

Guide to

**Methods for the assessment of
the influence of crack growth
on the significance of defects
in components operating at
high temperatures**

Committees responsible for this Published Document

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Foreword

This Published Document has been prepared under the direction of the Pressure Vessel Standards Policy Committee.

The increasing number of application standards specifying requirements for flaw acceptance levels and the growing understanding of the significance of flaws, makes it necessary to update and extend the guidance given for the assessment of such situations.

With the growing commercial need to extend the operating life of plant and the increasing statutory requirements for demonstrations of continued in-service integrity, a means of assessment of the life expectancy of plant becomes more necessary. This document provides assessment methods for the consideration of flaws which exist in conditions where creep crack growth is significant.

The document takes into account the most recent developments in the subject, such as those provided by the Nuclear Electric R5 Procedure [1]. Experience gained in using PD 6510 : 1983 (for making remanent life assessments of pressure vessels designed for high temperature service), PD 6493 : 1991 (methods for assessing the acceptability of flaws in fusion welded structures) and the Nuclear Electric R6 procedure [2] (for making safety estimates of structures containing defects that operate below the creep range) was used as background information. In addition consideration was given to the recommendations of VAMAS Working Party TWA 11 that was set up to prepare an International Standard for creep crack growth testing.

It is intended that the document will be kept under review and modifications made as necessary.

It has been assumed in the drafting of this Published Document that the execution of its provisions is entrusted to appropriately qualified and experienced people.

Guide

1 Scope

This Published Document gives guidelines for assessing the significance of defects in components that operate in the creep range. Procedures are presented for describing failure by net section rupture, crack growth or some combination of both processes. The influence of fatigue and the onset of brittle or ductile fracture in determining tolerable defect size is also considered. Information is included for specifying loading conditions and characterizing defects. The calculations make use of limit analysis methods, continuum damage mechanics and fracture mechanics concepts. Several levels of complexity are discussed depending on the criticality of the problem and the data available on the properties of the material. Approximations are presented for dealing with cracked components when only stress rupture data are available. A worked example is provided, which takes the user through the procedure, step by step. This document provides a method of assessing the significance of defects when time dependent creep effects have to be taken into account. It is intended for use at temperatures above the limits given in table 10 of PD 6493 : 1991, and is based on the Nuclear Electric R5 Procedure [1], simplified where appropriate. It is intended for use when assessing components made in ferritic and austenitic steels. The same principles are applicable to other metallic components, provided the user can obtain the relevant materials data.

The assessment procedure may be applied to components containing planar defects, including cracking or lack of fusion. It may be applied, subject to the restrictions given below, to defects which are actually discovered during pre-service or in-service inspection. The objective is to decide whether the defect is innocuous and will never affect the integrity of the plant, whether remedial action can be deferred until some time in the future or whether repairs are needed immediately. The procedure may also be applied at the design stage, subject to the same restrictions, to hypothetical defects, in order to set inspection sensitivity or to check that a proposed component is tolerant to defects.

The procedure is not applicable to defects that are caused by stress corrosion and similar environmental phenomena. The parameters that control environmentally assisted cracking and stress corrosion cracking at high temperatures are still under investigation.

A bibliography is given in annex A. References in square brackets can be found in the bibliography.

2 Normative references

This Published Document incorporates, by dated or undated reference, provisions from other publications. These normative references are made

at the appropriate places in the text and the cited publications are listed on the inside back cover. For dated references, only the edition cited applies; any subsequent amendments to or revisions of the cited publication apply to this Published Document only when incorporated in the reference by amendment or revision. For undated references, the latest edition of the cited publication applies, together with any amendments.

3 Symbols

For the purposes of this Published Document the following symbols apply.

Symbol	Definition	Unit	Notes
a	Full depth of surface breaking defect or half depth of embedded defect	m	1
A	Constant in creep crack propagation equation	1)	—
$\dot{a}_c$	Rate of crack propagation in depth direction due to creep	m/h	1
C	Constant in fatigue crack propagation equation	1)	—
C^*	Parameter defining creep crack propagation rate	MPa·m/h	—
D	Constant in creep strain equation	1)	—
D_c	Accumulated creep damage	2)	1
ΔD_c	Increment of creep damage in block	2)	1
$(da/dN)_f$	Rate of crack propagation per cycle in depth direction due to fatigue	m/cycle	—
$(da/dN)_c$	Rate of crack propagation per cycle in depth direction due to creep	m/cycle	—
$(dl/dN)_f$	Rate of crack propagation per cycle in length direction due to fatigue	m/cycle	—
$(dl/dN)_c$	Rate of crack propagation per cycle in length direction due to creep	m/cycle	—
E	Young's modulus	MPa	—
f	Frequency of fatigue loading cycle	Hz	—
F	Peak stress	MPa	2
K_{Ic}	Fracture toughness of material	MPa·m ^{1/2}	3

K_a	Linearly calculated stress intensity factor at maximum depth of crack	MPa · m ^{1/2}	3	δ_I	Crack opening displacement at initiation of creep crack growth	m	—
K_l	Linearly calculated stress intensity factor at extreme length of crack	MPa · m ^{1/2}	3	ε_c	Accumulated creep strain	2)	1
ΔK	Elastically calculated range of stress intensity factor arising from fatigue loading	MPa · m ^{1/2}	—	ε_f	Strain to failure of material, as measured in uniaxial test	2)	—
l	Half length of crack	m	1	$\Delta \varepsilon_c$	Increment of creep strain per block	2)	1
$\dot{l}_c$	Rate of crack propagation in length direction due to creep	m/h	1	θ	Temperature	°C	1
$L(\sigma_y)$	Limit load of component, with arbitrary yield stress	MN	—	σ_b	Linearized bending stress	MPa	1
m	Exponent in fatigue crack propagation equation	2)	—	σ_m	Linearized membrane stress	MPa	1
n	Exponent of stress in creep strain equation	2)	—	σ^p	Stress arising from loads which contribute to plastic collapse (see 6.4)	MPa	1
p	Exponent of time in creep strain equation	2)	—	σ_{ref}	Reference stress	MPa	1
P	Primary stress, including all stresses arising from internal pressure and external load	MPa	2	σ^s	Stress arising from loads which do not contribute to plastic collapse (see 6.4)	MPa	1
q	Exponent in creep crack propagation equation	2)	—	σ_y	Arbitrary yield stress used in limit load analysis	MPa	—
Q	Secondary stress, arising from thermal loading and residual stresses due to manufacturing processes	MPa	2	1) Consistent units to give crack growth in metres per hour and metres per cycle.			
R'	Parameter used in creep crack propagation equation	m	—	2) Dimensionless.			
t	Time accumulated from initial start-up of plant	h	1	NOTE 1. Subscript 0 is used to denote initial conditions. Subscripts 1, 2, 3 ... n are used to denote conditions relevant to each block. For consistency with PD 6493 : 1991, subscripts 1 and 2 are also used in annex A to denote surface stress.			
t_{cd}	Time to failure of plant by bulk creep rupture, measured from initial start-up	h	—	NOTE 2. Subscript m is used to denote membrane component of stress. Subscript b is used to denote bending component of stress. (See 6.4 for full information.)			
t_d	Required life of plant, measured from initial start-up	h	—	NOTE 3. Superscript p is used to denote the stress intensity factor due to stress arising from loads which contribute to plastic collapse.			
t_{ff}	Time to failure of plant by fast fracture, measured from initial start-up	h	—	Superscript s is used to denote the stress intensity factor due to stresses arising from loads which do not contribute to plastic collapse.			
$t_{R(ref)}$	Time to creep rupture at reference stress	h	—	Superscript (p + s) is used to denote the stress intensity factor due to all loading conditions, including thermal and residual stresses. (See 6.4 for full information).			
t_I	Incubation period	h	—				
Δt	Time span of block	h	1				

4 General restrictions and information requirements

4.1 Where cracks are discovered in material which has suffered extensive creep damage, it is essential to use materials data which relate to the material in its end-of-life condition.

Creep rupture data and fracture toughness are particularly sensitive in this respect.

4.2 Cracks in welds need special treatment. The properties of the heat affected zone and the weld metal usually differ from those of the parent material and local residual stress may need to be taken into account. Particular care is needed in situations which involve reheat cracking.

4.3 The Document does not suggest the factor of safety which should be applied to predictions of crack growth and final failure. The decision about this has to be left to the discretion of the assessor. The value chosen will depend on the degree of pessimism introduced into the input data and on the results of sensitivity analyses. Further guidance will be found in appendix A of PD 6493: 1991, although the factors of safety given there may need to be adjusted to suit the circumstances of the case under investigation.

5 Crack behaviour at high temperature

The behaviour of a crack at elevated temperature is shown schematically in figure 1. Following the initial loading of the component, the crack may blunt and, in these circumstances, there will be an incubation period before a further short crack forms and propagation initiates. Where such blunting does not occur, crack propagation may be assumed to start immediately on loading. The crack grows, in all cases, by a fracture mechanics controlled mechanism.

Crack propagation can theoretically continue until structural failure takes place. Creep damage may build up ahead of the crack and creep rupture of the remaining material may occur. Alternatively, the net section may fail through a short term phenomenon, such as plastic collapse if the material is ductile or fast fracture if the material is brittle. These conditions are shown diagrammatically in figure 2.

NOTE. In some circumstances, additional confidence against fast fracture may be obtained by demonstrating leak-before-break.

Where new plant is under consideration, it may be possible to benefit from the incubation period, starting the crack growth calculations at the end of this period. The incubation time should be calculated by the methods described in **B.8**.

When a defect has been discovered after the component has been in service, the conservative assumption should be made that the crack initiated earlier in life, unless there is strong evidence to the contrary.

The assessment of the defect in an actual component is carried out in a series of well defined steps.

- a) Clause 6 describes the initial work which needs to be undertaken to decide whether the procedure is applicable. It shows what needs to be done to establish service loads and temperatures, to characterize the dimensions of the defects and to define materials properties and stress levels.
- b) The calculations needed to predict defect growth are outlined in clause 6 and given in detail in annex C. These also describe the checks which are made to establish margins against creep rupture and fast fracture.
- c) The materials data required for the assessment are discussed in annex B and examples are quoted for the most commonly used materials. Annex B also provides a means of estimating materials properties when test data are not available.

It should be noted that only the basic procedures needed for defect assessment have been included in the document and these necessarily contain an element of conservatism. Background information can be obtained from references [1] to [6].

Where economic circumstances justify such a course of action, it may be appropriate to use less conservative procedures. These, however, involve more complex analysis than that described here and a certain amount of materials testing will also usually be necessary. In these situations it is desirable to take specialist advice.

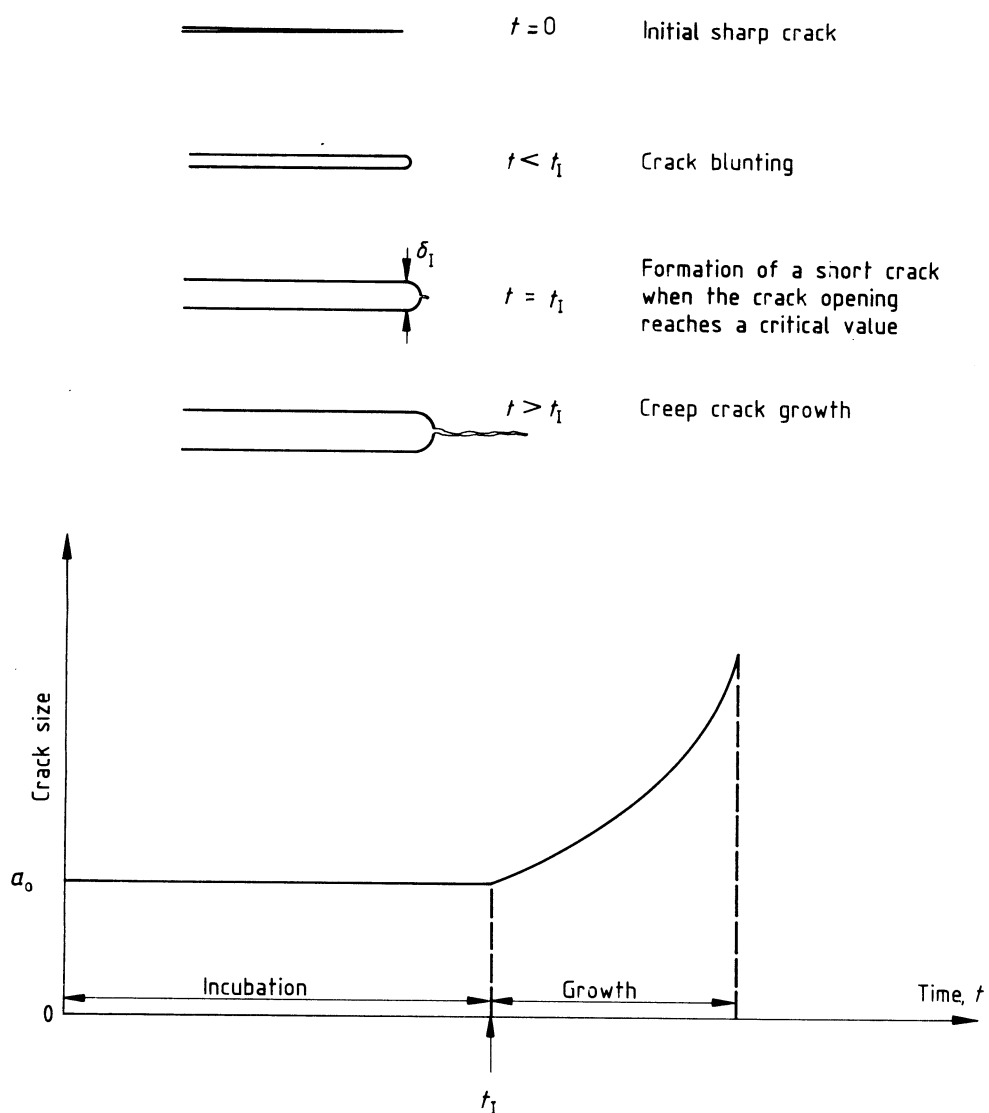
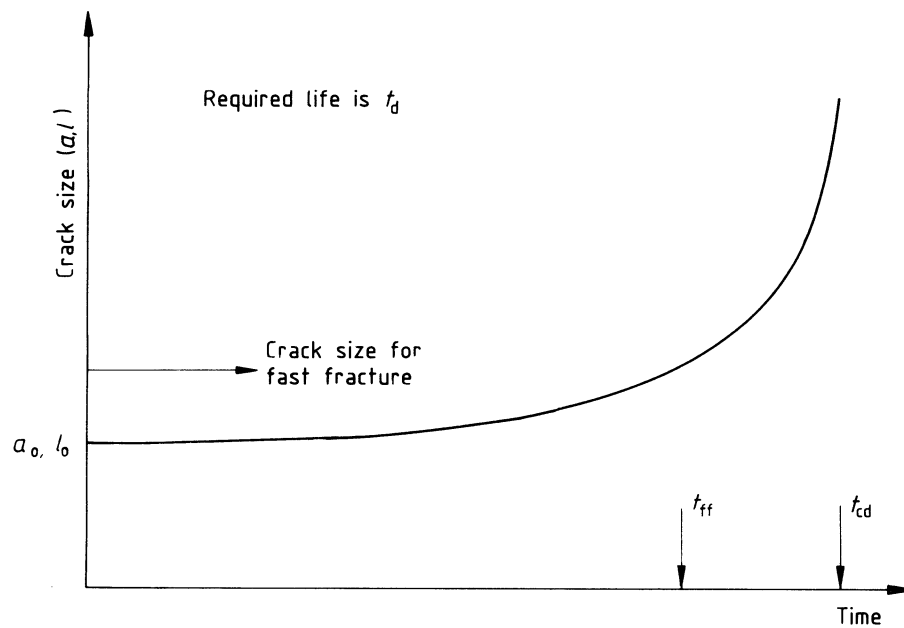


Figure 1. Schematic behaviour of crack at elevated temperature



If $t_d < t_{cd}$ and $t_d < t_{ff}$ then remedial action is not needed
 If $t_d > t_{cd}$ or $t_d > t_{ff}$ then remedial action is needed

Figure 2. Schematic representation of crack propagation and failure conditions

6 Assessment procedure

6.1 General

The procedure is implemented in a series of well defined steps, which are shown in flow sheet form in figure 3. The flow sheet and the detailed descriptions of the individual steps given below relate to a defect which has been discovered after a component has been in service for a period of time.

When considering a component before it enters service, containing either a postulated defect or one discovered during inspection, some modifications are needed. These are noted in the text, as appropriate.

6.2 Initial investigations to establish cause of cracking

Prior to performing calculations, an initial investigation should be carried out to identify the most likely cause of cracking. This may include a combination of non-destructive testing, visual examination and metallurgical examination, as appropriate. Also, if possible, a dimensional check should be carried out on the component to establish if there has been any significant distortion.

Often the cause of cracking will be obvious and, in these cases, only a relatively straightforward confirmatory metallurgical examination is required. When the reasons for the cracking cannot be established unequivocally in this way, a more detailed metallurgical study will be needed.

Specialist advice should be sought as a discussion of all the relevant metallurgical factors is outside the scope of this Published Document.

Where there is evidence of stress corrosion and environmentally assisted cracking, for example multiple intergranular cracking without cavitation, the methods given in this document should not be applied without specialist advice. It may not always be necessary to replace the component, provided it can be shown that the cracks will not propagate significantly. However, this is a topic on which specialist advice should be sought.

Significant creep damage away from the crack tip, particularly if accompanied by distortion of the component, is often an indication that there has been local overheating or some form of overstressing and that the material is nearing the end of its safe working life. Any crack propagation and failure calculations which are carried out should take into account the properties of the material in its damaged state.

Leaving aside overheating, overstressing and environmental effects, crack growth in high temperature plant is most likely to be associated with a pre-existing defect which has not been detected by pre-service inspection or with a crack which has been initiated by some form of fatigue loading. In both situations, the guidance given in this document is applicable.

Pre-existing defects often occur in welds and certain precautions, described in annex D, are necessary when applying the assessment procedure.

6.3 Define previous plant history and future operational requirements

The service loads and service temperatures for the component should be established for each operating condition. The previous history of the plant can usually be obtained from operating records. Where service loadings and service temperatures depend on plant output, the previous history should be broken down into a series of blocks, during which the stress and temperature are sensibly constant.

Where sufficiently detailed records are not available, an initial assumption may be made that the total period of operation has been under the most onerous conditions. Where this leads to an unduly pessimistic prediction about remaining life, a more detailed investigation should be undertaken.

In addition to tabulating the total time at each of the steady operating conditions, any events likely to contribute to fatigue damage need also to be taken into account. Where vibration or thermal fluctuations occur during periods of nominally constant load operation, an estimate of the frequency and magnitude of the fluctuations is required.

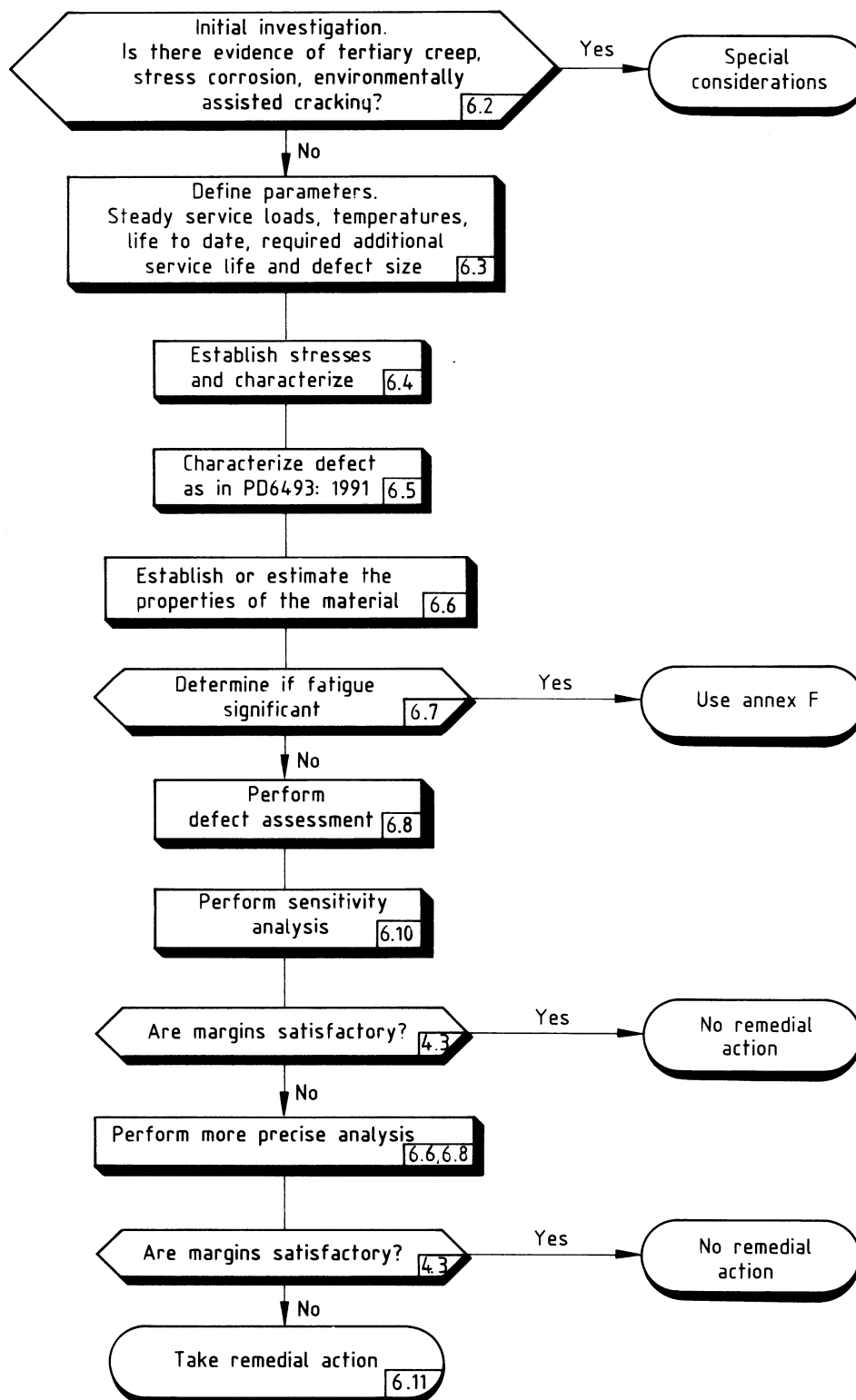
Where transient thermal or mechanical loads occur at start up or shut down or with change in plant output, the number of load cycles and their magnitude should be established.

In defining the future life which is required from the plant, predictions have to be made about the way in which the plant is likely to be operated. Where transient load conditions are likely to occur, it is important to consider future operating regimes which may involve more frequent output changes than previously.

6.4 Establish stresses

The relevant stresses to be used in the assessment should be those which would exist in the neighbourhood of the defect if the body were uncracked. They should not include stress intensification effects due to the defect itself, as these are naturally taken into account by the assessment procedure.

At all stages in the assessment it is necessary to distinguish between those stresses arising from loads which contribute to plastic collapse and those stresses arising from loads which do not do so. In the terminology of the Nuclear Electric R5 [1] and R6 [2] procedures, these are defined as σ^p and σ^s respectively. The σ^p stresses are used in calculating the stress intensity factor K_1^p and the σ^s stresses plus the σ^p stresses are used in calculating the stress intensity factor $K_1^{(p+s)}$.



NOTE. The numerals in the bottom right hand corner of each symbol give the relevant clause number of the procedure.

Figure 3. Flow sheet for the assessment procedure

It is sometimes necessary, for example when following certain of the procedures described in PD 6493 : 1991, to separate the stresses into different categories. While this follows the principles of the ASME Boiler and Pressure Vessel Code, Section III, NB 3000 and of appendix A of BS 5500 : 1994, special care is needed in dealing with the secondary and peak stresses. All stresses which are induced by internal pressure and external loads need to be categorized, for the purpose of the present document, as primary despite the fact that, in many instances, ASME Section III and BS 5500 would classify them as secondary. In the case of peak stresses, it is necessary to distinguish between those which are due to internal pressure and external load and those which are brought about by thermal loading or residual stresses in welds.

In carrying out the stress categorization, it is important to take into account any elastic follow up effect due to the spring action of adjacent parts of the structure. Unless it can be demonstrated to the contrary, long range thermal and residual stresses should be categorized as primary.

The stress categories used in this document are as follows:

P - primary stress, which includes all stresses arising from internal pressure and external loads and which includes some stresses classified as secondary by ASME Section III and appendix A of BS 5500 : 1994. The primary stress category also includes long range thermal and residual stresses, unless there is conclusive evidence to the contrary.

Q - secondary stress, arising from thermal loading and residual stresses due to manufacturing processes, including welding.

F - peak stresses, usually associated with local stress raising features.

Therefore the stress intensity factor K_1^P is calculated using the stresses which are categorized as *P*. The portion of the *F* stresses which are induced by internal pressure and external loads are added to the *P* stresses if the crack tip is situated in the *F* stress region.

The stress intensity factor $K_1^{(P + S)}$ is calculated using the sum of the *P* and the *Q* stresses. The *F* stresses arising from all causes are added if the crack tip is situated in the *F* stress region.

If the method of appendix E of PD 6493 : 1991 is used to evaluate stress intensity factors, it is necessary to linearize the stresses and obtain membrane and bending components. The way in which this should be done is described in annex E.

It is necessary to emphasize that many of the difficulties inherent in stress categorization and in linearization can be avoided if the finite element method is used to calculate the stresses in the vicinity of the defect. Stress intensity factors can be evaluated using a weight function method or by using a post processor program. Two calculations will generally be required. In the first, used to evaluate K_1^P , the component is subjected only to those loads which contribute to plastic collapse, including, where necessary, long range thermal and residual stresses. In the second calculation, to evaluate $K_1^{(P + S)}$, the calculation is carried out for the total loading to which the structure is subjected, i.e. internal pressure and external loads plus both long range and localized thermal and residual stresses.

6.5 Characterize defects

Defects are generally of irregular shape. The maximum depth and maximum length are used in this instance. The method to determine the size and circumscribing rectangle should be that given in 8.3 of PD 6493 : 1991, which also provides the method for characterizing and assessing the interaction of multiple defects.

An elliptical defect, inscribed within the rectangle, is used for the purpose of calculation. In the present document, the length is defined as $2l$ and the depth as $2a$, as shown in figure 4. The depth of a semi-elliptical surface breaking defect is taken as a .

Where there is doubt about the accuracy of the size of defect established by the inspection procedure, it may be necessary to assume a larger defect for the purpose of assessment in order to ensure a safe assessment. It is the intention of this document that upper bound sizes for defects should always be used.

Where the plane of the defect is not aligned with a plane of principal stress further consideration is needed. The first step is to project the defect on to each of the three planes normal to the principal stress and to evaluate the stress intensity factors and the reference stresses for each of the three projected defects. Often one of these projections will lead to a stress intensity factor and a reference stress which are both significantly higher than those of the other two projections. The assessment is then carried out taking a and l as the projected dimensions on that plane. This for example is the method often applicable to near circumferential defects in the wall of a pipe, where the defect is projected on to the circumferential plane.