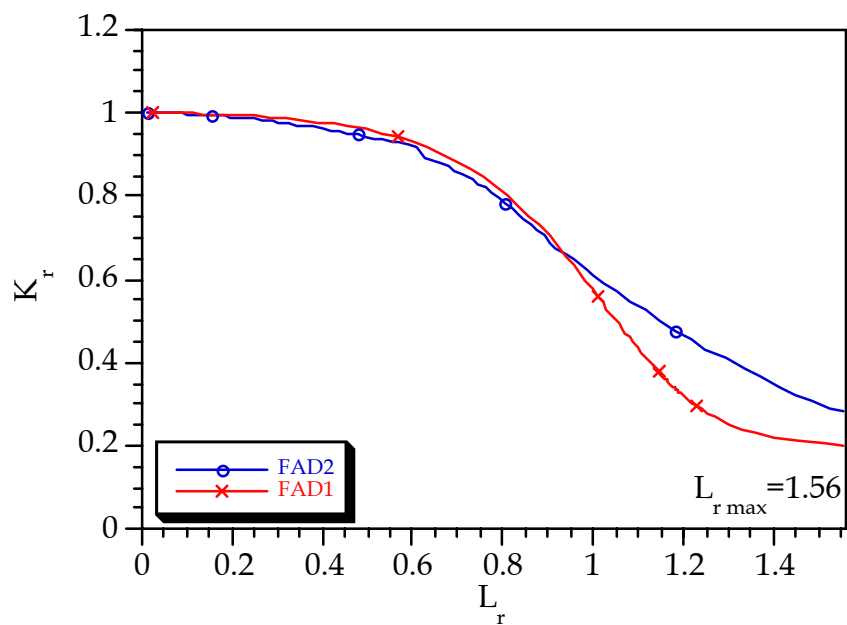


Figure 4.8. Aged stainless steel. FADs 1 & 2.

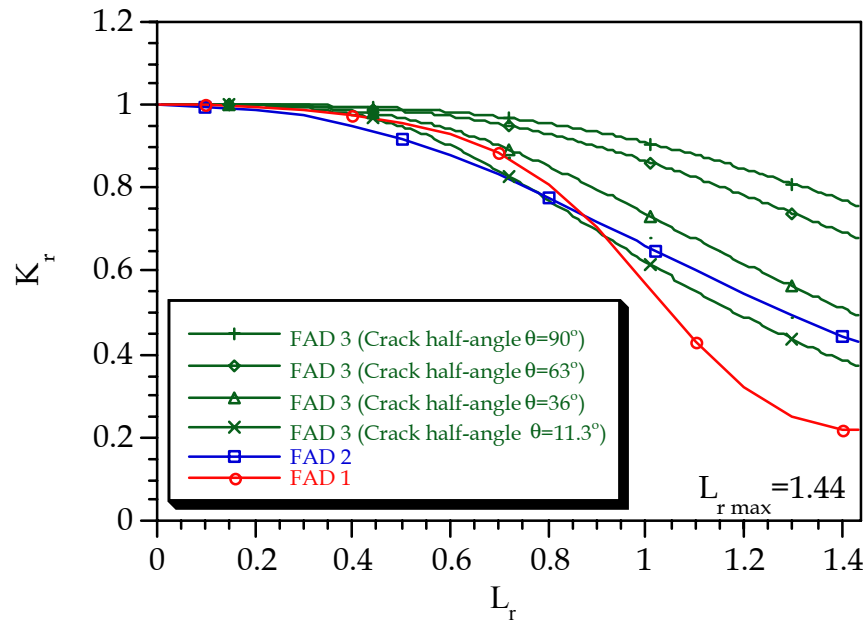


Figure 4.9. FADs 1, 2 & 3. Aluminium. Circumferential through-thickness crack in a pipe for uniform axial load.

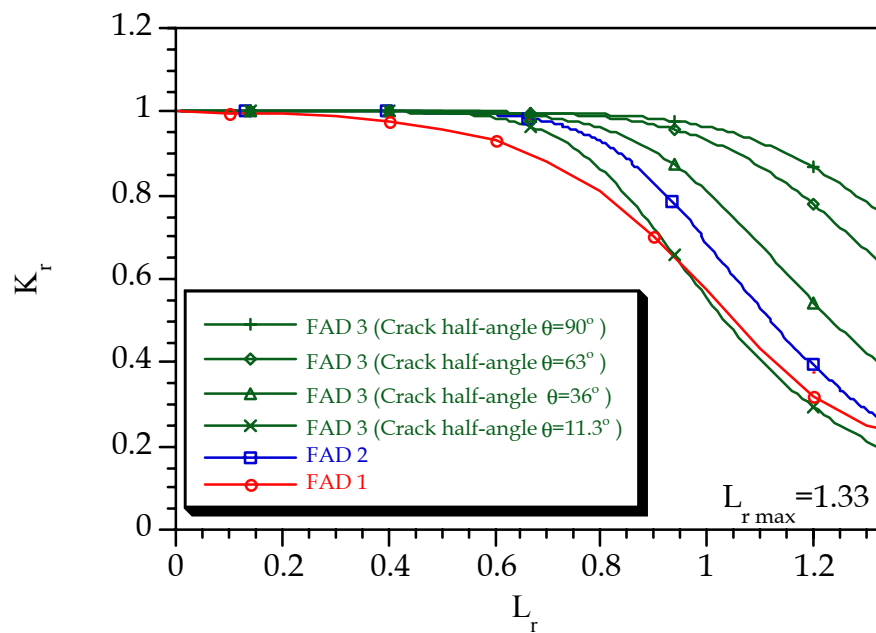


Figure 4.10. FADs 1, 2 & 3. A 533-B steel. Circumferential through-thickness crack in a pipe for uniform axial load.

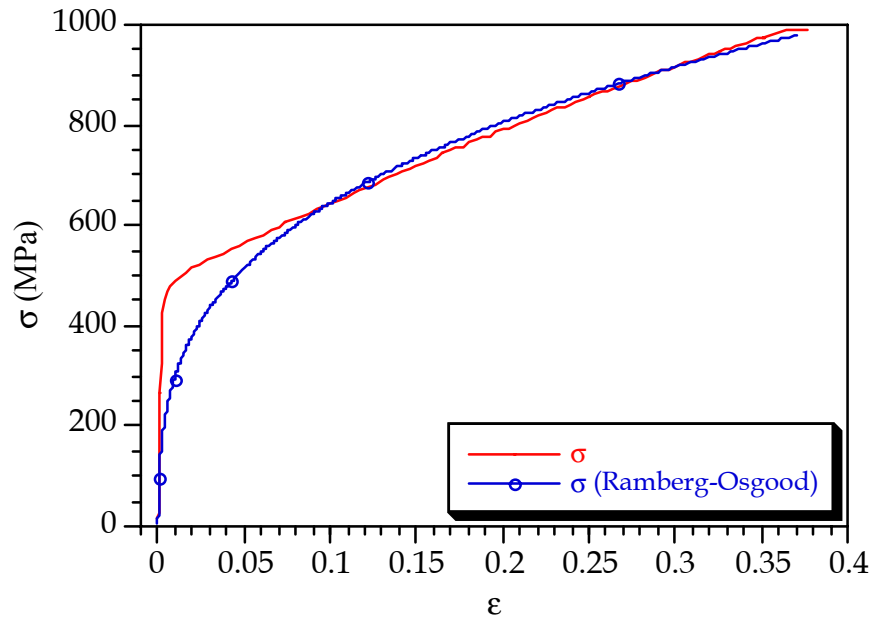


Figure 4.11. Weld stainless steel. Real and Ramberg-Osgood stress-strain curves.

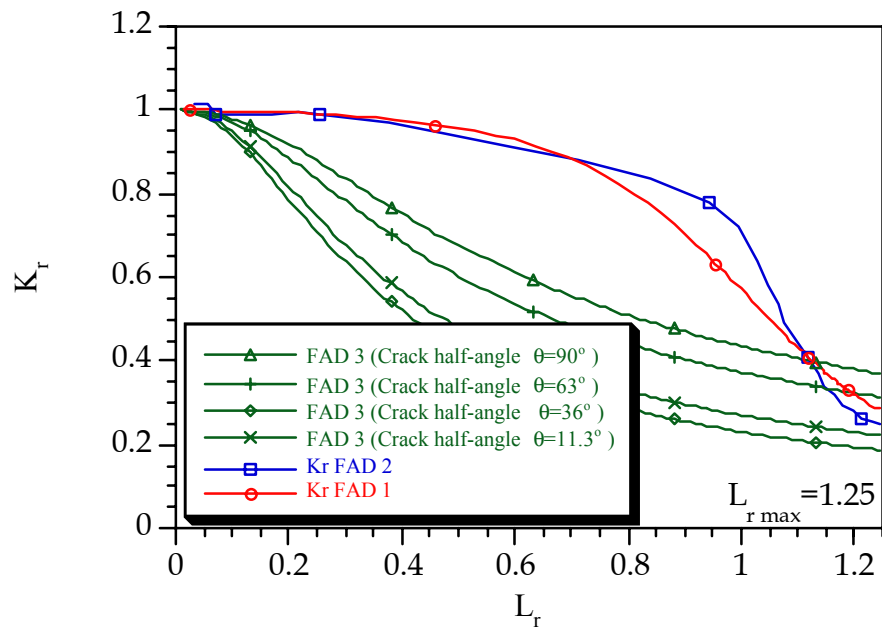


Figure 4.12. FADs 1, 2 & 3. Weld stainless steel. Circumferential through-thickness crack in a pipe for uniform axial load.

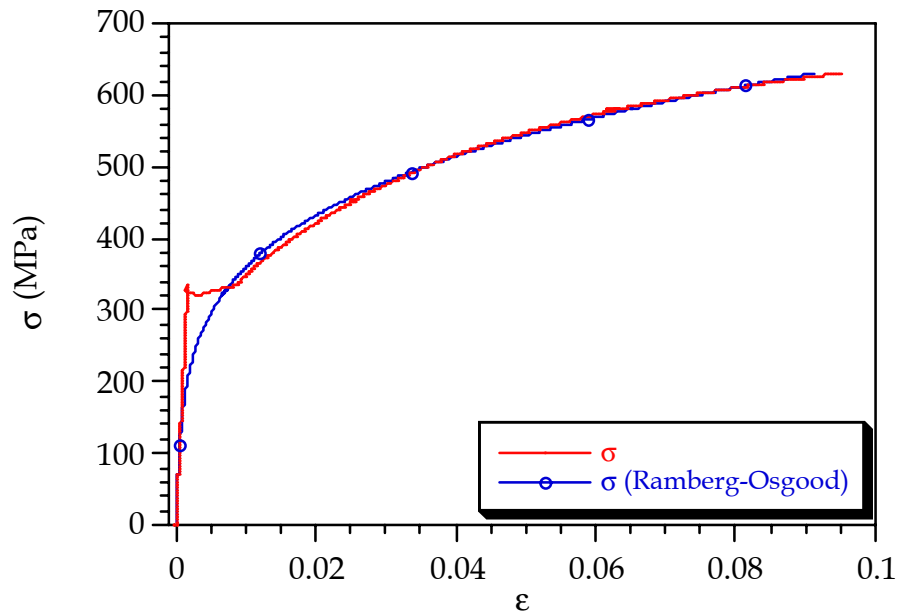


Figure 4.13. Carbon steel. Real and Ramberg-Osgood stress-strain curves.

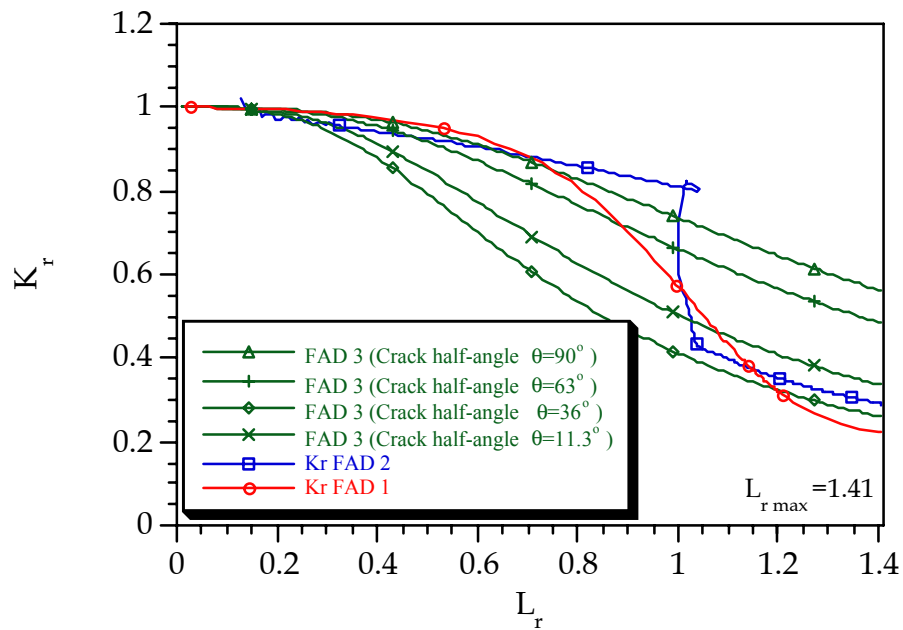


Figure 4.14. FADs 1, 2 & 3. Carbon steel. Circumferential through-thickness crack in a pipe for uniform axial load.

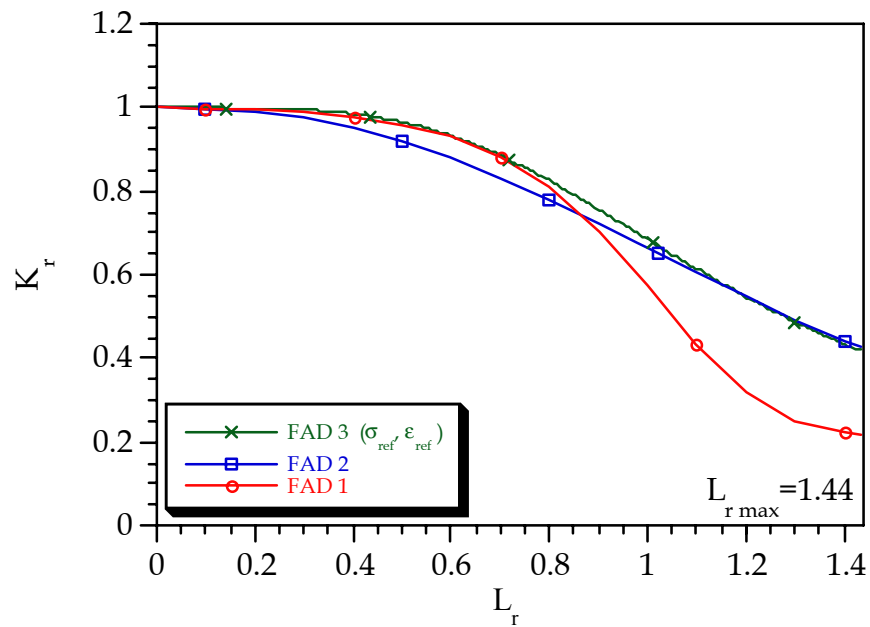


Figure 4.15. Aluminium. FADs 1 & 2, FAD 3 based on reference stress method.

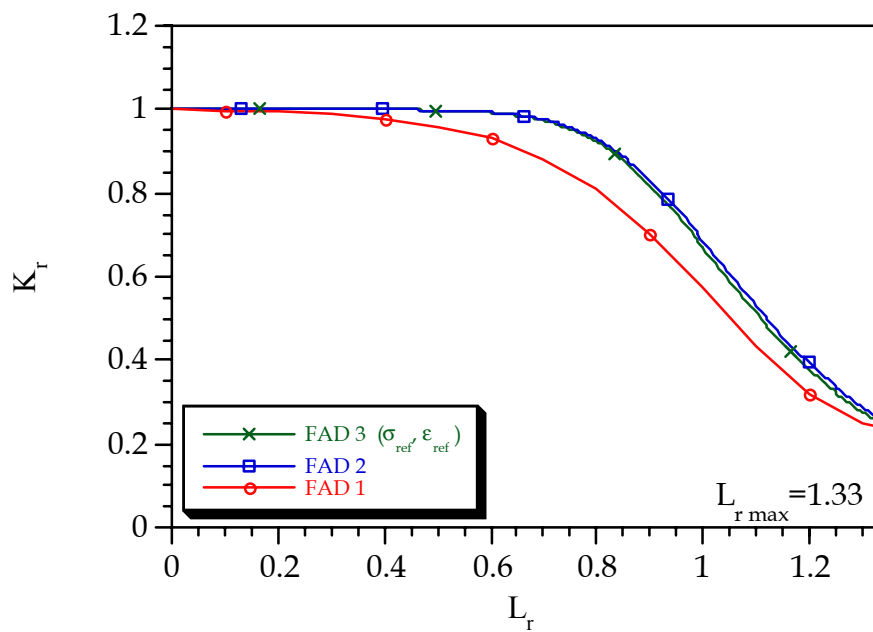


Figure 4.16. A 533-B steel. FADs 1 & 2, FAD 3 based on reference stress method.

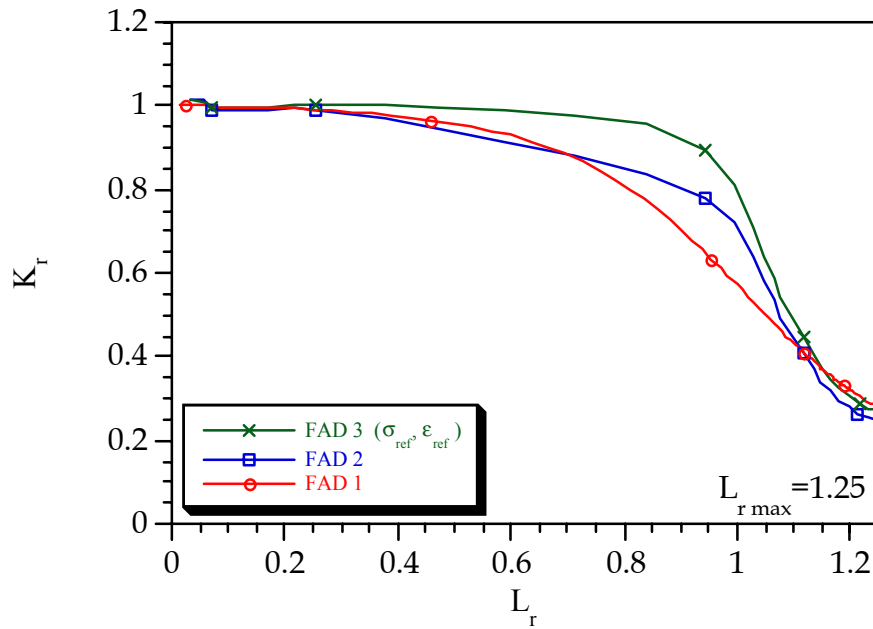


Figure 4.17. Weld stainless steel. FADs 1 & 2, FAD 3 based on reference stress method.

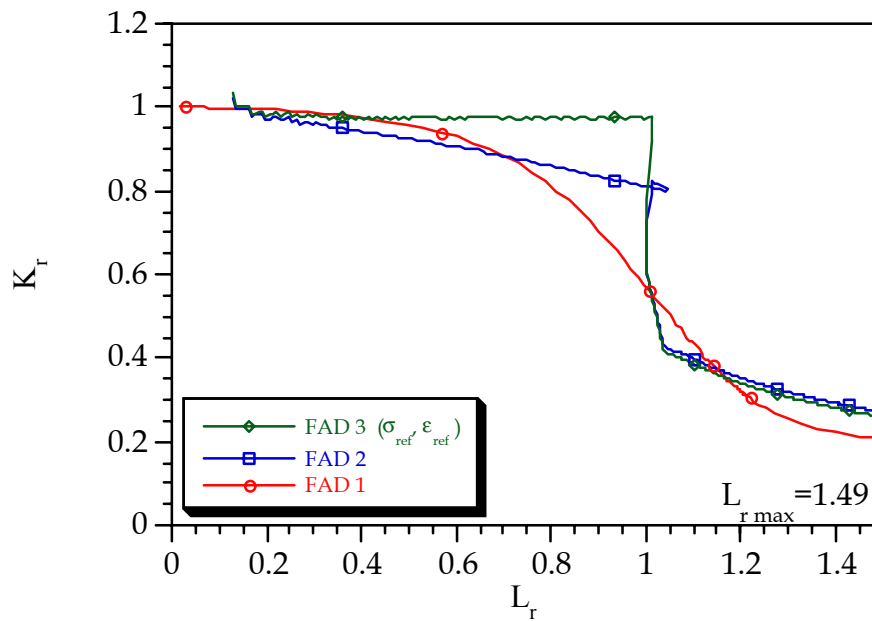


Figure 4.18. Carbon steel. FADs 1 & 2, FAD 3 based on reference stress method.

5. EXAMPLE 5

This example was chosen in order to verify the level of absolute conservativeness of each method compared with reality. Data have been taken from real tests performed on wide plates by TWI as a validation of the BSI PD6493 method [17]. This data was used to perform the calculations in accordance with the available procedures. An attempt was made to faithfully follow the indications of each option in individual procedures in order to evaluate the degree of real conservativeness of all the methods. If a handbook was available for the method then it was used.

GE-EPRI could not be used for this example because the corresponding solution for J_{app} was not available for us for the geometry studied. In spite of that, an effort was made to use all the procedures which were available to the University of Cantabria at that moment.

5.1. DEFINITION

The example chosen is the calculation of the maximum membrane tensile stress supported by a wide plate of steel A 533-B with a part-through surface crack. The geometry of the steel plate is shown in Figure 5.1.

The calculations were performed on two of these plates with different geometric dimensions called specimens M01-01 and M01-12 [17].

- Geometrical dimensions:

- Specimen M01-01

Thickness of plate, B	51.5 mm
Width of plate, W	496 mm
Crack depth, a	24.9 mm
Crack length, 2c	145.8 mm

- Specimen M01-12

Thickness of plate, B	25 mm
Width of plate, W	500 mm

Crack depth, a	14.6 mm
Crack length, $2c$	135 mm

The stress-strain curve values for the material are shown in Table 5.1, defining the following:

- Mechanical characteristics (for both specimens):
 - Yield stress 471 MPa
 - Ultimate tensile strength 591 MPa
 - Fracture stress of specimen M01-01 476 MPa
 - Fracture stress of specimen M01-12 447 MPa
- Fracture toughness:

The Fracture Toughness data come from SENB type specimens and are valid for the two specimens considered in the example, M01-01 and M01-12.

- δ_{Ic}	0.57 mm
- δ_R	$\delta_R = 1.032 (\Delta a)^{0.475}$
- K_{Ic}	354.3 MPa m ^{1/2}
- J_R	$J_R = 846 (\Delta a)^{0.475}$

where δ_R and Δa are expressed in mm and J_R in KN/m.

Given that fracture toughness can be expressed through δ or K_I and that this information is available although the data is slightly different, the calculations will be made using these two types of inputs to also observe the sensitivity of the procedures to variations in the input data.

5.2. CALCULATIONS AND RESULTS

The calculations were made using the different analysis options of each method on the two specimens mentioned above. Special care has been taken in applying all the steps described in each procedure and two types of input have been used for fracture toughness.

The calculations have been made using the following methods and options:

- R6 Method: Categories 1 and 3, FADs 1 and 2.
- BSI PD6493: Level 1, 2 and 3, FADs 1 and 2.
- SAQ.
- MPC.
- EFAM ETM 95: Simplified method.

In this example, the type of fracture considered depends on the two parameters, depth (a) and length ($2c$). The procedures that consider ductile tearing do not clarify in which of the two parameters the tearing has to take place. Only MPC provides some guidelines which can be used in the calculations. One of these guidelines given by the document has been used in this and in all the other methods. In order to simplify the calculations it was assumed for both specimens that the ductile tearing only occurred in the direction of crack depth.

For both specimens the points representing the real fracture load have been calculated using both K_{Ic} and δ_{Ic} as toughness input data. Once this was done the reserve factor was calculated as the quotient between the load predicted by each method as fracture and the real fracture load of the element (the one represented in the FAD). This reserve factor gives us an idea about the absolute conservativeness of each method, and it also enables a comparison to be established between all the procedures evaluated. In the ETM method, which does not use the FAD, the critical load was calculated following the simplified method (initiation of stable or unstable crack growth) and also according to the Crack Driving Force (Initiation of unstable crack growth). Once the fracture load predicted by the method has been obtained the reserve factor was obtained in the same way as in the methods which use the FAD. Therefore, the results according to ETM could also be compared with the rest in the same way.

5.2.1. Specimen M01-01

Figure 5.2 shows the results obtained following Level 1 of PD6493. This figure also shows the points which represent the real failure of the element, each one representing the same load but taking the fracture toughness value as K_{Ic} in one and as δ_{Ic} in the other. As can be seen the fracture toughness value (K_{Ic}) is less conservative than that corresponding to δ_{Ic} given that for the same load it is located in a lower position.

Figure 5.3 shows the results following PD6493 using Level 2 of analysis, with the FADs Default and Specific. Like in Figure 5.2, the point resulting from the use of K_{Ic} as the input value in the calculation is less conservative than that corresponding to δ_{Ic} . Both points are represented for the real failure load of the element.

Figures 5.4 and 5.5 show the results following PD6493 using Level 3 of analysis. For Figure 5.4 the loci corresponding to the element have been represented using as fracture toughness input data that which was previously specified as J_R . Three loci have been represented, one corresponding to the real failure value of the element, the other two are those predicted by the analysis as critical according to the FADs Default and Specific. An identical situation is presented in Figure 5.5 but with the curve δ_R given in the definition of the example as the input toughness data.

The results according to R6 are shown in Figures 5.6 and 5.7. In this procedure only (K_{Ic}) has been used as input toughness data given that it does not contemplate the use of the CTOD. Figure 5.6 presents the result using the Category 1 of analysis with the FADs Default and Specific, while the results in the case of using Category 3 of analysis with the same FADs are presented in Figure 5.7.

The point corresponding to the fracture of the element following the SAQ procedure is presented in Figure 5.8. Only K_{Ic} is used since this method does not contemplate the use of the CTOD.

The results found through MPC in which the two toughness values (K_{Ic} and δ_{Ic}) are used are presented in Figure 5.9.

Figure 5.10 shows the Crack Driving Force obtained by ETM. In order to elaborate this graph the J_R toughness curve given in the definition of the example was used and represented in the figure for the crack size. Then, the critical load which makes the J_{app} curve tangential to J_R was found.

All the analytical results of the methods used are shown in Table 5.2 along with the corresponding analysis options applied. In the methods which use the FAD the points represented in Figures 5.2 to 5.9 corresponding to the real failure of the specimen, are given in the table by their coordinates. Their "x" axis (plastic collapse parameter) are presented by the row " S_r or L_r ", while the "y" axis values (fracture failure parameter) are presented in the rows " K_r " or " δ_r " depending whether the input toughness data has been K_{Ic} or δ_{Ic} , respectively. The conservativeness factors (failure load predicted by the method divided by the real failure load) are given in the final rows in the table for each option of all the methods studied. " $F^*(K_{Ic})$ " represents these conservativeness factors found when the input toughness was K_{Ic} or J_R , and " $F^*(\delta_{Ic})$ " when it was δ_{Ic} or δ_R .

In Figure 5.11 a comparison, based on the conservativeness factors found, is established between the results of each method when the input toughness was K_{Ic} or J_R . Finally, in Figure 5.12, the same type of comparison is made as in the previous figure when the input values were δ_{Ic} or δ_R .

5.2.2. Specimen M01-12

Figures 5.13, 5.14, 5.15 and 5.16 show the graphic results obtained following PD6493. Figure 5.13 presents the results using Level 1 of analysis. Figure 5.14 presents the identical situation but using Level 2 and the FADs Default and Specific. While Figures 5.15 and 5.16 use Level 3 of analysis for the input toughness data J_R or δ_R , respectively.

The graphic results for R6 are shown in Figures 5.17 and 5.18, where analysis Categories 1 and 3 have been used, respectively. As stated in the previous section, this procedure does not contemplate the use of CTOD as input data, and therefore this possibility was not used.

The result according to SAQ is shown in Figure 5.19, and that corresponding to MPC, in Figure 5.20.

Finally, Figure 5.21 shows the calculation of the critical load following ETM using the CDF, the graphic solution of which was drawn the same way as in the case of specimen M01-01.

All the analytical results obtained by the methods used are expressed in Table 5.3. along with the conservativeness factor values obtained in each method. In order to obtain a comparative graphic expression of the values obtained for these factors coming from each method and their corresponding options, a graphic comparison is established in Figures 5.22 and 5.23 which show, on the one hand the conservativeness factors obtained from K_{Ic} or J_R , and on the other, those coming from δ_{Ic} or δ_R , respectively. In these two last figures it can be seen that Specimen M01-12 presents lower conservativeness factors than those of specimen M01-01 (Figures 5.11 and 5.12), a fact indicating that all the procedures considered have been more conservative in the prediction of fracture load for specimen M01-12. This can be associated to the reduction of thickness which is the main difference presented by this specimen when compared to the first one.

5.3. CONCLUSIONS

Although the calculations were only made for two specimens, a series of conclusions can be drawn from an analysis of the results of Example 5.

- All the methods evaluated are conservative, and in no case the load predicted as critical for each of the methods passes 80% of the real failure load.
- The less conservative methods at the most precise level of analysis are R6 and PD6493.
- ETM is the most conservative method. This is so because the solution for the plastic collapse of the studied section is much more conservative than in the rest of the methods. For example, if the PD6493 solution is used then similar results to those of the least conservative methods are obtained.
- The specimen geometry has an important effect on the obtained reserve factor for each procedure.

Steel A 533-B	
s (MPa)	e (%)
50	0.0242
100	0.0483
150	0.0725
200	0.0966
250	0.1208
300	0.1449
350	0.1691
400	0.1932
450	0.2174
471	0.228
479	1.348
502	2.098
526	2.978
545	3.848
569	4.848
573	5.848
581	6.978
588	8.098
589	9.348
591	10.598
591	11.848
590	12.228

Table 5.1. Stress-strain data. A 533-B steel.

	Method	PD6493					R6				SAQ	MPC	ETM	
	Variable	L 1	L 2.1	L 2.2	L 3.1	L 3.2	C 1.1	C 1.2	C 3.1	C 3.2			1 (*)	2 (**)
Real	Kr	0.459	0.505	0.505	-	-	0.459	0.459	-	-	0.447	0.459	-	-
Failure	$\sqrt{\delta_r}$	0.597	0.761	0.761	-	-	-	-	-	-	-	0.491	-	-
Coordinates	Sr or Lr	1.251	1.551	1.551	-	-	1.410	1.410	-	-	1.409	1.410	-	-
	F*(K _{Ic})	0.638	0.642	0.688	0.706	0.789	0.707	0.765	0.706	0.789	0.708	0.707	0.687	0.691
	F*(δ_{Ic})	0.642	0.644	0.660	0.792	0.706	-	-	-	-	-	0.710	-	-

Table 5.2. Specimen M01-01. Analytical results.

1 (*) Stable or unstable crack growth initiation.

2 (**) Unstable ductile crack growth.

	Method	PD6493					R6				SAQ	MPC	ETM	
	Variable	L 1	L 2.1	L 2.2	L 3.1	L 3.2	C 1.1	C 1.2	C 3.1	C 3.2			1 (*)	2 (**)
Real Failure Coordinates	K _r	0.416	0.458	0.458	-	-	0.416	0.416	-	-	0.405	0.416	-	-
	$\sqrt{\delta_r}$	0.552	0.689	0.689	-	-	-	-	-	-	-	0.445	-	-
	S _r /L _r	1.467	1.819	1.819	-	-	1.654	1.654	-	-	1.653	1.654	-	-
	F*(K _{Ic})	0.547	0.549	0.620	0.597	0.672	0.606	0.681	0.597	0.672	0.606	0.606	0.492	0.526
	F*(δ_{Ic})	0.541	0.548	0.579	0.597	0.673	-	-	-	-	-	0.604	-	-

Table 5.3. Specimen M01-12. Analytical results

1 (*) Stable or unstable crack growth initiation.

2 (**) Unstable ductile crack growth.

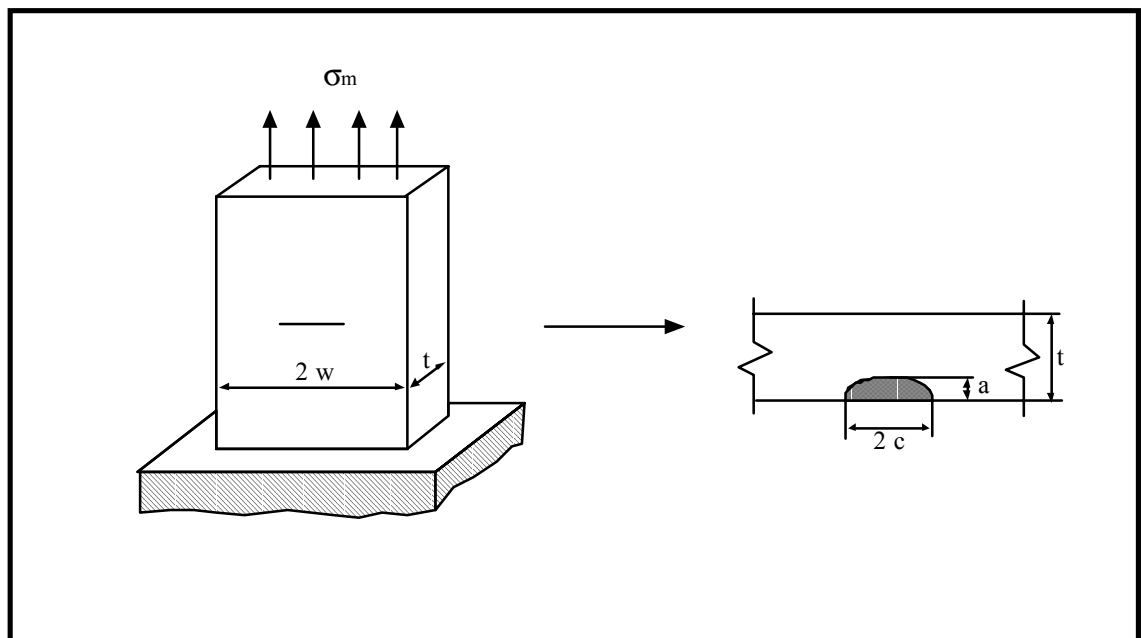


Figure 5.1. Geometrical definition of Example 5.

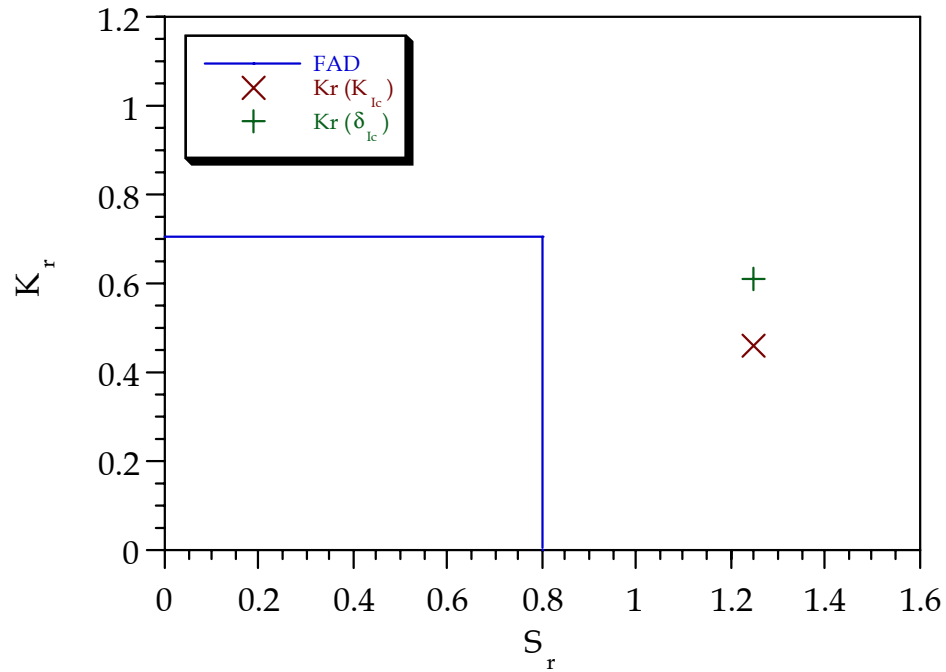


Figure 5.2. Specimen M01-01. Level 1 PD6493. Input toughness data K_{Ic} & δ_{Ic} .

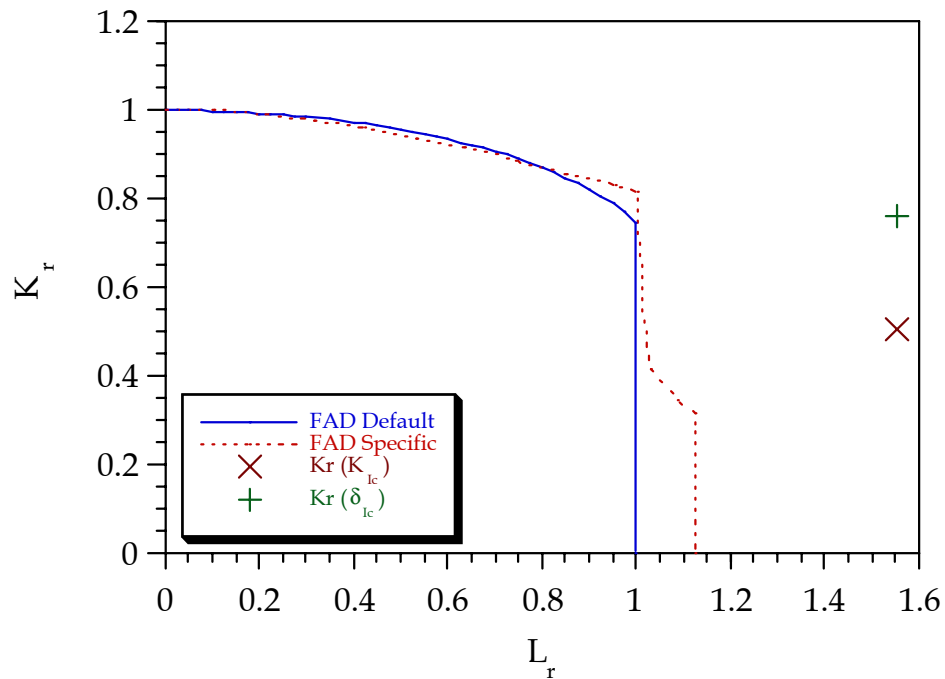


Figure 5.3. Specimen M01-01. Level 2 PD6493. FADs Default & Specific. Input toughness data K_{Ic} & δ_{Ic} .

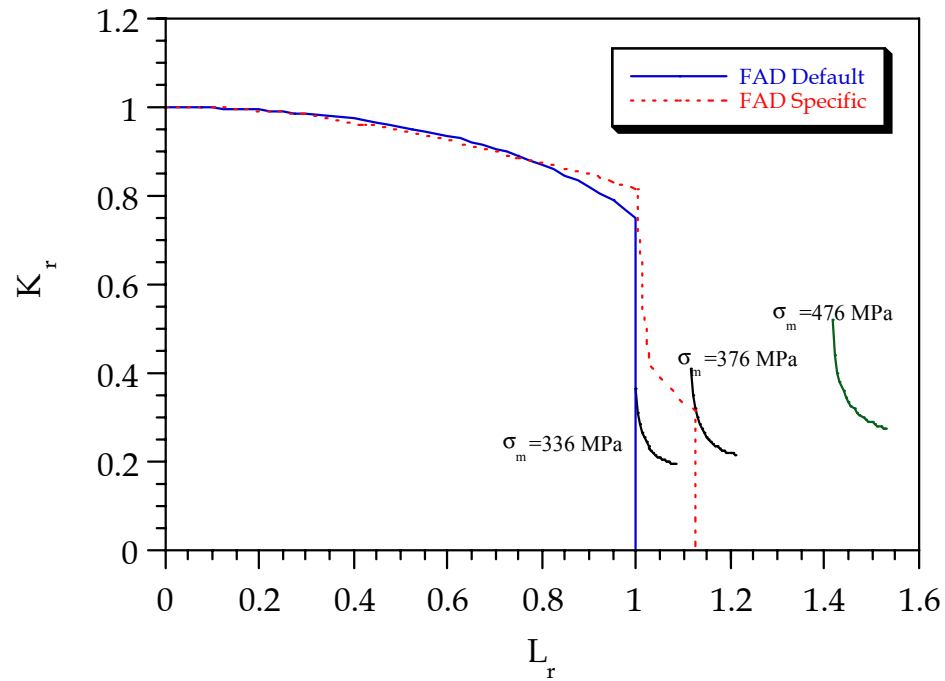


Figure 5.4. Specimen M01-01. Level 3 PD6493. FADs Default & Specific.
Input toughness data J_R .

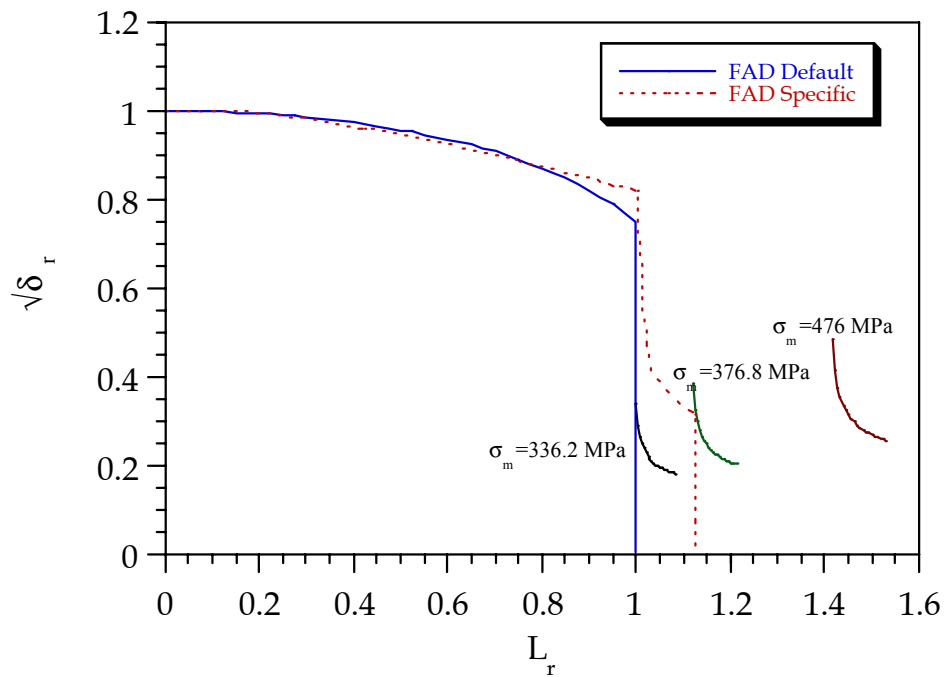


Figure 5.5. Specimen M01-01. Level 3 PD6493. FADs Default & Specific.
Input toughness data δ_R .

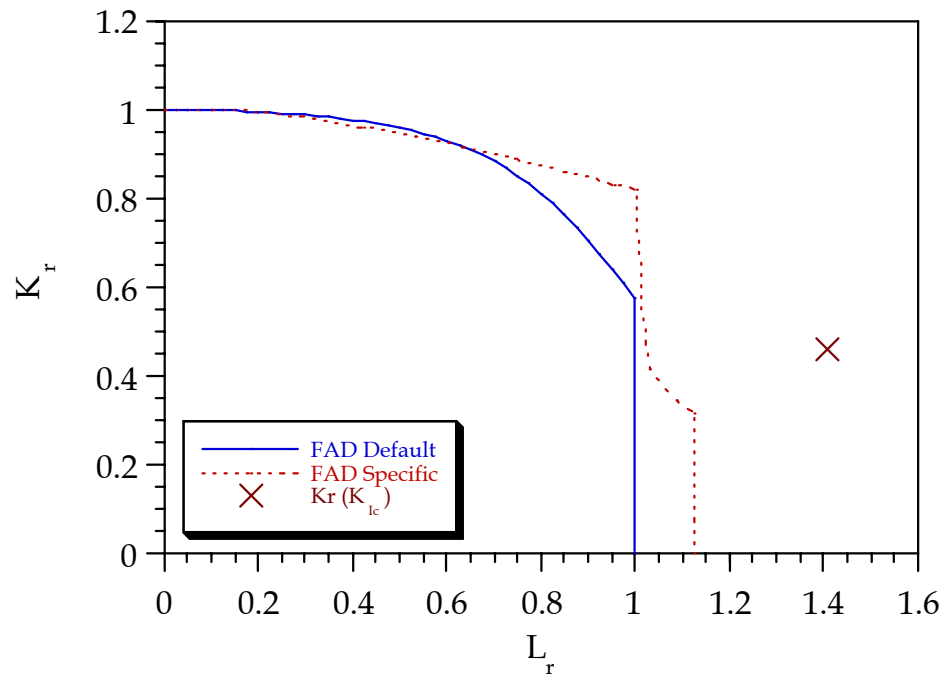


Figure 5.6. Specimen M01-01. Category 1 R6. FADs Default & Specific. Input Toughness data K_{Ic} .

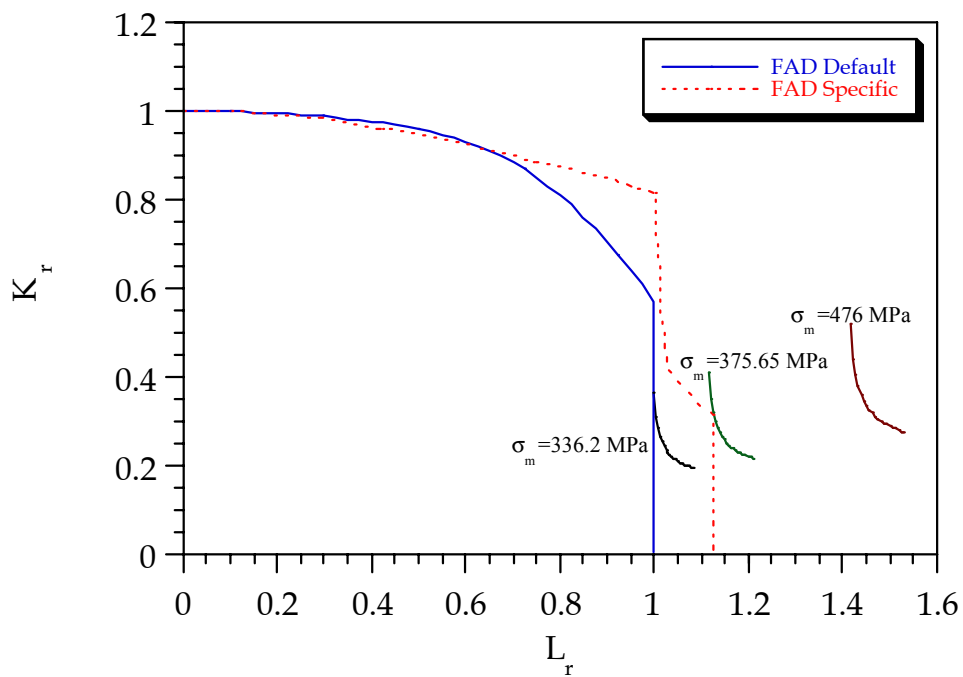


Figure 5.7. Specimen M01-01. Category 3 R6. FADs Default & Specific. Input toughness data J_R .

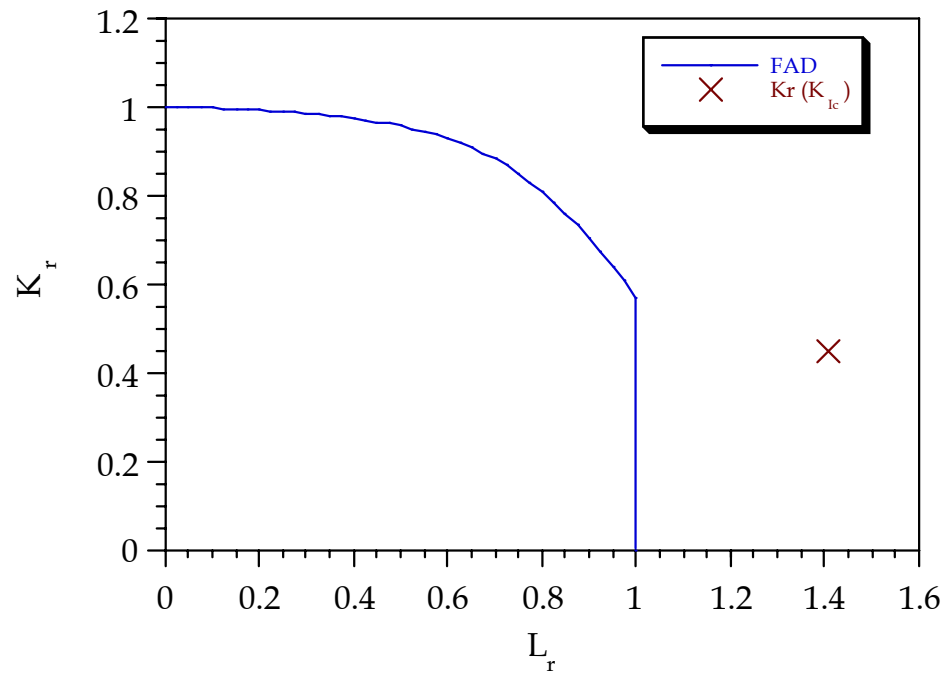


Figure 5.8. Specimen M01-01. SAQ. Input toughness data K_{Ic} .

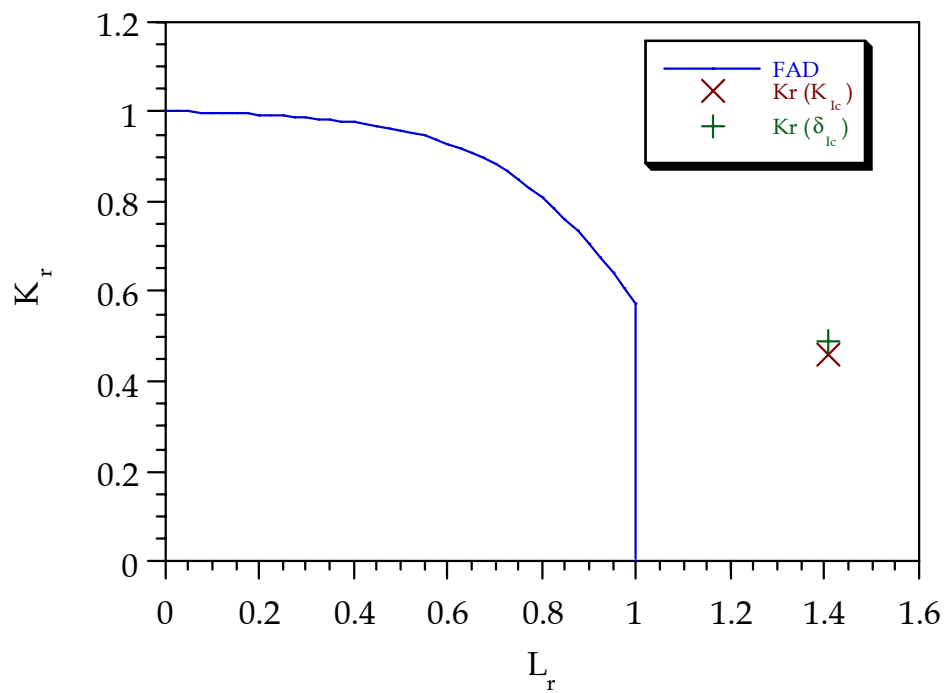


Figure 5.9. Specimen M01-01. MPC. Input toughness data K_{Ic} & δ_{Ic} .

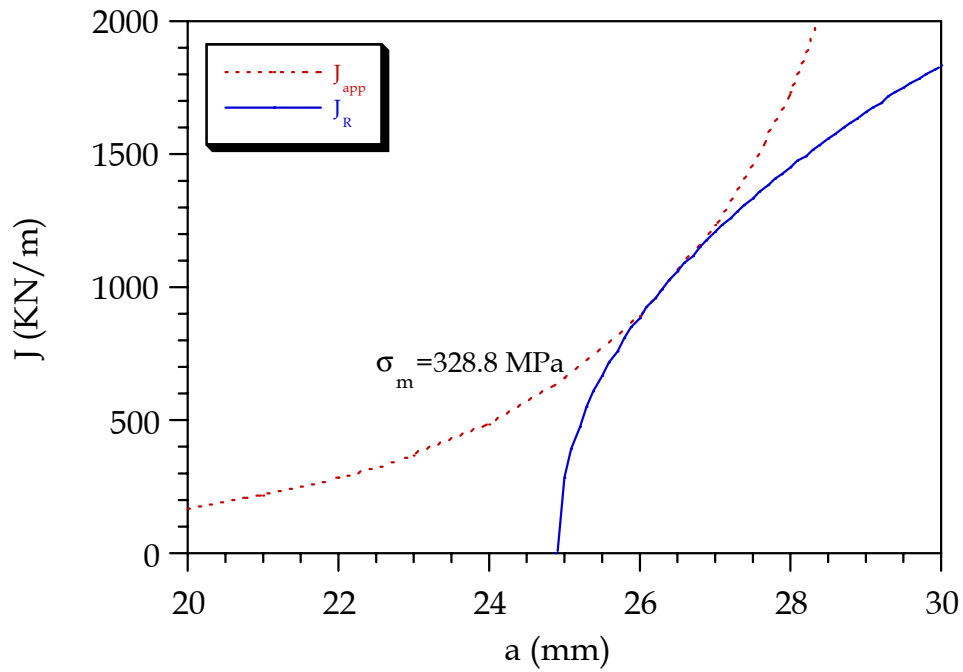
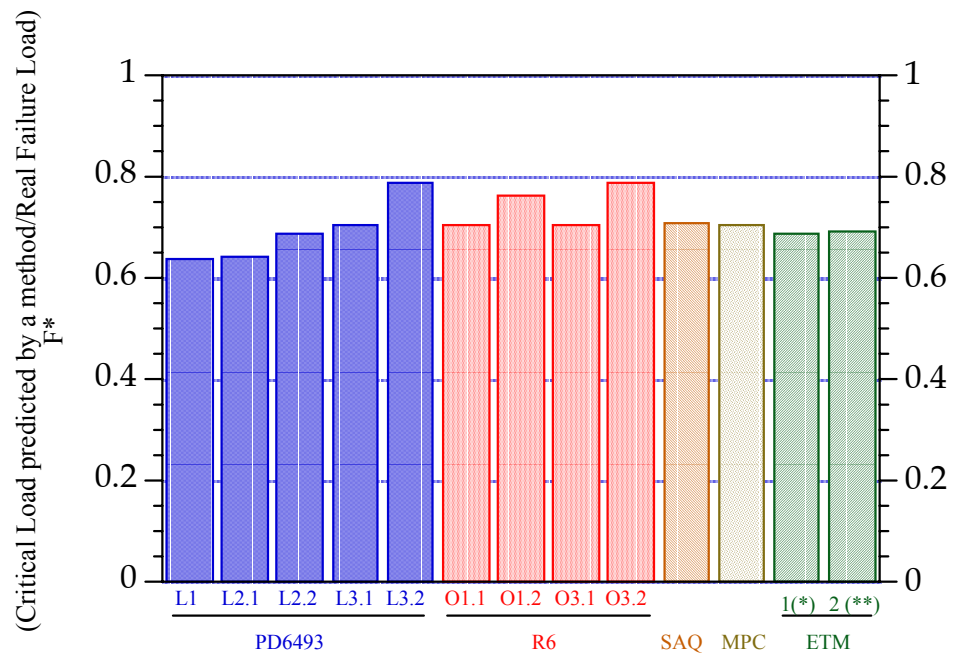


Figure 5.10. Specimen M01-01. ETM. Input toughness data J_R .



1(*) Stable or unstable crack growth initiation.

2(**) Unstable ductile crack growth.

Figure 5.11. Comparison between methods. Critical axial load results. Specimen M01-01. Fracture toughness input K_{Ic} & J_R .

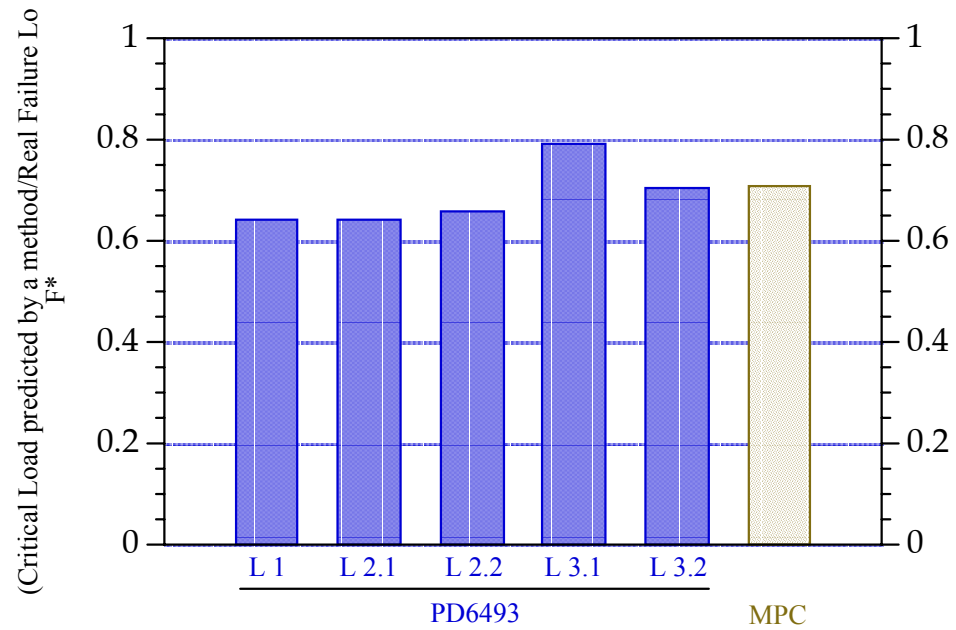


Figure 5.12. Comparison between methods. Critical axial load results. Specimen M01-01. Fracture toughness input δ_{Ic} & δ_R .

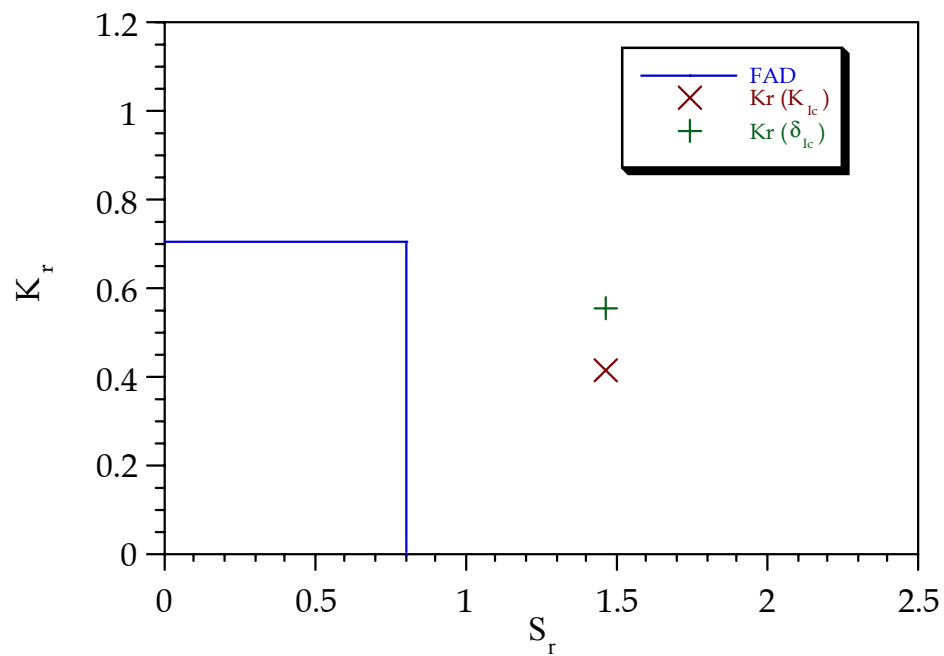


Figure 5.13. Specimen M01-12. Level 1 PD6493. Input toughness data K_{Ic} & δ_{Ic} .

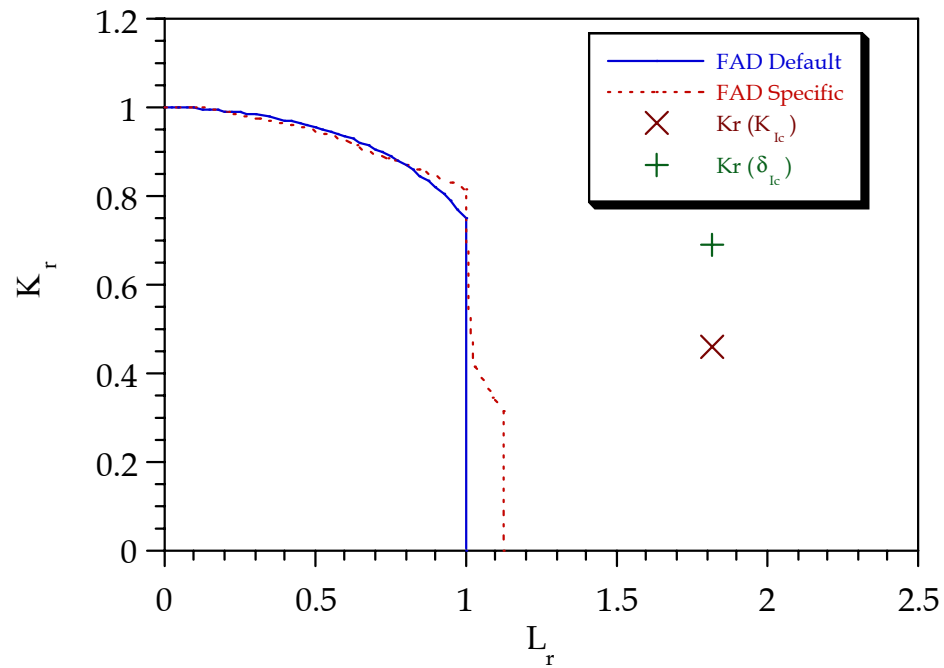


Figure 5.14. Specimen M01-12. Level 2 PD6493. FADs Default & Specific.
Input toughness data K_{Ic} & δ_{Ic} .

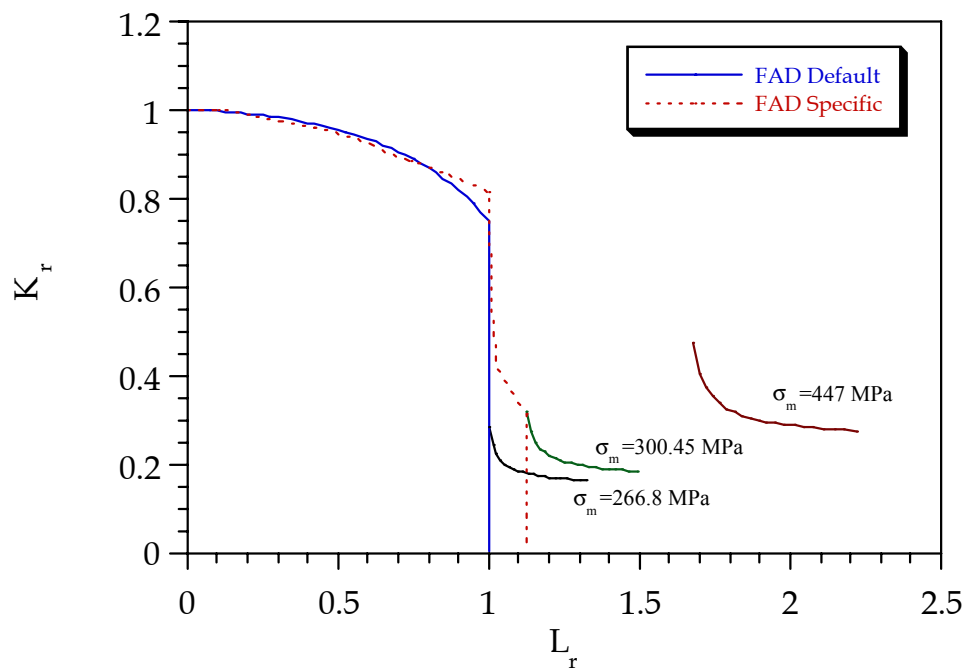


Figure 5.15. Specimen M01-12. Level 3 PD6493. FADs Default & Specific.
Input toughness data J_R .

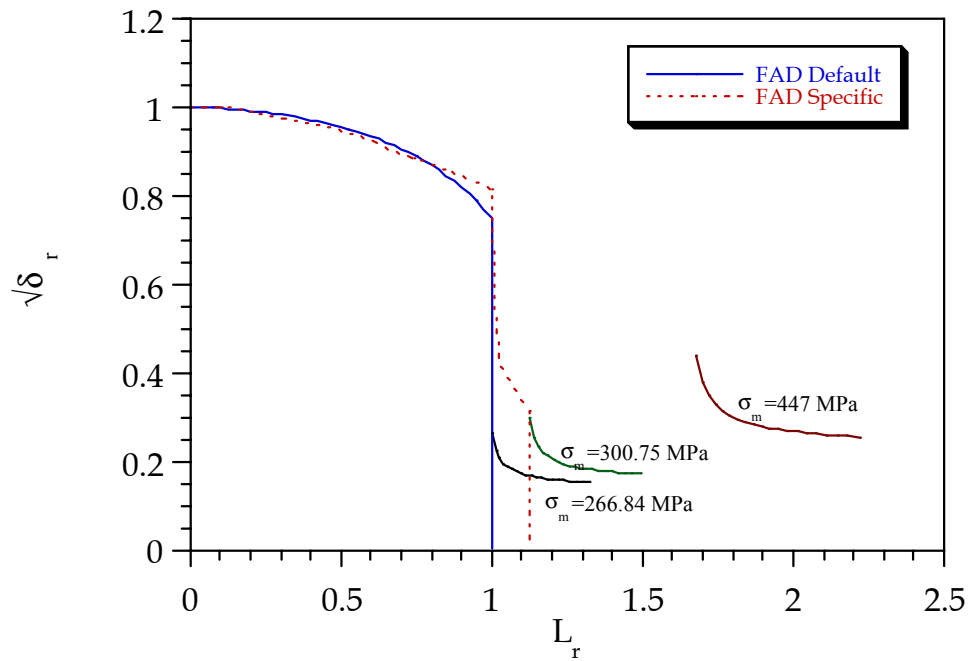


Figure 5.16. Specimen M01-12. Level 3 PD6493. FADs Default & Specific.
Input toughness data δ_R .

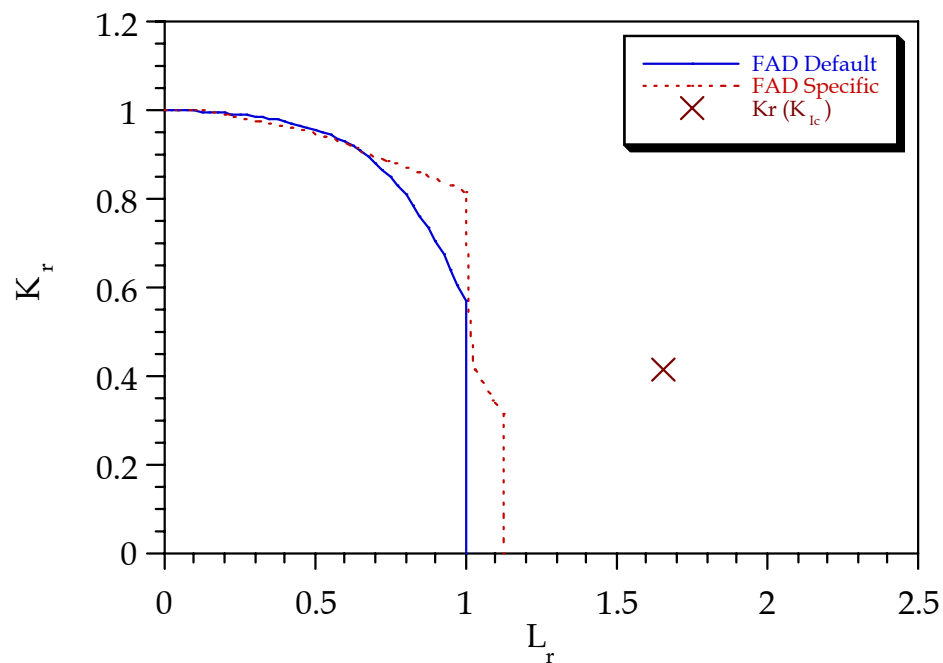


Figure 5.17. Specimen M01-12. Category 1 R6. FADs Default & Specific.
Input toughness data K_{Ic} .

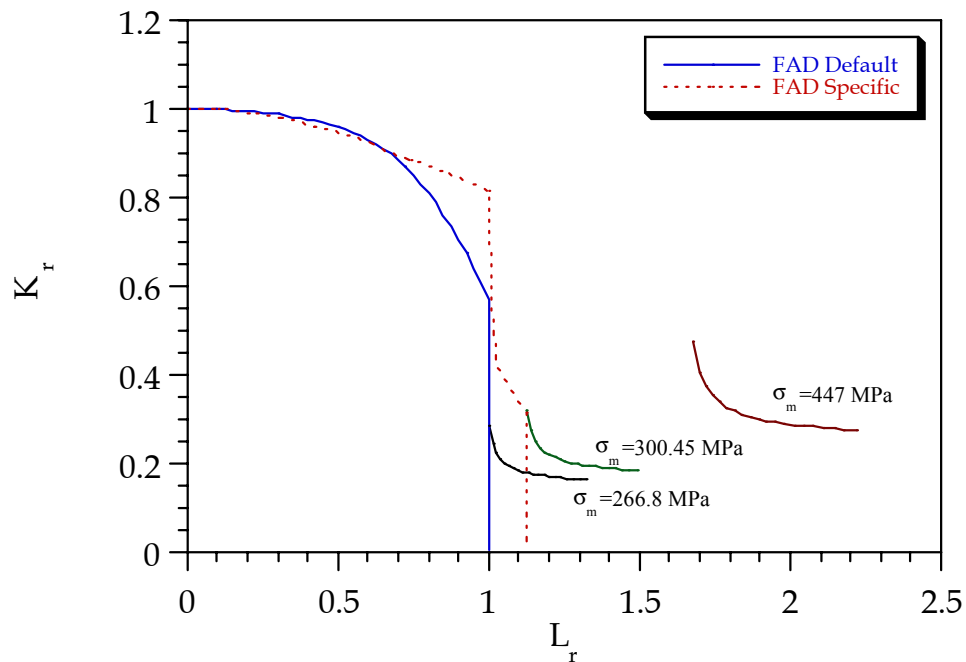


Figure 5.18. Specimen M01-12. Category 3 R6. FADs Default & Specific. Input toughness data J_R .

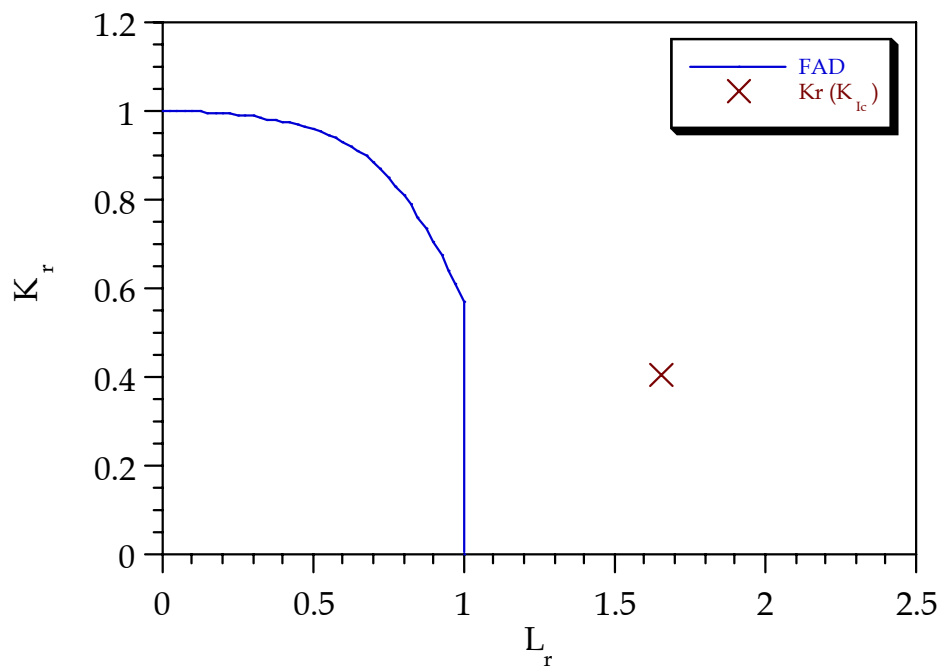


Figure 5.19. Specimen M01-12. SAQ. Input toughness data K_{Ic} .

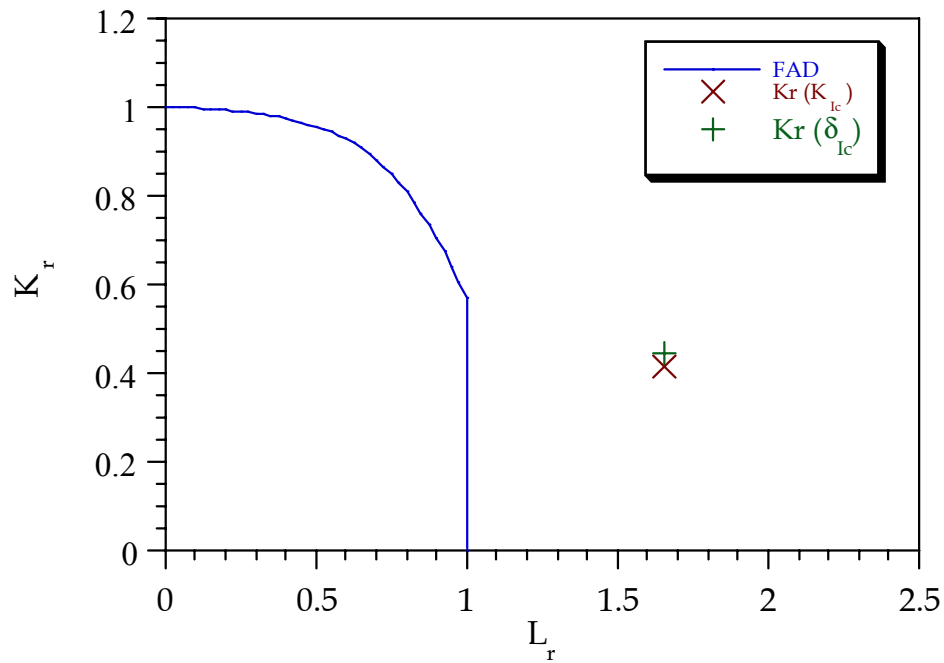


Figure 5.20. Specimen M01-12. MPC. Input toughness data K_{Ic} & δ_{Ic} .

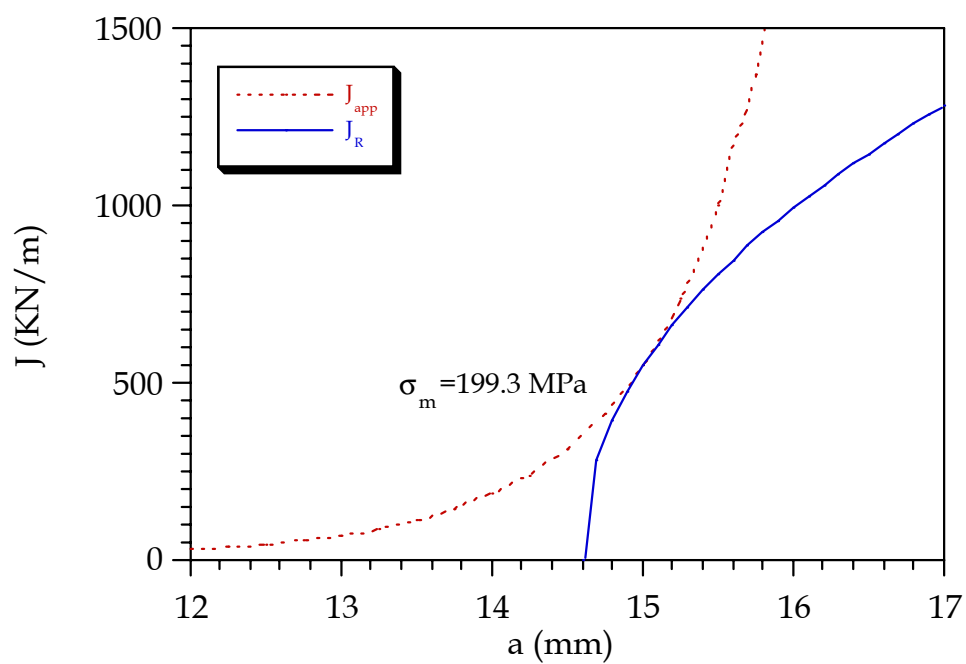


Figure 5.21. Specimen M01-12. ETM. Input toughness data J_R .

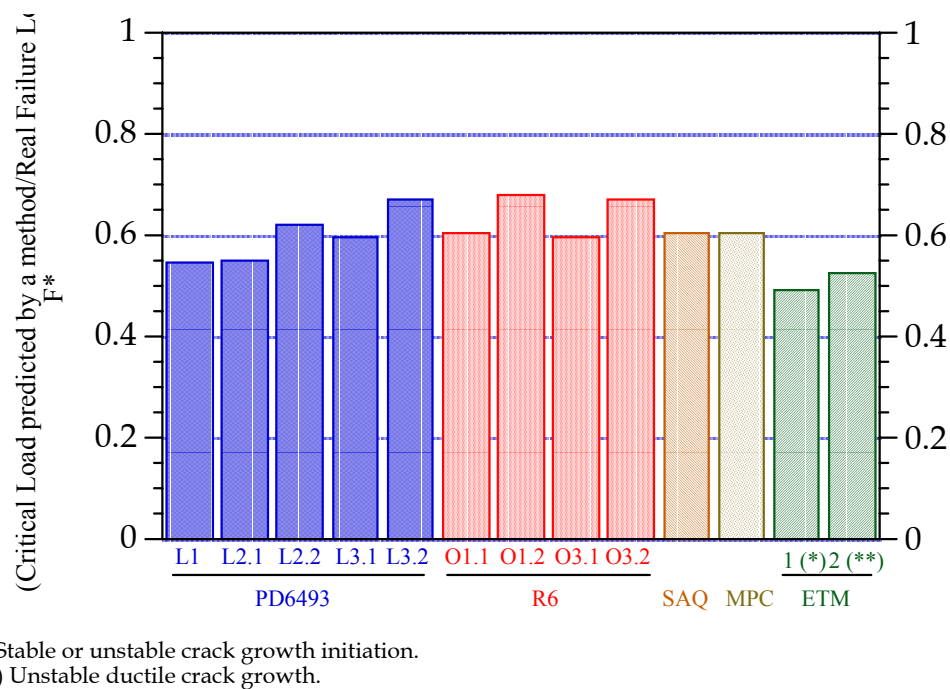


Figure 5.22. Comparison between methods. Critical axial load results. Specimen M01-12. Fracture toughness input K_{Ic} & J_R .

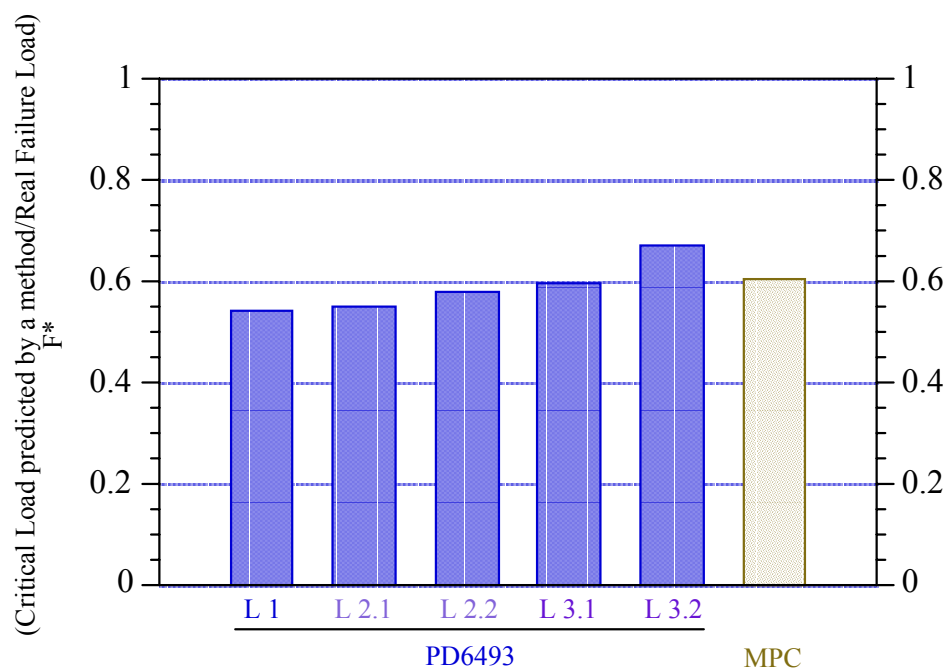


Figure 5.23. Comparison between methods. Critical axial load results. Specimen M01-12. Fracture toughness input δ_{Ic} & δ_R .

IV. CONCLUSIONS

This third part summarises the work done by the University of Cantabria with the aim of proposing a working framework for the final procedure as mentioned in the Introduction.

Although nine methods or procedures have been analysed, these could be reduced to two different ways of working. The first one, based on the use of Failure Assessment Diagrams, could be exemplified by the R6 Method; the second one, based on the use of Crack Driving Force Diagrams, is represented by the GE-EPRI Approach and the ETM Procedure.

The final procedure should combine both groups, paying special attention to the fact that they are intended for different purposes so the characteristics of each one could be an advantage for some situations while in others they could be a disadvantage. According to Milne, “the R6 based procedures are meant to provide safe estimates, not predictions, while the GE scheme is meant to give predictions, as has also been claimed for ETM” [18].

However, some important conclusions may be pointed out referring to the advantages of both philosophies that should be incorporated in the final procedure:

- The procedures based on FADs have a closed structure with perfectly defined sections and steps, thus simplifying the method’s application for the user.
- The simplicity and swiftness of the FADs techniques recommends their use for simple calculations and quick decision-making.
- On the other hand, the CDF-based techniques are intended to provide more accurate predictions and therefore are suitable for situations where more exact information is needed.

In spite of the fact that, during the early meetings, mention was made of “complete user freedom” to decide which representation to use, in view of the above mentioned comments, we feel it necessary to recommend the use of specific techniques under specific circumstances.

So, in the case of assessing a structure or a component in which, there are not available input data except the yield stress, the ultimate tensile strength and a single value of fracture toughness, the recommendation is to perform a single evaluation.

Therefore, as the intention of the assessment is to give a quick and easy answer where the accuracy of the prediction is not so important, it would be preferable to use a Failure Assessment Diagram.

On the other hand, if a complete study of crack growth is needed and the input data allow this kind of analysis (full knowledge of material characteristics, i.e. stress-strain curve and fracture toughness R-curve), the recommendation is to make use of a Crack Driving Force Diagram where the prediction is intended to be more exact and precise.

Between these two options, when the intention and extension of the assessment is not so clear, the user would have “complete freedom”.

A schematic representation of this recommendation is shown in the following table where the choice distribution can be clearly seen.

Level	A	B	C
Input data	$\sigma_y + \sigma_u$ K_{Ic}	$\sigma - \epsilon$ K_{Ic}	$\sigma - \epsilon$ R - curve
FAD	Default FAD + Partial safety factors or FAD based on $\sigma_y + \sigma_u$	Material Specific FAD	Material Specific FAD
CDF	Compatible: Default or based on $\sigma_y + \sigma_u$	Compatible: Based on material's $\sigma - \epsilon$ curve	Compatible: Based on material's $\sigma - \epsilon$ curve
Critical condition	Initiation	Initiation	Tearing

	Recommended
	Up to the user

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