Unclassified **NEA/CSNI/R(2001)14**

Organisation de Coopération et de Développement Economiques
Organisation for Economic Co-operation and Development **06-Jul-2001**

English text only

NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

Technical Report on the Fatigue Crack Growth Benchmark Based on CEA Pipe Bending Tests

JT00110626

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Unclassified

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ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

Pursuant to Article 1 of the Convention signed in Paris on 14th December 1960, and which came into force on 30th September 1961, the Organisation for Economic Co-operation and Development (OECD) shall promote policies designed:

- to achieve the highest sustainable economic growth and employment and a rising standard of living in Member countries, while maintaining financial stability, and thus to contribute to the development of the world economy;
- to contribute to sound economic expansion in Member as well as non-member countries in the process of economic development; and
- to contribute to the expansion of world trade on a multilateral, non-discriminatory basis in accordance with international obligations.

The original Member countries of the OECD are Austria, Belgium, Canada, Denmark, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The following countries became Members subsequently through accession at the dates indicated hereafter: Japan (28th April 1964), Finland (28th January 1969), Australia (7th June 1971), New Zealand (29th May 1973), Mexico (18th May 1994), the Czech Republic (21st December 1995), Hungary (7th May 1996), Poland (22nd November 1996), Korea (12th December 1996) and the Slovak Republic (14 December 2000). The Commission of the European Communities takes part in the work of the OECD (Article 13 of the OECD Convention).

NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1st February 1958 under the name of the OEEC European Nuclear Energy Agency. It received its present designation on 20th April 1972, when Japan became its first non-European full Member. NEA membership today consists of 27 OECD Member countries: Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, Norway, Portugal, Republic of Korea, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The Commission of the European Communities also takes part in the work of the Agency.

The mission of the NEA is:

- to assist its Member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes, as well as
- to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has a Co-operation Agreement, as well as with other international organisations in the nuclear field.

COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

The NEA Committee on the Safety of Nuclear Installations (CSNI) is an international committee made up of scientists and engineers. It was set up in 1973 to develop and co-ordinate the activities of the Nuclear Energy Agency concerning the technical aspects of the design, construction and operation of nuclear installations insofar as they affect the safety of such installations. The Committee's purpose is to foster international co-operation in nuclear safety amongst the OECD Member countries.

CSNI constitutes a forum for the exchange of technical information and for collaboration between organisations which can contribute, from their respective backgrounds in research, development, engineering or regulation, to these activities and to the definition of its programme of work. It also reviews the state of knowledge on selected topics of nuclear safety technology and safety assessment, including operating experience. It initiates and conducts programmes identified by these reviews and assessments in order to overcome discrepancies, develop improvements and reach international consensus in different projects and International Standard Problems, and assists in the feedback of the results to participating organisations. Full use is also made of traditional methods of co-operation, such as information exchanges, establishment of working groups and organisation of conferences and specialist meeting.

The greater part of CSNI's current programme of work is concerned with safety technology of water reactors. The principal areas covered are operating experience and the human factor, reactor coolant system behaviour, various aspects of reactor component integrity, the phenomenology of radioactive releases in reactor accidents and their confinement, containment performance, risk assessment and severe accidents. The Committee also studies the safety of the fuel cycle, conducts periodic surveys of reactor safety research programmes and operates an international mechanism for exchanging reports on nuclear power plant incidents.

In implementing its programme, CSNI establishes co-operative mechanisms with NEA's Committee on Nuclear Regulatory Activities (CNRA), responsible for the activities of the Agency concerning the regulation, licensing and inspection of nuclear installations with regard to safety. It also co-operates with NEA's Committee on Radiation Protection and Public Health and NEA's Radioactive Waste Management Committee on matters of common interest.

Foreword

This benchmark was organized by CEA Saclay, under the sponsorship of the CSNI Working Group on Integrity and Aging (IAGE WG). IAGE WG has three sub-groups, dealing with the integrity of metal components and structures, aging of concrete structures, and the seismic behavior of structures. The sub-group dealing with metal components has three mains areas of activity: Non-Destructive Examination; fracture mechanics; and material degradation. In the area of fracture mechanics, a series of round robin have been organised under IAGE WG. The two phases of FALSIRE (Fracture Analysis of Large Scale International Reference Experiments) considered large Pressurized Thermal Shock tests. This includes thermal hydraulic analysis (thermal mixing), and both deterministic and probabilistic fracture mechanics analysis. In addition to the FALSIRE round robin, the group completed a benchmark on a plate containing a semi-elliptical crack and submitted to a cyclic bending load in the topic of Leak Before Break.

The idea of this fatigue crack growth benchmark is a continuation of the latter one, and studies a cracked pipe under 4 point bending.

Fracture mechanics reports issued by the group since 1992 are:

NEA/CSNI/R(92)21 Proceedings of IAEA/CSNI Specialists Meeting on Fracture mechanics verification by large scale testing, ORNL, October 1992 (NUREG/CP-0131, ORNL/TM-12413)

NEA/CSNI/R(94)12 FALSIRE Phase I Comparison Report

NEA/CSNI/R(95)1 SOAR on Key fracture mechanics aspects of integrity assessment

NEA/CSNI/R(95)4 Report on Round robin activities on the Calculation of crack opening behaviour and leak rates for small bore piping components

NEA/CSNI/R(96)1 FALSIRE Phase II - Fracture Analyses of Large Scale International Reference Experiments

NEA/CSNI/R(96)4 Proceedings of Workshop on Probabilistic structural integrity analysis and its relationship to deterministic analysis, Stockholm, March 96

NEA/CSNI/R(97)8 Fatigue crack growth benchmark.

NEA/CSNI/R(99) 3 Comparison report of RPV pressurized thermal shock international comparative assessment study (PTS ICAS)

NEA/CSNI/R(2001)6 Micro-mechanical versus conventional modeling in non-linear fracture mechanic

The complete list of CSNI reports, and the text of reports from 1993 on, is available on http://www.nea.fr/html/nsd/docs/

Current activities include a benchmark on Probabilistic Structural Integrity of a PWR Reactor Pressure Vessel and a benchmark on crack propagation under thermal loading. An other activity is aiming towards the completion of the compendium of large PTS tests.

Acknowledgement

Gratitude is expressed to the CEA Saclay as well as to the Organization for Economic Co-operation and Development (OECD) / Nuclear Energy Agency (NEA) / Committee on the Safety of Nuclear Installations (CSNI) / Integrity and Aging Working Group (IAGE) (Integrity of Components and Structures) for sponsoring our work. Further, the author thanks each participant listed in Appendix 1 for cooperation in performing analytical work.

Abstract

In order to improve the estimation methods of surface crack propagation through the thickness of components, CEA has proposed a benchmark to members of the IAGE WG, sub-group on Integrity of metal components and structures. The subject is a simple configuration of a pipe containing an axisymetric notch and submitted to a cyclic bending load. An experimental data-set form CEA was used to validate three issues in the topic of Leak Before Break.

- Crack initiation,
- Crack propagation through the thickness,
- Crack penetration.

All material and geometrical data which are necessary for the simulation were given in the proposal, including experimental results. Due to the peculiar complexity of the problem, it was decided to focus the work on methodologies comparison so as to allow participants to tune up parameters and adjust their models and tools.

This report presents all estimations performed by the participants and collected by CEA. They are compared to the experimental results. An analysis of the used procedures is also proposed. This, associated with the study of the accuracy of different methodologies, leads to comments and recommendations on the analysis of fatigue crack growth.

The participation in the first step was important: nine participants have proposed analyses, sometimes parametric analysis to estimate crack growth. Results sorted out three estimation methods groups that give results in accordance with experimental ones (these three groups are based on a strain range evaluation and the fatigue curve of the material):

- The use of an elastic stress at the notch tip and a fatigue notch concentration factor to determine the strain range.
- The use of a K_I (or elastic F.E. calculation) and a Neuber rule for the estimation of the strain range at a characteristic distance from the crack tip.
- The direct calculation of the strain range at the characteristic distance by an elastic plastic F.E. calculation.

Only 4 participants have proposed an estimateof the crack growth rate. However, these applications have shown that, for the important level of cyclic load imposed to the pipe, two phenomenon are to be taken into account in the effective ΔK to have a good estimate of the crack growth rate:

- The effect of plasticity. This can be estimated with the reference stress concept and the cyclic curve of the material.
- The closure effect due to a negative R ratio.

For the third step, crack penetration was estimated with a ductile tearing criterion. This gives a good estimate in this case but has to be confirmed for other materials or geometries. The same remark applies to crack shape estimations for which methodologies are specific to the configuration.

For leak area estimates, two proposals with similar results were proposed but no experimental measurements are available for confirmation.

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1. INTRODUCTION

In order to improve LBB methodology, a benchmark was proposed by the CEA on the configuration of a pipe submitted to a cyclic bending. The proposed analysis is supported by a test, preformed by the CEA, in which a cyclic four point bending load was imposed to a pipe containing an axisymetric notch. The test is conducted from the crack initiation to the crack penetration of the wall thickness of the pipe.

In the benchmark proposition (Annex II), the complete description of experimental results and material data needed for the analysis are described. This choice was made because of the complexity of the proposed problem. Thus the main interest of the benchmark is on the comparison of methodologies and approaches: the proposition allowed the participant to adjust their own methods.

Three main items of fracture mechanics are investigated in this benchmark in three independent phases:

- Fatigue crack initiation from a geometrical singularity.
- Crack propagation under cyclic load.
- Crack penetration.

It follows a first blind benchmark focused on crack propagation of surface crack in plates [1].

This report gives a synthesis of the analysis performed by the participants on the three phases:

- For first phase, it concerns the crack initiation from the machined notch in the pipe. The report is composed by a global description of the employed methodologies, a description “participant by participant” of the used analysis and finally a synthesis of the calculation results compared to the number of cycles for crack initiation.
  A total of 42 applications proposed by 8 participants is presented in this report.
- For the second and third phases, due to the technical difficulties, the number of propositions was smaller (only 4 participants). Then the report describes these difficulties and the methodology and assumptions performed by the participants.

Finally, a recommendation to estimate the crack initiation, the crack propagation and penetration, and the leak area is proposed in the report.

2. PARTICIPANT ANALYSIS TO FIRST STEP

In this chapter, a global description of the methodologies employed by participants to estimate the number of cycles to crack initiation is proposed. The comparison of calculation results to the experimental ones is proposed in the next chapter.

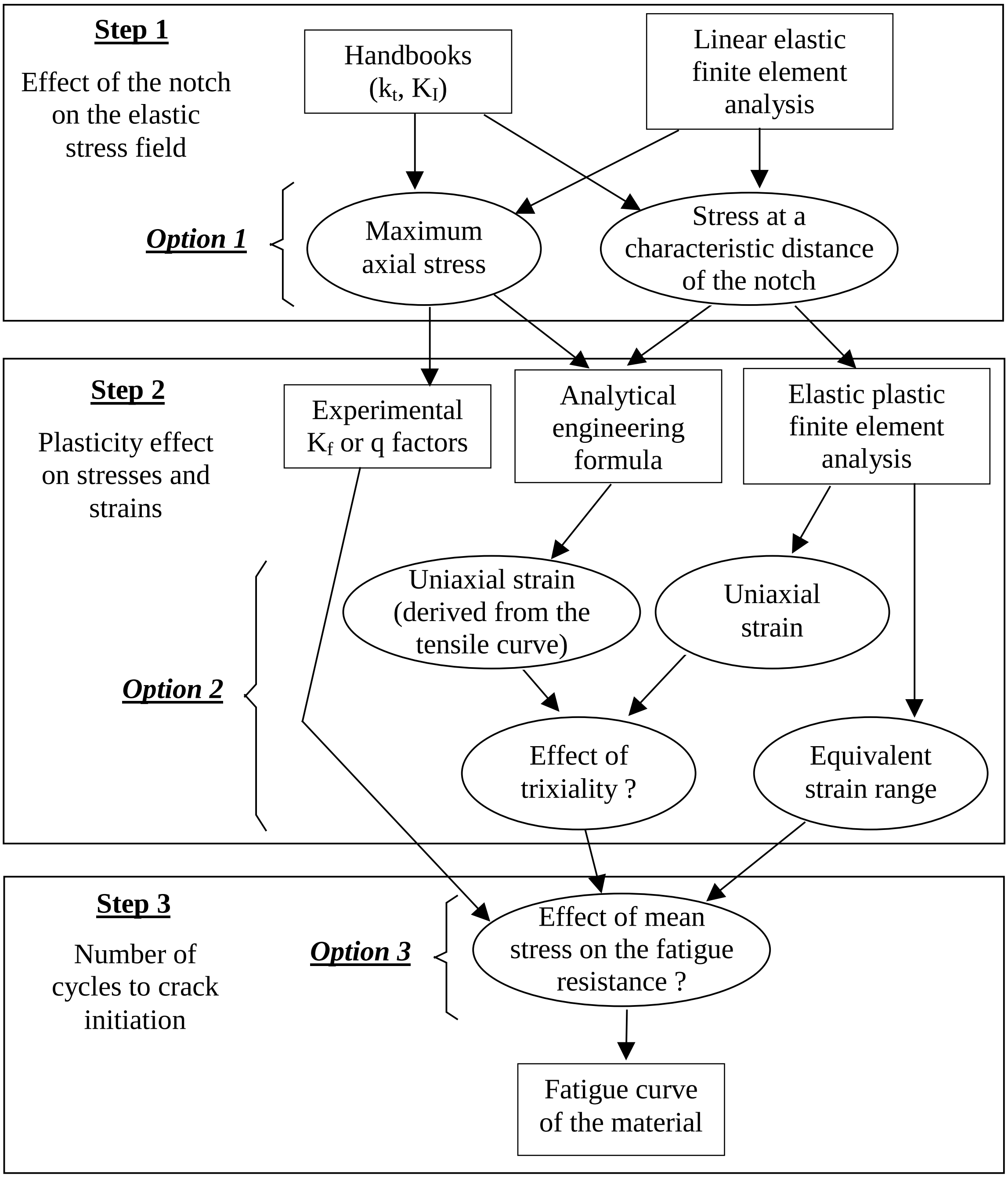
Global description

In the fatigue analysis, the material data given for the fatigue initiation are:
- The monotonic stress-strain curve.
- The cyclic stress-strain curve. This curve connects an imposed symmetric and uniaxial cyclic strain $\Delta\varepsilon$ to the resultant uniaxial stress range $\Delta\sigma$.
- The fatigue best-fit curve which gives the number of cycle to failure for an imposed strain range. This curve is also obtained with uniaxial test under symmetric load.

This exercise consists in determining the number of cycles to initiate a crack from the notch. This number of cycles, for most applications, is derived from the fatigue curve, thus the problem consists in determining the effective strain range $\Delta\varepsilon$ for this geometry.
Only a few applications propose other methodologies: One uses an energetic approach. In this case, like the previous determination of the number of cycles, the methodology is based on an effective strain range. Others are based on rules, expressed in terms of imposed stress range or not detailed in the analysis description.

Thus, to propose a coherent description of employed methodologies and because it concerns a majority of proposed analysis, the following step by step decomposition of the problem is adopted:
1. In the first step, the effect of the notch on the elastic stress field in the pipe is determined. Two main solutions are proposed: the use of formula or handbooks for stress concentration and for stress intensity factors, or the use of linear elastic finite element analysis. Inside these two solutions, different options are chosen to determine how to calculate the stress which characterizes the load near the notch (maximum of the stress field or at a particular distance of the notch).
2. The second step is the determination of the effect of plasticity on the stress and strain fields. Three main solutions are proposed: Analytical formula using the elastically determined stress field (such as Neuber rule), experimental factors for strain concentration determined for the material in function of the singularity, or elastic plastic finite element analysis. Like the previous step, different options are chosen to define the effective strain range (uniaxial or equivalent strain, the account of triaxiality…).
3. The third step consists on determining the number of cycles to crack initiation (knowing the effective strain range). This was done using the proposed fatigue curve of the material (except for several applications) with, for some participants, taking account of the non-symmetry of the imposed global load.

Next figure summarizes all these steps and options. The methodologies adopted by each participants are presented in next chapters, following this decomposition of the problem.



Proposition of participant 1

Participant one uses an analytical evaluation of the number of cycles.

- The evaluation of the effect of the stress field is made with a K_I handbook for pipes under global bending: the notch is approximated by an axisymmetrical crack. The Creager formula is then used to determine the axial stress at 50µm of the notch tip (the notch radius ρ is neglected).
- The effect of plasticity around the notch is estimated with the Neuber rule. The effect of triaxiality is added by a K_v factor.
- The resultant effective strain is fed into the fatigue curve of the material, without any account of the mean stress due to non-symmetric cycle.

Next table summarizes the application.

Step 1	Option 1	Step 2	Option 2	Option 3	Effective Δε (%)	N
K_I	Principal stress at 50 µm	Neuber	Axial strain + triaxiality	No mean stress	1.56	1150

Commentary

The simple analytical methodology based on K_I handbook and stress at 50µm from the notch gives a reasonable underestimation of the experimental number of cycles.

Proposition of participant 3

Participant 3 uses a finite element analysis to calculate the stress and strain field near the notch. The calculation is elastic and uses 2D axisymmetric harmonic elements and describes the notch shape. In the modeling, the full moment is applied and stress and strain fields are calculated around the notch.
The axial stress (principal stress) is calculated for two different values:

- The maximum of the strain field around the notch.
- The strain range at the distance of 100µm (corresponding to the notch radius).

To take into account the effects of plasticity, engineering methods are used (such as Neuber rule or a modification to Neuber rule proposed by Glinka) with the cyclic stress strain curve.
In this estimation, the effect of triaxiality is estimated by the application of the Neuber or modified Neuber methodology (the Neuber hyperbola is expressed in terms of the full stress tensor). The results with account of triaxiality factor are compared to results without this factor.

The effect of the global non-symmetric load is not taken into account

In all, 8 different results are proposed and are summarized in the table.

Step 1	Option 1	Step 2	Option 2	Option 3	Effective Δε (%)	N
F.E.A.	Maximum	Neuber	Axial strain + triaxiality	No mean stress	2.9	177
F.E.A.	Maximum	Neuber	Axial strain	No mean stress	3.8	78
F.E.A.	d=100µm	Neuber	Axial strain + triaxiality	No mean stress	1.3	2009
F.E.A.	d=100µm	Neuber	Axial strain	No mean stress	1.7	891
F.E.A.	Maximum	Modified Neuber	Axial strain + triaxiality	No mean stress	2.3	357
F.E.A.	Maximum	Modified Neuber	Axial strain	No mean stress	3.0	159
F.E.A.	d=100µm	Modified Neuber	Axial strain + triaxiality	No mean stress	1.1	3333
F.E.A.	d=100µm	Modified Neuber	Axial strain	No mean stress	1.4	1468

Commentary

In his presentation, participant 3 proposes an estimation of the stress field by finite element analysis. Two kinds of stresses are suggested for this estimation (maximum or at a characteristic distance of the notch). It seems that the maximum stress leads to pessimistic estimations of the number of cycles (78 – 357 cycles). On another hand, the axial stress calculated at 100µm provide estimation in good accordance with the experimental number of cycles (891 – 3333, depending on the option to evaluate plasticity).

Proposition of participant 4

Participant 4 uses an elastic-plastic finite element analysis to evaluate the stress and strain fields around the notch.

The model is 3D with massive elements and evaluates, with the calculation of the half cycle, the elastic-plastic stress and strain ranges around the notch.

The effective strain is then defined as the maximum axial strain. No triaxiality effect is taken into account.

With this effective strain range, three options of criterion are presented to determine the number of cycles to crack initiation:

- A Russian rule for structural integrity. This criterion is not detailed but presented as a conservative estimation of the number of cycles to crack initiation.
- The Mason criterion defined with the tensile characteristics of the material. This methodology takes into account the asymmetry of the cycle (the mean stress around the notch is determined by the finite element calculation). A comparison is made with the same methodology and without mean strain effect.
- The fatigue best-fit curve given in the benchmark proposition. In this application, there is no account of the mean stress.

Next table summarizes the application

Step 1	**Option 1**	**Step 2**	**Option 2**	**Option 3**	**Effective** $\Delta\varepsilon$ (%)	**N**
F.E.A.	Maximum	F.E.A.	Axial strain (no triaxiality)	___	1.44	65 (Russian design rule)
F.E.A.	Maximum	F.E.A.	Axial strain (no triaxiality)	Mean stress	1.44	1707 (Manson)
F.E.A.	Maximum	F.E.A.	Axial strain (no triaxiality)	No mean stress	1.44	1428 (Manson)
F.E.A.	Maximum	F.E.A.	Axial strain (no triaxiality)	No mean stress	1.44	1560 (best-fit curve)

Commentary

Participant 4 proposes a sophisticated evaluation of the effective strain range based on finite element analysis. The advantage is here to avoid approximate methods to evaluate plastic effects on stress field. On the other hand, this kind of methodology needs a large computer capability in a structural application.

With the calculated effective stress range, three criteria are employed:

- The first one, corresponding to a design rule gives too conservative results.
- The two other ones, based on the material characteristics, give very similar results, in good accordance with the experimental number of cycles.

Proposition of the participant 5

Participant 5 uses two different analyses of the crack initiation problem. In each analysis different options are chosen.

First analysis

In the first analysis of participant 5, three different kinds of methodology are proposed.

In the first one, an overview of analytical estimations of the number of cycles to crack initiation at the notch tip is performed. Different options are used:

- The geometrical singularity is taken into account by an elastic stress concentration factor k_t or an elastic-plastic stress concentration factor k_f. Two different formula are proposed for k_t and 3 for k_f. The stress and strain used to determine the effective strain are uniaxial (corresponding to the maximum of the axial stress).
- Evaluation of the effect of plasticity on the local stress and strain fields is performed by engineering methodologies (such as Neuber rule or modified Neuber rule). No effect of triaxiality is taken into account.
- Finally, the resultant effective strains are fed into the fatigue curve, without any effect of non-symmetric load.

  It should be noticed that one application is performed with an energetic approach which does not use the fatigue curve but the monotonic and cyclic stress-strain curves.

Next table summarizes the application of these analytical estimations.

Step 1	**Option 1**	**Step 2**	**Option 2**	**Option 3**	**Effective $\Delta\varepsilon$ (%)**	**N**
k_t (1)	Max. stress	Neuber	Axial strain	No	2.89	182
k_t (2)	Max. stress	Neuber	Axial strain	No	2.79	203
k_f (1)	Max. stress	Neuber	Axial strain	No	0.73	15300
k_f (1)	Max. stress	Neuber	Axial strain	No	0.72	17000
k_f (2)	Max. stress	Neuber	Axial strain	No	0.81	10500
k_f (2)	Max. stress	Neuber	Axial strain	No	0.79	11400
k_f (3)	Max. stress	Neuber	Axial strain	No	0.61	39600
k_f (3)	Max. stress	Neuber	Axial strain	No	0.60	40000
k_t (1)	Max. stress	Modified Neuber (1)	Axial strain	No	1,52	1300
k_t (1)	Max. stress	Modified Neuber (2)	Axial strain	No	1.92	620
k_t (1)	Max. stress	Modified Neuber (1)	Axial strain	No	1,52	80*

(*) This value is obtained by the energetic approach.

In the second methodology participant 5 uses an elastic finite element analysis to determine the stress and strain fields at the notch tip.
The model is 3D and is composed by specific volume 37 nodes element and describes the notch shape. It calculates the stress and strain fields associated to the global bending moment.

- To determine the characteristic stress, different options are proposed: the maximum of the axial stress field or the stress at a distance d equal to 50µm of the crack tip (axial or principal stress).
- The effect of plasticity is evaluated by the Neuber rule or a modified Neuber rule and the triaxiality effect is evaluated by three different formulae (amplification of the effective strain)
- The effect of non symmetric load is not taken into account in the determination of the number of cycles to crack initiation.

A complementary detailed elastic-plastic finite element analysis is performed with the same model. In this calculation, a mixed isotropic/kinematic hardening law is employed and four cycles are calculated. From this calculation, a maximum equivalent strain range is deduced and injected into the fatigue curve of the material to determine the number of cycles to crack initiation.

Next table summarizes these estimations

Step 1	**Option 1**	**Step 2**	**Option 2**	**Option 3**	**Effective** $\Delta\varepsilon$ (%)	**N**
F.E.A.	Maximum (axial stress)	Neuber	Triaxiality (1)	No mean stress	2.54	263
F.E.A.	50 µm (axial stress)	Neuber	Triaxiality (1)	No mean stress	1.11	3210
F.E.A.	50 µm (principal stress)	Neuber	Triaxiality (1)	No mean stress	1.44	1420
F.E.A.	50 µm (principal stress)	Modified Neuber	Triaxiality (1)	No mean stress	1.11	3180
F.E.A.	50 µm (principal stress)	Modified Neuber	Triaxiality (2)	No mean stress	1.59	1063
F.E.A.	50 µm (principal stress)	Modified Neuber	Triaxiality (3)	No mean stress	1.22	2295
F.E.A.	Maximum around the notch	F.E.A.	Equivalent strain	No mean stress	1.37	1700

Second analysis

In the second analysis, two other methodologies are suggested.

The first one is analytical and based on the following procedure.

- The elastic stress and strain fields are deduced from a K_I handbook (assuming a uniform tensile load). The characteristic stress is the axial stress calculated at 50 µm of the notch tip.
- The effect of plasticity is estimated by the Neuber rule. A complementary strain due to global plasticity is added to this global strain (strain range associated to applied nominal stress range in the cyclic curve). No effect of triaxiality is taken into account.
- A possibility to take into account a mean stress during the imposed cyclic load is deserved. However, this correction is insignificant in this case.

The second one is based on two elastic plastic finite element analysis where the half cycle is modelized with the cyclic tensile curve of the material. Two models are employed:

- One 3D with quadratic volume elements. The total bending load is imposed.

- The other 2D under axisymetric assumption (under a tensile load corresponding to the mean stress of the most loaded cross section.

These two calculations allow to obtain the elastic-plastic stress and strain fields ranges.
- The effective strain is the maximum equivalent strain.
- A mean of taking into account the non symmetry of the cycle is deserved but it remains insignificant in this example.

Next table detail the results of this second analysis.

Step 1	**Option 1**	**Step 2**	**Option 2**	**Option 3**	**Effective** $\Delta\varepsilon$ (%)	**N**
K_I	Axial stress (at 50µm)	Neuber	No triaxiality	No mean stress	1.58	1082
F.E.A. (2D)	Axial stress (at 50µm)	F.E.A.	Equivalent strain	No mean stress	1.49	1277
F.E.A. (3D)	Axial stress (at 50µm)	F.E.A.	Equivalent strain	No mean stress	1.53	1200

Commentary

Participant 5 proposes two different levels of estimations of the number of cycles to initiation:
In the first one, the estimations are based on calculations of stresses with handbooks or formula:
- Results which are obtained with the Neuber rule (or equivalent) after a maximum axial stress estimation with an elastic k_t factor give a large underestimation of the number of cycles to initiation (80 – 620 cycles).
- On the other hand, estimations obtained with the same procedure but with an elastic-plastic concentration factor k_f give a large overestimation of the number of cycles (15300 – 40000). This is mainly due to the fact that the k_f factor already takes into account a reduction of stress field with plasticity.
- The estimations following a stress calculation at a characteristic distance of the notch using a K_I handbook yield better results.

In the second one, a finite element analysis is proposed. Main results are the following:
- In an elastic calculation, a maximum stress is calculated. As already shown, this stress used in the Neuber rule provide an underestimation of the number of cycle. This result is similar to results obtained with k_t.
- On the other hand, a stress calculated at a characteristic distance of the notch provide a better estimation. This is in accordance with results yield with K_I formula.
- In elastic-plastic finite element analysis, an equivalent maximum strain allows to obtain a good estimation of the number of cycles to initiation. This was also obtained by participant 4.

Proposition of participant 6

Participant 6 uses an analytical methodology to estimate the number of cycles to crack initiation. Its description is the following:

- The elastic stress field around the notch is evaluated with a stress concentration factor. The deduced stress is a maximum axial stress.
- The effect of plasticity is derived from a fatigue notch factor k_f defined for the material. No account is taken for the triaxiality of the loading.
- No effect of mean stress is taken into account in the determination of the number of cycles to crack initiation with the fatigue curve of the material.

Next table summarizes the application.

Step 1	**Option 1**	**Step 2**	**Option 2**	**Option 3**	**Effective** $\Delta\varepsilon$ (%)	**N**
k_t	Maximum axial stress	k_f	No triaxiality	No mean stress	1.27	1964

Commentary

The simple analysis used by participant 6 shows that a k_t factor (estimation of the maximum axial stress), associated to an experimental fatigue concentration factor, provides an estimation of the number of cycles in good accordance with experiments.

Proposition of participant 8

Participant 8 proposes two different analyses: the first one is analytical and based on two different rules to estimate the crack initiation; the second is based on a finite element analysis.

Analytical propositions

Two different analytical estimations of the number of cycles to crack initiation are made.

- In the first one, the evaluation of notch effect on stress field is made with a K_I formula, and the Creager formula (which takes into account the notch radius). The determined stress to evaluate crack initiation is the maximum principal stress at a characteristic distance d = 50µm.
- The effect of plasticity on the stress field is evaluated with the Neuber rule and the cyclic stress-strain curve of the material. Triaxiality is taken into account with a tabulated value of K_v.
- Finally, the number of cycles to crack initiation is derived from the design fatigue curve of the material (the calculated strain range being devised by 1.5). No effect of mean stress is taken into account.

- In the second proposed analytical method, the elastic stress field is estimated with a stress concentration factors k_t. The stress used to estimate initiation is then a maximum axial stress.
- Like in previous method, the effect of plasticity is estimated with the Neuber formula and the cyclic stress-strain curve. Again, a triaxiality correction is made but the K_v coefficient is derived from an analytical estimation based on ν parameter.
- At last, knowing the effective strain, the number of cycles to crack initiation is derived from the best-fit fatigue curve of the material.

Solutions based on finite element analysis

In this second solution, a finite element analysis is proposed. The model is 2D axisymmetric and the load is a uniform axial stress. The material is linear elastic.
Two options are used:

- In the first one, a k_t factor is determined for the stress at 50µm and then the second analytical methodology is performed (Neuber + K_v + best-fit fatigue curve).
- In the second option, k_t factor is determined numerically for the maximum axial stress and used in an analytical effect of plasticity estimated with a fatigue concentration factor k_f (derived from a tabulated notch sensitivity parameter q).

Next table summarizes all the different applications performed by the participant 8.

Step 1	**Option 1**	**Step 2**	**Option 2**	**Option 3**	**Effective** $\Delta\varepsilon$ (%)	**N**
K_I	Principal stress at 50 µm	Neuber	K_v (1)	No mean stress	1.43 / 1.5	616 (design)
k_t (1)	Maximum axial stress	Neuber	K_v (2)	No mean stress	2.15	460
F.E.A.	50 µm (axial stress)	Neuber	K_v (2)	No mean stress	1.64	1010
F.E.A.	Maximum axial stress	k_f	No triaxiality	No mean stress	1.07	3355

Commentary

The analysis used by participant 8 is composed of two kinds of evaluation of elastic stresses around the notch:

- The estimation of the number of cycles to crack initiation with a stress calculated at 50µm of the notch underestimates the experiment. However this result is in reasonable agreement with the test (one of the application is performed with the design curve).
- The analysis performed with a k_t factor and Neuber rule obtains, as already shown, a larger underestimation of the number of cycles. However, if this stress is used with an experimental fatigue concentration factor, a good estimation is obtained.

Proposition of participant 9

The participant 9 uses an elastic-plastic finite element analysis to determine the number of cycles to crack initiation.
The model is 3D using 20 nodes volume elements with a description of the notch. The plastic criterion is based on the Von-Mises equivalent stress, assuming a multi-linear kinematic hardening (the cyclic yield strength is assumed to be the monotonic one).
Four cycles are modeled in which the maximum elastic-plastic stress and strain field ranges around the notch are determined (the cycle is stabilized after 4 cycles).
The effective strain is defined with all components of the strain tensor so that it takes into account the effect of triaxiality. This strain is injected into the fatigue curve of the material, assuming that mean stress effects are insignificant.

Next table summarizes the application

Step 1	**Option 1**	**Step 2**	**Option 2**	**Option 3**	**Effective $\Delta\varepsilon$ (%)**	**N**
F.E.A.	50 µm (axial stress)	F.E.A.	Equivalent strain	No mean stress	1.19	2574

Commentary

The elastic-plastic analysis used by participant 9 provide results similar to the previous elastic-plastic analysis: a maximum equivalent elastic-plastic strain range near the notch allows obtaining an estimation in good accordance with the experiment.

Proposition of participant 13

Participant 13 proposes 3 different analyses:

- Two of them are based on handbook formula and experimental concentration factors (stress or strain analysis).
- The third one is based on an elastic plastic finite element analysis.

Analytical propositions

The 2 analytical solutions proposed by participant 13 are based on a stress analysis or on a strain analysis at the crack tip of the notch.

- In the stress analysis, a stress concentration factor derived from an handbook is used to estimate the maximum axial stress at the notch tip.
- The effect of plasticity is evaluated at different stress levels with fatigue notch factors k_f derived from values from literature.
- With these fatigue notch factors (at 10^6 cycles and 10^3 cycles) and the monotonic tensile data of the material, an approximate S-N curve for the material is proposed. This S-N curve is then used to determine the number of cycles (taking into account an effect of mean stress).

- In the strain analysis, the calculation is started with the same value of maximum axial stress derived from the same stress concentration factor.
- To evaluate the effect of plasticity and mean stress, an original procedure is used with the Neuber formula to take into account plasticity:
  - The stresses and strains at maximum load are obtained with a bending load from 0 to the maximum bending with the cyclic behavior curve (σ vs ε) derived from the cyclic curve ($\Delta\sigma$ vs $\Delta\varepsilon$).
  - The stresses and strains at minimum load are then obtained from this maximum point to the minimum one with the total bending amplitude and the cyclic curve ($\Delta\sigma$ vs $\Delta\varepsilon$).
  - From these two points, the mean stress during the cycle and the strain variation are deduced.
- Finally, the number of cycles to crack initiation are deduced from the fatigue curve of the material, taking into account a mean stress effect with the Morrow's formula.

Finite element analysis

In the third solution, an elastic-plastic 3D finite element analysis is proposed. The model uses 20 nodes quadratic elements and represents ¼ of the pipe with the notch (ρ = 0.1 mm).

Four cycles are modeled with an approximate bilinear cyclic stress-strain curve (σ vs ε). In this calculation, the maximum equivalent strain variation and the equivalent strain variation at 43 µm are calculated to estimate the number of cycles to initiation.

Next table summarizes the applications of participant 13

Step 1	Option 1	Step 2	Option 2	Option 3	Effective $\Delta\varepsilon$ (%)	N
k_t	Maximum axial stress	k_f	No triaxiality	Effect of mean stress	Use of an estimate S-N curve	1418
k_t	Maximum axial stress	Neuber	No triaxiality	Effect of mean stress	2.24	348*
F.E.A.		F.E.A.	Max. equi. strain		2.36	233*
F.E.A.		F.E.A.	Equi strain at 43 µm		0.84	7090*

* results obtained with a wrong fatigue curve

Commentary

The first application, based on an estimate S-N curve is original and gives a good estimation of the number of cycles to crack initiation.

For the other applications, results noted by (*), a confusion was made when using the cyclic curve of the material given in the technical proposition: coefficients m and K are related to the ($\Delta\sigma$ vs $\Delta\varepsilon$) curve (or hysterisis curve) and not to the behavior curve (σ vs ε). This explains why strain range calculated at 43 µm gives a too large number of cycles.

Proposition of participant 14

Participant 14 proposes an elastic- finite element analysis to determine maximum stress around the notch.

Two 3D models with linear interpolation or mixed Linear-Fourier interpolation are used. Stresses from these calculations are post-treated near the notch with a polynomial topological parallelepiped extrapolation to obtain the maximum stress at the notch tip.

The criterion used to determine the number of cycles is expressed in terms of the calculated maximum stress range but is not detailed in the presentation of the methodology (corresponding to a standard on strength calculation).

Next table summarizes the application

Step 1	Option 1	Step 2	Option 2	Option 3	Effective $\Delta\varepsilon$ (%)	N
F.E.A.	Maximum stress					188
F.E.A.	Maximum stress					264

Commentary

The elastic- analysis proposed by participant 14 provide elastically calculated stresses in good accordance with the other methodologies. However, the criterion based on this stresses and employed to determine the number of cycle to crack initiation leads to a pessimistic evaluation of the number of cycles.

Comparison of methodologies

To complete the description of methodologies, a comparison of starting points is given. It concerns:

- The maximum elastic stresses calculated at the notch tip with a k_t factor or finite element analysis.
- The stresses calculated at a characteristic distance of the notch by a K_I value or finite element analysis.
- The maximum equivalent strain calculated with an experimental fatigue concentration factor or finite element analysis.

This comparison is given in next table.

	$\Delta\sigma_{\mathbf{max}}$	**Method**		$\Delta\sigma_{\mathbf{d}}$	**Method**		$\Delta\varepsilon$ (%)	**Method**
Part. 3	2790	F.E.A.	*Part. 1*	1338	K_I	*Part. 4*	1.44	F.E.A.
Part. 5.1	2284	k_t	*Part. 3*	1590	F.E.A.	*Part. 5.1*	1.37	F.E.A.
	2235	k_t	*Part. 5.1*	1416	F.E.A.	*Part. 5.2*	1.49	F.E.A.
	2866	F.E.A.	*Part. 5.2*	1364	K_I		1.53	F.E.A.
Part. 8	1894	k_t	*Part. 8*	1298	K_I	*Part. 6*	1.27	k_f
	2940	F.E.A.		1491	F.E.A.	*Part. 9*	1.19	F.E.A.
Part. 13	2336	k_t				*Part. 13*	0.84*	F.E.A
	2723	F.E.A.						
Part. 14	2492	F.E.A.						
	2149	F.E.A.						

(*) results obtained with a wrong cyclic curve of the material

The first main result from this comparison is the good agreement between the different participants: for the main kind of calculation, there is only a small variation of results (even if the problem is complex).

The second result is that elastic stresses calculated with formula or handbooks are a little smaller than the same stresses calculated with Finite Element Analysis. This is more pronounced for the maximum axial stress. This result show the difficulty in estimating the maximum stress from the notch with a k_t factor for this 3D configuration.

To complete this comparison of results, the estimations of number of cycles to crack initiation are compared in the next table. In this table, six different families of methods are presented. For each family, a mean value is calculated and compared to the experimental number of cycles on the following figure.

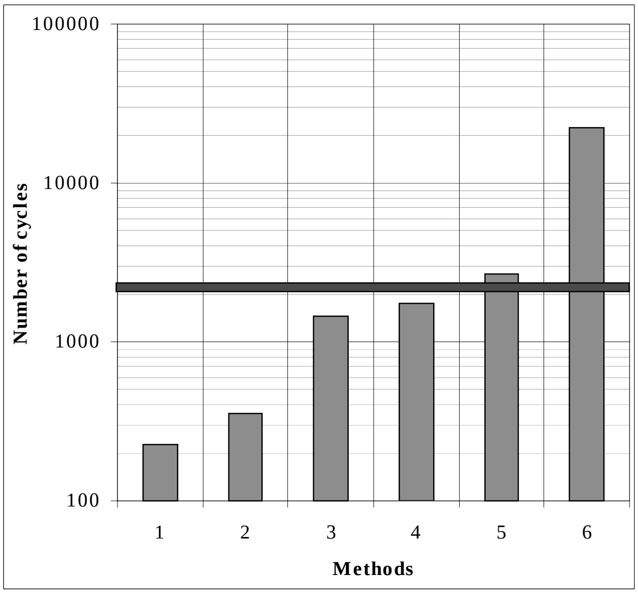
	N	**Method**		**N**	**Method**		**N**	**Method**
Methods 2			***Methods 4***			***Methods 3***		
Part. 3	177	$\Delta\sigma_m$ + Neuber	*Part. 1*	1150	$\Delta\sigma_d$ + Neuber	*Part. 4*	65^x	F.E.A
Part. 3	78	$\Delta\sigma_m$ + Neuber	*Part. 3*	2009	$\Delta\sigma_d$ + Neuber	*Part. 4*	1707	F.E.A
Part. 3	357	$\Delta\sigma_m$ + Neuber	*Part. 3*	891	$\Delta\sigma_d$ + Neuber	*Part. 4*	1428	F.E.A
Part. 3	159	$\Delta\sigma_m$ + Neuber	*Part. 3*	3333	$\Delta\sigma_d$ + Neuber	*Part. 4*	1560	F.E.A
Part. 5.1	182	$\Delta\sigma_m$ + Neuber	*Part. 3*	1468	$\Delta\sigma_d$ + Neuber	*Part. 5.1*	1700	F.E.A
Part. 5.1	203	$\Delta\sigma_m$ + Neuber	*Part. 5.1*	3210	$\Delta\sigma_d$ + Neuber	*Part. 5.2*	1277	F.E.A
Part. 5.1	1300	$\Delta\sigma_m$ + Neuber	*Part. 5.1*	1420	$\Delta\sigma_d$ + Neuber	*Part. 5.2*	1200	F.E.A
Part. 5.1	620	$\Delta\sigma_m$ + Neuber	*Part. 5.1*	3180	$\Delta\sigma_d$ + Neuber	*Part. 9*	2574	F.E.A
Part. 5.1	80	$\Delta\sigma_m$ + Neuber	*Part. 5.1*	1063	$\Delta\sigma_d$ + Neuber	*Part. 13*	7090°	F.E.A
Part. 5.1	263	$\Delta\sigma_m$ + Neuber	*Part. 5.1*	2295	$\Delta\sigma_d$ + Neuber	***Methods 1***		
Part. 8	460	$\Delta\sigma_m$ + Neuber	*Part. 5.2*	1082	$\Delta\sigma_d$ + Neuber	*Part. 14*	188^+	F.E.A
Part. 13	348°	$\Delta\sigma_m$ + Neuber	*Part. 8*	616*	$\Delta\sigma_d$ + Neuber	*Part. 14*	264^+	F.E.A
Methods 6			*Part. 8*	1010	$\Delta\sigma_d$ + Neuber			
Part. 5.1	15300	k_f + Neuber	***Methods 5***					
Part. 5.1	17000	k_f + Neuber	*Part. 6*	1964	$\Delta\sigma_m + k_f$			
Part. 5.1	10500	k_f + Neuber	*Part. 8*	3355	$\Delta\sigma_m + k_f$			
Part. 5.1	11400	k_f + Neuber	*Part. 13*	1418	$\Delta\sigma_m + k_f$			
Part. 5.1	39600	k_f + Neuber						
Part. 5.1	40000	k_f + Neuber						

* Obtained with the design curve

$^+$ Obtained with a strength criteria

^{x} Obtained with a design rule

° Obtained with a wrong cyclic curve



Conclusions on first step

This chapter presents the results of the first step of the benchmark. The analysis proposed by the participants are explained and compared. This showed that three families of methodology have obtained a good agreement with experimental results:

- The first one is an evaluation of the maximum elastic stress around the notch followed by a fatigue stress concentration factor (experimentally determined).
- The second one is an evaluation of a stress at a characteristic distance from the notch followed by a Neuber evaluation of plastic strain.
- The third one is an elastic-plastic finite element calculation. In this case, a maximum elastic-plastic equivalent strain is directly obtained from the calculation.

In the opposite, two formulations provide results which largely overestimate or underestimate the experimental number of cycles:

- The evaluation of a maximum stress followed by the Neuber rule to determine the effect of plasticity. This methodology leads to large strain range and thus to a low number of cycles to crack initiation.
- The evaluation of the maximum stress with a k_f factor (instead of k_t) followed by a Neuber evaluation of plasticity. The strain range issued from this kind of methodology is too low and thus the experimental number of cycles is largely overestimated.

Following the description of the analysis, a comparison of several results is described. This has shown a very good homogeneity between participants, even for complex methodologies such as elastic-plastic finite element analysis.

3. PARTICIPANT ANALYSIS ON SECOND AND THIRD STEPS

General description

The second and third steps proposed in the benchmark consist of an estimation of the crack propagation from the initial axisymetrical notch to the crack penetration. Three results are calculated by the participants:

- The number of cycles from the crack initiation to the penetration. In this step, participants have to estimate the crack growth rate of the defect.
- The crack shape after wall penetration. To do so, participants have to propose a rupture criterion for the end of the life of the defect.
- The leak area of the through wall defect.

For the two first points, the participant results can be compared to the experimental result. This is not the case for the third point because no measurement of the crack opening was performed during the test.

Main difficulties

The main difficulties of this step are due to the high level of reverse cyclic bending imposed to the pipe. This induces:

- Cyclic plasticity which has to be taken into account to have a good estimation of the crack growth rate.
- Closure effects due to the negative R ratio (R = Minimum Load / Maximum load).
- Interaction between fatigue crack growth and ductile tearing, specially at the end of the propagation (last cycles and crack penetration).

A second kind of difficulty is related to the defect shape and evolution: the crack create from the axisymetrical notch does not remain axisymetrical and an assumption on this shape has to be proposed by participants.

Propagation through the thickness: step II

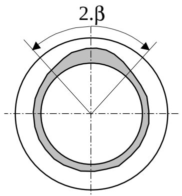
Participants

Four participants have proposed an estimation of the crack growth rate from the initial notch to the penetration of the defect. The employed methodologies are based on the evaluation of an effective ΔK (ΔK_{eff}) and the use of a Paris law with, sometimes, the account of a cyclic ductile tearing at each cycle.

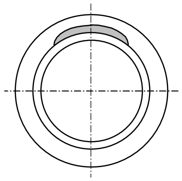
Crack shape and evolution assumptions

The assumptions adopted on the crack shape and its evolution are the following:

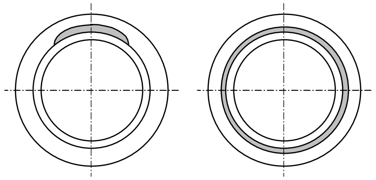
- *Part. 1* proposes the analysis of a 3D complex crack shape including the initial notch. The propagation is assumed to occur only at the deepest point (the angle of the defect 2β is constant and defined by the $\Delta K_{threshold}$ value on the initial notch).



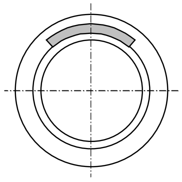
- *Part. 5* assumes a semi-elliptical defect and the notch. The semi-elliptical defect propagates in depth and in length.



- *Part. 8* proposes two different assumptions: the notch with a semi-elliptical crack or the notch with a fully axisymetrical crack. In the first case, the propagation occurs in depth and in length.



- *Part. 13* assumes an internal rectangular defect with, like *Part. 1*, a constant length defined by $\Delta K_{threshold}$.



ΔK_{eff} estimation

For each participant, the need to take into account cyclic plasticity and crack closure is shown. These two phenomena are included in the ΔK_{eff} parameter deduced from a K_I handbook, a reference stress formula (or equivalent) to take into account plasticity and a crack closure coefficient:

- For K_I handbooks, participants have used fully axisymetrical or semi-elliptical solutions, except for *Part. 1* who has proposed a specific formula for the assumed complex 3D defect.
- To take into account the effect of cyclic plasticity, participants have used methodologies based on the reference stress concept: these stresses are deduced from semi-elliptical or rectangular solutions and define the level of load in the cracked section. The amplification of the elastic ΔK is then related to the ratio elastic-plastic reference strain / elastic reference strain (elastic-plastic strain is deduced from the cyclic curve of the material).
- For crack closure reduction, *Part. 1, 5* and *8* have proposed the following coefficient:

$$q = \frac{1 - R/2}{1 - R}$$

Part. 13 assumes that $K_{min} = 0$. The correction factor is then:

$$q = \frac{1}{1 - R}$$

Crack growth rate

For each participant, the crack growth rate is estimated with the Paris Law of the material (given in the benchmark proposition). This criterion is applied for the crack propagation in depth (for all participants) and in length (*part. 8*).

In complement:

- *Part. 8* proposes to take into account a ductile tearing at each cycle when the maximum applied J is greater then $J_{0.2}$. The ductile propagation is added to the fatigue one and the total crack growth rate is:

$$\frac{da}{dN} = C.\Delta K_{eff}^{n} + \frac{dJ}{dN}.\frac{d(\Delta a)}{dJ_R} \quad (\Delta a \text{ is the total crack extension})$$

- *Part. 8* also proposes to take into account the effect of the stress singularity at the notch tip for the propagation in length of the defect (amplification of the influence function and the effective crack depth).
- *Part. 5* proposes to estimate the length evolution by a fatigue crack initiation criteria from the notch. The angle where critical damage is obtained is calculated at each cycle.
- *Part. 13* proposes a fully elastic analysis to show that this calculation largely underestimate crack propagation..

Defect penetration: step III

Participants

Participants who have estimated the crack propagation have proposed a criterion for crack penetration. For two of them, the analysis is then stopped: only two propositions to evaluate crack shape after penetration are made.
Concerning leak area, two estimations are made.

Crack penetration criteria

There was more discrepancy in the determination of crack penetration:

- For *Part. 1,* it's a geometrical criterion: penetration occurs when a/t > 0.8.
- For *Part. 5,* the employed criterion is based on a J_R curve (of an equivalent material): penetration occurs when applied J (at maximum load of the cycle) is greater than $J_R(\Delta a)$:

$$J_{max}(\Delta a) > J_R(\Delta a)$$

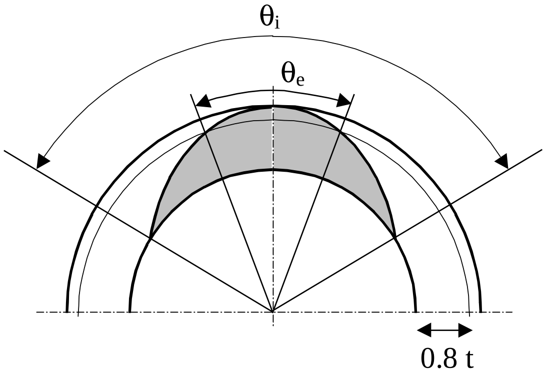
- For *Part. 8* and *13,* the crack penetration is based on J_{IC} : ($J_{max}(\Delta a) > J_{IC}$)
- For the analysis taking into account ductile tearing at each cycle, *Part. 8* proposes the following criterion based on the J_R curve:

$$\frac{dJ_{max}}{da} > \frac{dJ_R}{d(\Delta a)}$$

Penetration defect shape

The defect just after penetration is difficult to estimate because, in one cycle, the surface crack moves to a large through wall defect: the sudden complex crack propagation observed in the test in support of the benchmark is important and not constant in the thickness of the pipe (figure 7 of Annex 2).

- To propose a solution, *Part. 1* gives a geometrical evaluation in which, for a crack with maximum depth a/t = 1, all points on the crack front deeper than 80% of the thickness are supposed to penetrate.



- *Part. 13* proposes a determination of the crack angle at external radius based on a mean value of J between J_{IC} and J for the through wall crack with a length equal to the length of the defect at internal radius:

$$J(TWC\_\theta_e) = \frac{J_{IC} + J(TWC\_\theta_i)}{2}$$

Evaluation of the leakage area

For leakage area, like the evaluation of the defect shape after crack penetration, there were only two propositions:

- *Part. 1* proposes an estimation of the leakage area taking into account plasticity for the maximum load by the following formulae:

$$A_{leak} = \frac{\pi}{2}.c_{ext.}.\left(\delta_{el}.\frac{E.\varepsilon_{ref}}{\sigma_{ref}}\right)$$

Where : δ_{el} is the elastic crack opening deduced from K_I formula for through wall crack (with $\theta = \theta_e$).
σ_{ref} is the reference stress (ε_{ref} the associated strain) associated to the maximum load for the through wall crack.

- *Part. 10* proposes an estimation for a mean through wall crack ($\theta_e + \theta_i/2$) with the elastic plastic Dugdale model.

Obtained results

The following table summarizes the assumptions proposed by the participants and results obtained.

	Crack shape	**ΔK_{eff} evaluation**				**Penetration criteria**	**Crack after penetration**	**N**	**External angle**	**Leakage area**
		Plasticity	**Closure**	**In depth**	**In length**					
Part. 1	Complex 3D	Yes	Yes	Paris law	Constant	a/t = 0.8	Geometrical estimation	100	53°	370 mm²
Part. 5	Semi elliptical	Yes	Yes	Paris Law	Crack initiation	J_R-Δa curve	No	69	—	—
Part. 8.1$^{(1)}$	Fully axisymetric	Yes	Yes	Paris Law	—	J_R-Δa curve	No	58 to 82 (4 cases)	—	—
Part. 8.2$^{(1)}$	Fully axisymetric	Yes	Yes	Paris Law + tearing	—	J_R-Δa curve	No	55 to 80 (4 cases)	—	—
Part. 8.3$^{(1)}$	Semi elliptical	Yes	Yes	Paris Law	Paris Law + K_t	J_R-Δa curve	No	47 to 86 (9 cases)	—	—
Part. 8.4$^{(1)}$	Semi elliptical	Yes	Yes	Paris Law + tearing	Paris Law+ K_t+ tearing	J_R-Δa curve	No	0 to 66 (9 cases)	—	—
Part. 13.1$^{(2)}$	Rectangular	No	Yes	Paris law	Constant	a/t = 1	No	3495	—	—
Part. 13.2$^{(2)}$	Rectangular	Yes	Yes	Paris law	Constant	J_R curve	J_R curve	49	49°	—
Part. 10$^{(3)}$	—	—	—	—	—	—	—	—	—	330 mm²

(1)*Part. 8* has proposed a parametric analysis on the amplification of the effect of the initial crack size, the effect of ductile tearing and the effect of the ΔK_{eff} amplification at the surface point (for the semi elliptical crack): 10 different analyses for an axisymetrical defect and 20 for a semi elliptical one are made.

(2) *Part. 13* has proposed two analyses: one fully elastic and on elastic-plastic.

(3) *Part. 10* has only proposed a leakage area evaluation based on the experimental mean crack length.

Comments:

Concerning the crack growth rate and the number of cycles to crack penetration, the results proposed by the participants show a good accordance (except for the fully elastic analysis proposed by *Part. 13*):

- The effects of plasticity and crack closure have to be taken into account for a good estimation of crack growth rate.
- *Part. 8* proposes to account for a cyclic tearing but this seems to overestimate the crack growth rate and underestimate the crack depth at penetration.

Concerning the external angle of the defect after penetration, there were only two propositions. These two propositions are in agreement with the experimental observation but are not based on validated procedures: they should not be transferable to other material or loading.

For leakage area, the two propositions are in agreement. They are not validated by the experiment because there was no measurement of this area during the test.

Conclusions on the second and third steps

The number of participants to the second and third steps of the benchmark was smaller than for the first step: only four participants have proposed an estimation of the crack growth rate and crack penetration. This is mainly due to the complexity of the problem due to the loading conditions.

Concerning the crack growth rate evaluation, it was shown that it is necessary to take into account cyclic plasticity and crack closure to obtain a good estimation.

For crack penetration criteria, the main part of proposition are based on J_R curve. This assumption which does not account for the interaction between fatigue and ductile tearing seems to provide good estimations in this example.

For the third step (defect size after penetration and leakage area) there were only two propositions. This is mainly due to the complexity of the proposed problem:

- For the crack size, two different propositions are made but they are particular to this example and should not be transferable to other configurations.
- For leakage area, two results in accordance are proposed. They are not validated by the test because no measurement was performed.

4. PROPOSITION OF RECOMMENDATION FOR THE COMPLETE ANALYSIS

Based on the results of this benchmark we propose the following recommendations for the complete analysis (crack initiation, crack propagation and penetration, leak area):

For crack initiation from a sharp geometrical singularity three kinds of estimation methodologies should be employed:

- The first one is an evaluation of the maximum elastic stress around the notch followed by a fatigue stress concentration factor (experimentally determined) to determined the elastic-plastic strain. The stress can be calculated with a F.E. model or a formulae.
- The second one is an evaluation of an elastic stress at a characteristic distance from the notch followed by a Neuber evaluation of the plastic strain. As in first dot, the elastic stress can be determined with an engineering method or a F.E. model.
- The third one is an elastic-plastic finite element calculation which can directly give, for a notch singularity, the maximum elastic-plastic equivalent strain.

The more useful of these three methodologies is the second one because the elastic stress and elastic plastic strain can be evaluated by a K_I formulae and engineering rules such as Creager and Neuber Rules.

For crack propagation, the estimation of crack growth rate should be done with the Paris law of the material. The ΔK_{eff} used as parameter in this law should take into account:

- Cyclic plasticity. One way to estimate this cyclic plasticity is to use the reference stress concept and the cyclic curve of the material.
- Closure effects depending on the load ratio K_{min}/K_{max}.

The penetration of the defect (or the stability of the remaining ligament) should be evaluated, cycle by cycle, with a tearing criterion ($J_{0.2}$ or J_R-Δa curve). In this example, this procedure gives good results but it has to be confirmed on other geometrical and loading configurations.

Concerning the defect shape after penetration, two methodologies were proposed. They are not physical and validated enough to be proposed in a recommendation.

Finally for leak estimation, two propositions were made. The first one is based on an elastic estimation (obtained with K_I formulae) and a plastic correction (based on the reference stress concept). The second one is not detailed but gives a result similar than the first one. Thus, the first proposition based only on formulae should be a good start of recommendation for leak area estimation. However, it has to be confirmed by comparison to test results in different kind of defect and loading.

5. FINAL CONCLUSION

This report presents the results of a benchmark proposed by the CEA on the problem of Leak Before Break. This benchmark concerns a pipe containing a geometrical singularity and submitted to a cyclic bending and is supported by an experiment performed in the CEA laboratory.

For the exercise, the main part of experimental results were given to the participants with the proposition. Thus, the main interest of the benchmark is on the comparison of methodologies. This choice was maid because of the complexity of the proposed problem.

The benchmark was proposed in three steps, with an increasing difficulty:

- The first step concerns the crack initiation at the tip of a notch and under cyclic bending load. The main difficulties of this step are the 3D problem and the non symmetric imposed load ($R = M_{min}/M_{max} = 0$). In this step, participants have to estimate the number of cycles to crack initiation.
- The second step of the benchmark concerns the crack propagation from the notch. For this step, the main difficulties are due to the complex shape of the defect, its evolution with the propagation, the crack closure due to the negative R ratio ($R = M_{min}/M_{max} = -1$) and the end of the crack propagation where an interaction of fatigue crack growth and ductile tearing was observed. For this step, the participants have to estimate the crack growth rate through the thickness of the pipe.
- The third step concerns the crack penetration, the crack shape after penetration and the leakage area. The main difficulty of this step is due to the complex shape of the crack just before penetration and after penetration.

The participation in the first step was important: nine participants have proposed analyses, sometimes parametrical analyses, to estimate the crack growth from the notch. From these results, three family of estimations where shown to give a good accordance with experimental ones (these three families are based on a strain range evaluation and the fatigue curve of the material):

- The use of an elastic stress at the notch tip and a fatigue notch concentration factor to determine the strain range.
- The use of a K_I (or elastic F.E. calculation) and a Neuber rule for the estimation of the strain range at a characteristic distance from the crack tip.
- The direct calculation of the strain range at the characteristic distance by an elastic plastic F.E. calculation.

Only 4 participants have proposed an estimation of the crack growth rate. However, these applications have shown that, for the important level of cyclic load imposed to the pipe, two phenomenon are to be taken into account in effective ΔK to have a good estimation of the crack growth rate:

- The effect of plasticity. This can be estimated with the reference stress concept and the cyclic curve of the material.
- The closure effect due to negative R ratio.

For the third step, the crack penetration is estimated with a ductile tearing criterion. This gives a good estimation in this example but has to be confirmed on other material or geometry. It is the same for crack shape estimations where methodologies are particular to the configuration.

For leak area estimations, two propositions in accordance are proposed but no experimental measurements confirm these results.

ANNEX I:
List of potential participants

Correspondent	Organisation	
S.Chapuliot	**CEA Saclay – (France)**	**1**
M. Batishchev	ENERGOPROEKT – (Bulgaria)	2
B. Brickstad	**SAQ Kontroll AB – (Sweden)**	**3**
V. Tkachev	**Russian Research Center – (Russia)**	**4**
H. S. Kushwaha	**Bhabha Atomic Research Centre – (India)**	**5**
H. Grebner	**GRS – (Germany)**	**6**
L. Lund	US NRC – (USA)	7
J. Sharples	**AEA Technology – (UK)**	**8**
C. Cueto-Felgueroso	**Tecnatom SA – (Spain)**	**9**
R. Wellein	SIEMENS AG – (Germany)	10
K. S. Kim	Pohang University of Science and Technology – (Korea)	11
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ANNEX II

BENCHMARK PROPOSAL ON A CRACKED PIPE SUBMITTED TO A CYCLIC FOUR POINTS BENDING

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(technical description - April 1998)

1. INTRODUCTION

In order to improve LBB methodology, more precisely the crack growth evaluation, a benchmark was proposed by the CEA Saclay [1]. The aim of this benchmark was to evaluate the crack growth of a semi-elliptical defect in a plate subjected to bending. Calculations were compared to experimental results in terms of crack velocity and in terms of shape evolution, and were shown to give, in most cases, a good agreement.
However, this test and numerical applications on this test are analytical and validations of models on a more representative structure are needed for piping system.

Thus, to continue the improvement of LBB analysis and compare methodologies, the CEA proposes another benchmark on a new configuration : a tube submitted to global bending. Like the benchmark proposed on plates, this proposal has the support of detailed experimental results in three main fields of fracture mechanics :

- Fatigue crack initiation from a geometrical singularity (a notch in this example) ;
- Crack propagation under cyclic load ;
- Wall penetration of the defect.

On these three topics, different approaches based on simplified methodologies or finite element analysis can be used. However, the subject is difficult and many questions are not solved. That is why we propose this benchmark as an experimental basis to compare the methodologies and thus improve their capability.

EXPERIMENTAL BASIS

The experimental basis proposed for this benchmark is the case of a tube submitted to a cyclic four point bending at room temperature. In this tube, the initial geometrical singularity is an axisymetrical notch, machined in the mid section of the tube.

During the test, two different aspects were studied :

- The first aspect which was analyzed was the conditions of fatigue crack initiation at the singularity. Thus, the cyclic load is applied until the crack initiation is detected by an Electric Potential Drop method.
- Then, a second aspect is studied : the crack growth under a high level of load amplitude from the initial defect to the total penetration through the thickness. To determine the crack penetration, a small internal pressure is applied so that, when the defect penetrates, the fall of pressure is detected and the test stopped. Two main data are then available : the number of cycles to cross the thickness of the tube and the shape of the through-wall defect at the moment of penetration.

Specimen geometry

The description of the test geometry is given on figure 1. In the cross section, an axisymetrical notch is machined on a depth of 1.2 mm. The precise description of the notch is given on Fig 1.

Loading

The test was carried out under an imposed cyclic loading. Two different levels and R ratios ($R=F_{min}/F_{max}$ where F is the total load imposed by the jack) were adopted (Fig 1).

- For the crack initiation analysis, the imposed R ratio is R = 0.
- For the crack growth analysis, the imposed R ratio is R = -1.

MATERIAL

The material employed for this study is a 316L pipe. Material properties given for the analysis are mean characteristics of the appendix A3.3S of the RCC-MR [2] and laboratory data.

Tensile stress-strain curve

Tensile characteristics were determined by tests on 6 mm diameter specimen and can be compared to the mean values given in the appendix A3.3S [2] at room temperature :

Young modulus : E = 187800 MPa (192000 in [2])
Poisson's ratio : $\nu = 0.3$
Yield stress : σ_y = 235 MPa (235 in [2])
Ultimate stress : σ_u = 530 MPa (592 in [2])

This comparison shows that the tested tube is in good agreement with the A3.3S data. The figure 2 gives a view of the measured true stress-strain curve.

Cyclic curve

The cyclic curve at room temperature is given by the appendix A3.3S [2] :

$$\Delta\varepsilon(\%) = 100.\frac{\Delta\sigma}{E} + \left(\frac{\Delta\sigma}{K}\right)^{\frac{1}{m}}$$

where : $\Delta\sigma$ is the stress range (in MPa)
$\Delta\varepsilon$ is the strain range (in %)
K and m are material constants (K = 712 and m = 0,351)

Fatigue curve

The mean fatigue curve of the material is deduced from the design curve given by the appendix A3.3S taking out the safety factors 2 on the strain range and 20 on the number of cycles. Figure 3 gives a description of the so obtained best-fit curve.

Paris law

The Paris law given for the analysis is obtained from the laboratory data base on 316 stainless steel :

$$\frac{da}{dN} = C.\Delta K^n \quad \text{with} \quad \left| \begin{array}{l} C = 1{,}2.10^{-8} \\ n = 2{,}84 \\ \Delta K \text{ is in MPa.}\sqrt{m} \\ da/dN \text{ is in mm/cycle} \end{array} \right.$$

This law was obtained on CT specimen (19 mm width) with a loading factor R = 0,1. The $\Delta K_{threshold}$ associated to this law is :

$$\Delta K_{threshold} = 15 \text{ MPa.}\sqrt{m}$$

Tearing resistance

The given crack tearing resistance also comes from the laboratory data base. The normalized $J_{0.2}$ value is :

$$J_{0.2} = 490 \text{ kJ/m}^2$$

AIM OF THE BENCHMARK

For this benchmark, we propose to split the study in three separate independent steps.

First step : The crack initiation

Test results

The first part of the test concerns crack initiation under a cyclic load. The cyclic 4 points bending conditions imposed during this part are :

Maximum bending moment : $M_{max} = 38250$ N.m
Minimum bending moment : $M_{min} = 0$

The associated rotation, measured at 175 mm from the mid section of the tube is (fig. 4) :

Maximum rotation : $\beta_{max} = 0{,}212°$
Minimum rotation $\beta_{min} = 0$

The crack initiation was detected by an Electric Potential Drop measurement after 2157 cycles. However, the associated crack propagation is not known because the sensibility of the measurement at crack initiation is not known.

Aim of the calculation

In this first step, we propose to participants to give an estimation of the number of cycles which are necessary to reach the crack initiation. This will provide to a comparison of methodologies to estimate a crack from a geometrical singularity.

Second step : Crack propagation

Test results

The second part of the test has concerned the crack growth under high cyclic loading. The cyclic 4 points bending conditions imposed during this part are :

Maximum bending moment : M_{max} = 53000 N.m
Minimum bending moment : M_{min} = -51200 N.m

The associated rotation of the stabilized cycle, measured at 175 mm from the mid section of the tube is (fig. 4) :

Maximum rotation : β_{max} = 0,63°
Minimum rotation β_{min} = 0,61°

The figure 5 gives a representation of the stabilized cycle. During the test, the crack propagation is monitored by EDP measurement. As a result, the calibration curve, determined for this specific test series, allows to estimate the crack propagation during the cycles : figure 6 shows the evolution of the maximum crack growth (at the maximum loading point of the tube).

Aim of the calculation

In this second step, we propose to participants to estimate the crack growth (depth and length) versus the number of cycles under high cyclic loading. Crack growth estimations will be compared to the measured evolution of the defect and thus the methodologies employed to estimate the crack growth rate, specially in the way to take into account cyclic plasticity.

Third step : crack penetration

Test results

The third part of the test concerns the crack penetration. This occurs experimentally for a maximum crack depth to thickness ratio a/t = 0,77 and at the cycle number 69. Figure 7 gives a view of the defect just before crack penetration and just after the crack penetration.

Aim of the calculation

For this third step, we propose to participants to estimate the number of cycles for the maximum stable crack depth obtained by the fatigue load, before the wall penetration, and the shape of the through-wall defect. This will provide a comparison of defect penetration criteria and through-wall shape evaluation.
In addition, we propose to calculate the leakage area of the through-wall defect. This was not measured during the test, but it seems interesting to compare the leakage area evaluation methods.

Comments on calculations

Due to the complexity of the problem, it is proposed to participants to detail their evaluation methodologies (assumptions, comments on results...). This will increase the understanding and the benefits of comparisons.
It is possible to participate only to steps 1 or 2 of the benchmark.

CO-ORDINATOR

All results and methodologies will be compared between themselves and with experimental results. The coordination of the benchmark will be made at the CEA Saclay by :

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TIMESCALE

The proposed problem is complex and may need particular development. Thus, we propose to distribute the analysis on two years:

1998 : - Submission of the technical description of the benchmark ;
- Response of interested organizations and possible technical questions ;
- Response of the CEA on technical questions ;
- First analysis (on step 1).

1999 : - Analysis of steps 2 and 3 ;
- Comparison of results ;

2000 : - Final report.

CONCLUSIONS

An experimental data- set from CEA is proposed for a benchmark to validate the LBB analysis in fatigue crack propagation from the initiation at a geometrical singularity to the penetration of the component. This benchmark is in continuity with the first one proposed on a plate with a semi-elliptical flaw in a new geometry and loading.

The results generated from the study will contribute to increase the knowledge of fatigue crack growth and improve the methodologies used in LBB analysis in complex phenomena such as growth under high level of load amplitude and break-through.

References :

[1] Report of the benchmark on the fatigue propagation of a semi-elliptical crack in plate subjected to cyclic bending.
NEA/CSNI/R(97)8

[2] Design and construction rules for mechanical components of FBR islands.
RCC-MR - Section I - Subsection Z : Technical appendix A3 (June 1985 edition)

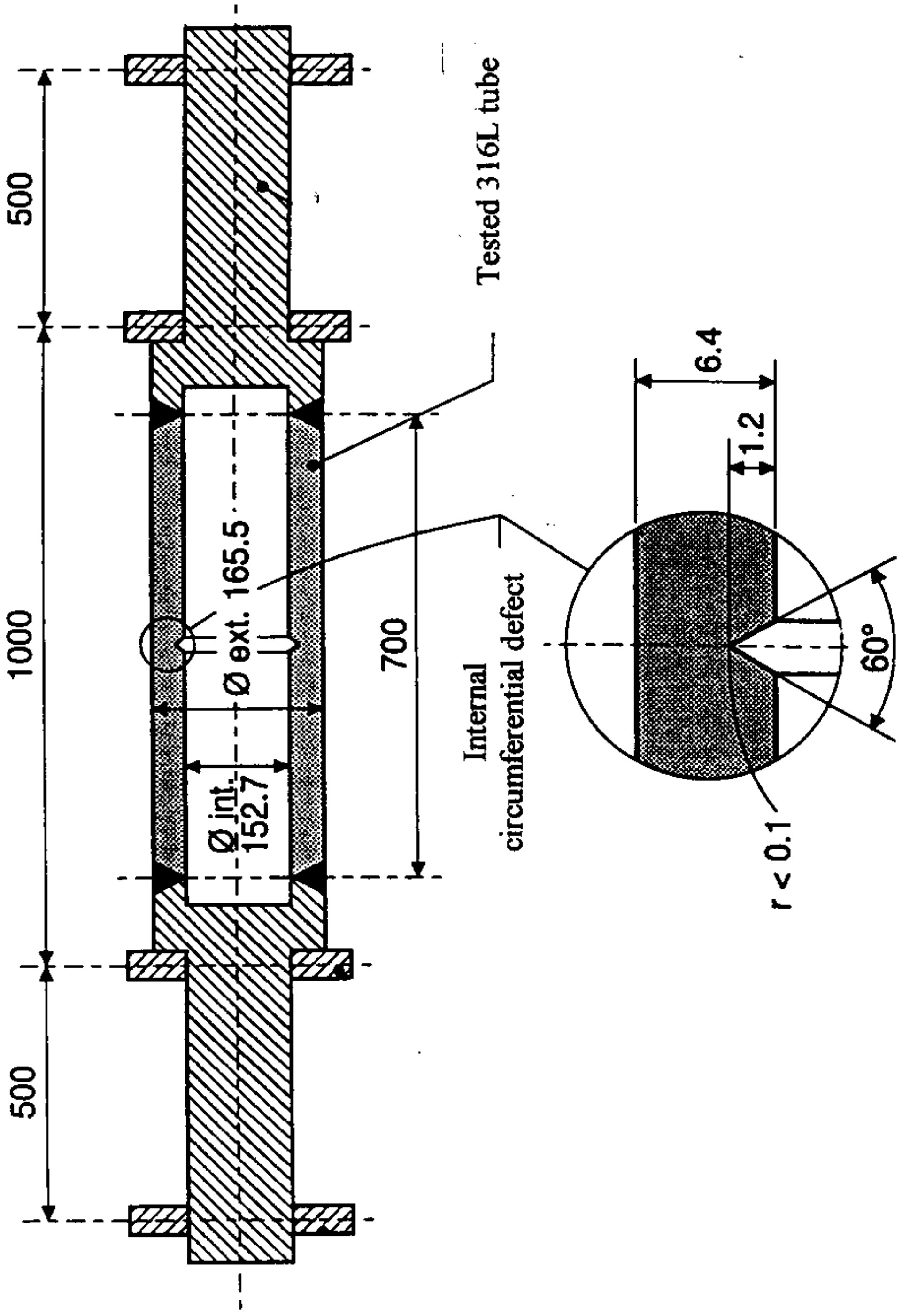
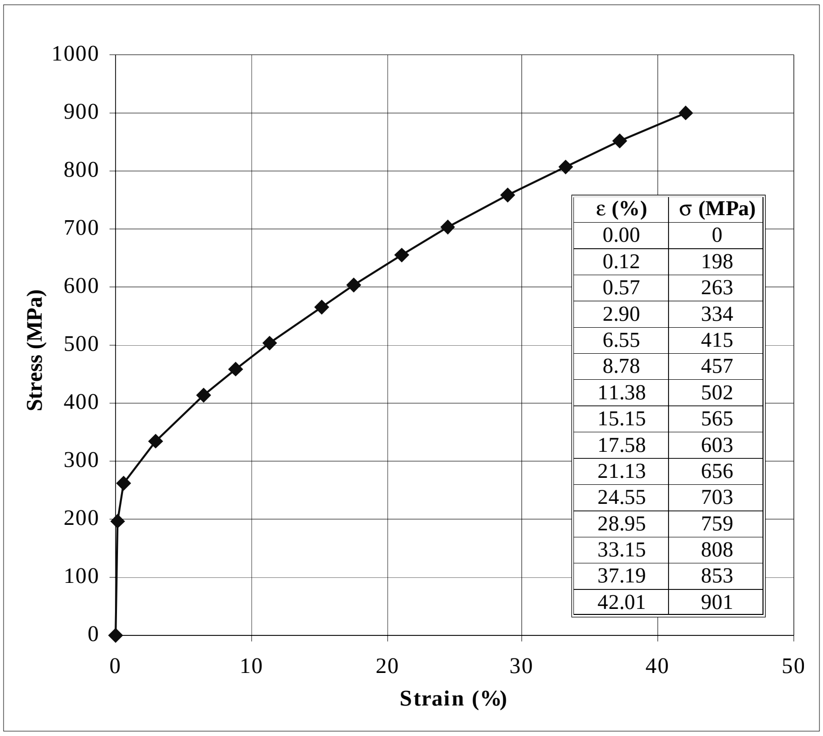
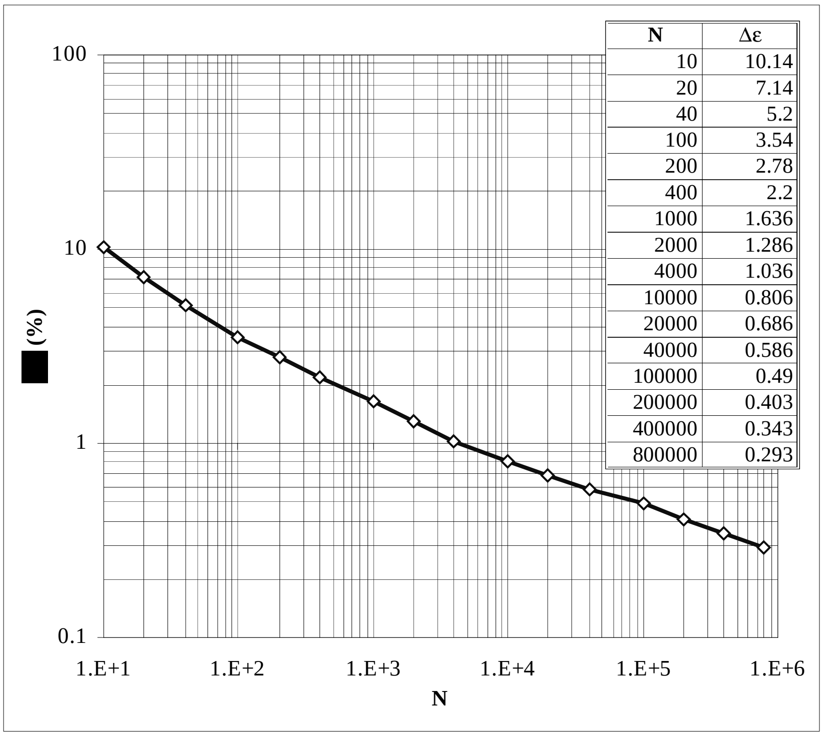


Figure 1 : Test description



ε (%)	σ (MPa)
0.00	0
0.12	198
0.57	263
2.90	334
6.55	415
8.78	457
11.38	502
15.15	565
17.58	603
21.13	656
24.55	703
28.95	759
33.15	808
37.19	853
42.01	901

Figure 2 : True stress-strain curve of the material



N	Δε
10	10.14
20	7.14
40	5.2
100	3.54
200	2.78
400	2.2
1000	1.636
2000	1.286
4000	1.036
10000	0.806
20000	0.686
40000	0.586
100000	0.49
200000	0.403
400000	0.343
800000	0.293

Figure 3 : Fatigue best-fit curve

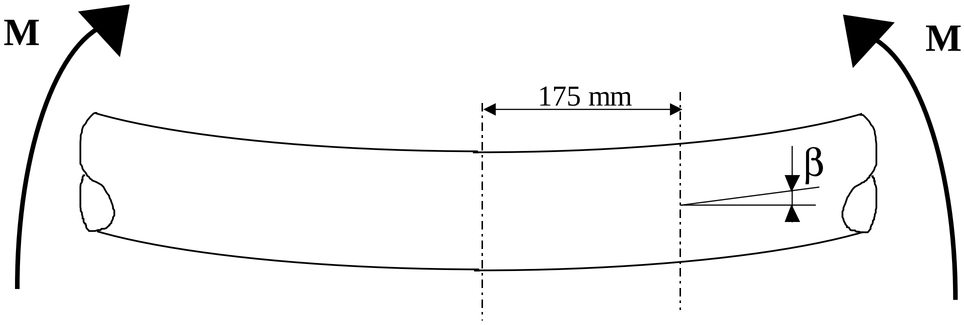


Figure 4 : Tube rotation measurement

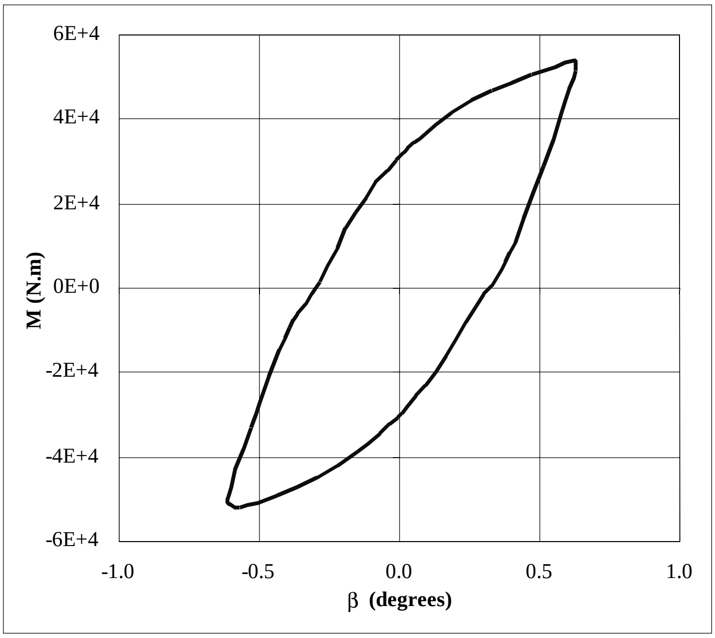
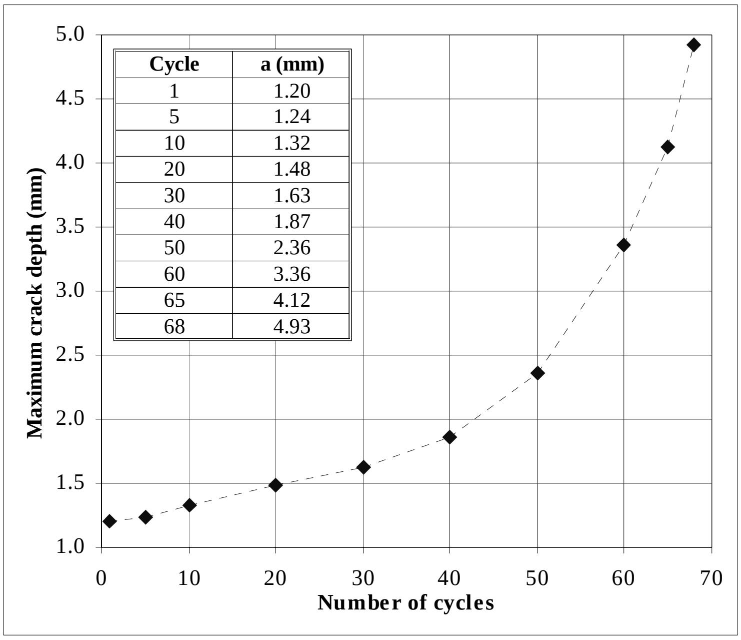


Figure 5 : Stabilized cycle



Cycle	a (mm)
1	1.20
5	1.24
10	1.32
20	1.48
30	1.63
40	1.87
50	2.36
60	3.36
65	4.12
68	4.93

Figure 6 : Maximum crack growth evolution

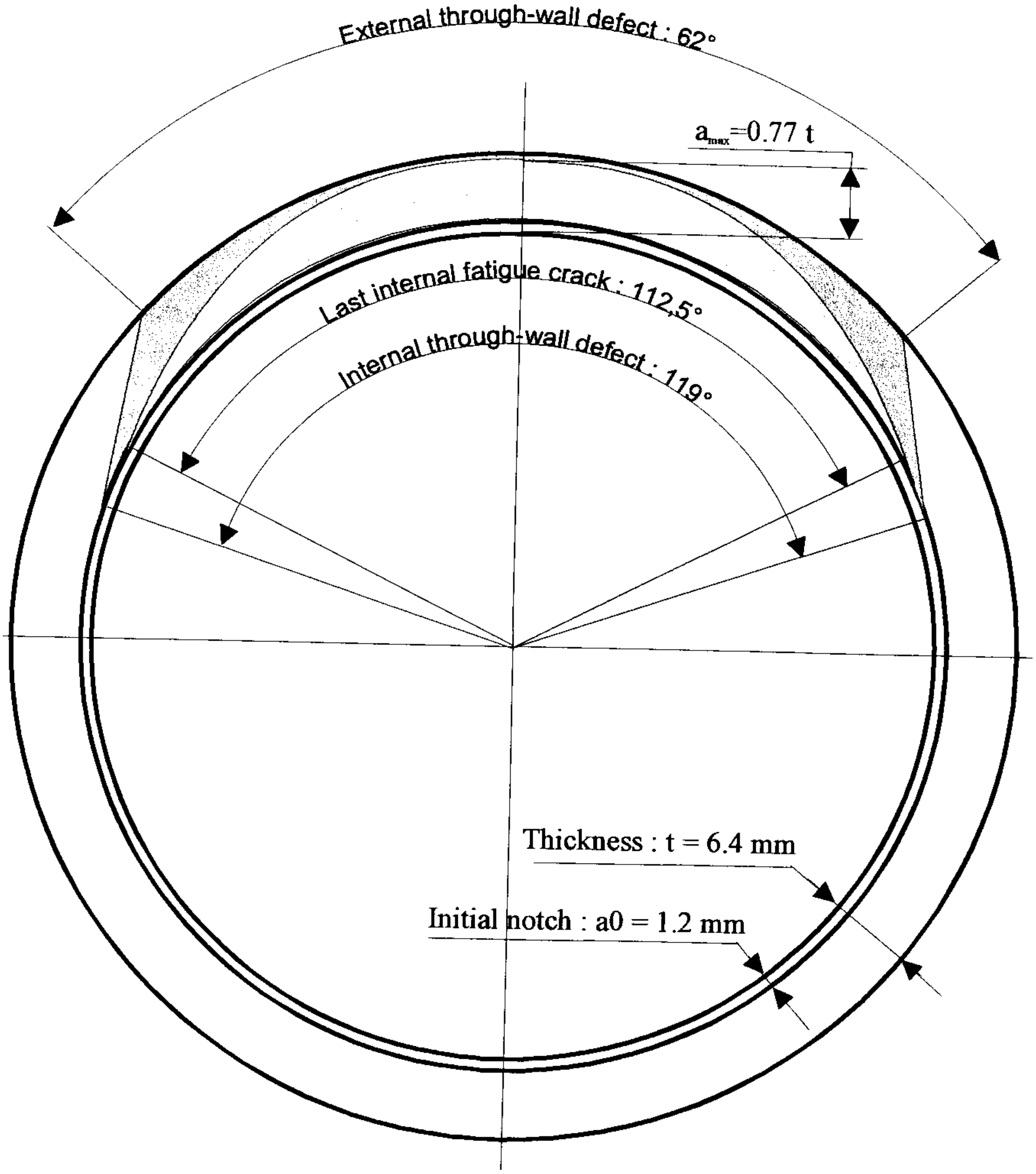


Figure 7: Crack shapes