T73S02 Session 22B – Leak-before-Break, Proof Test Argument, etc

Last Update 24/10/2012

Relates to K&S Questions 4.16, 4.17, 4.18, 4.19, 4.20, 4.21, 4.22, 4.24, 4.26, 4.28

Leak-before-break; proof test argument; strength mismatch assessments; crack arrest

Qu.: Was is meant by “Leak-before-Break (LbB)”?

When a part-penetrating crack in a pipe grows it may (at least initially) become a stable through-thickness crack, and hence result in leakage of the fluid from the pipe – as opposed to causing a complete guillotine fracture of the pipe. If this happens it is referred to as “leak-before-break” (LbB). A leaking crack is often more tolerable than complete guillotine failure and so it is valuable to distinguish the two modes of failure.

Qu.: When does LbB happen?

That’s what an LbB assessment tries to determine.

Qu.: Where is the LbB assessment procedure specified?

In EDF Energy we would probably use R6, the relevant part being Chapter III.11. Internationally, especially in the context of light water reactors, a widely used procedure is the US Nuclear Regulatory Commission’s NUREG 1061 Volume 3. These notes are biased towards R6.

Qu.: What are the basic requirements of LbB?

R6 III.11 requires the following,

(a) That the defect is stable for some period after penetrating the pressure boundary, and,

(b) That the resulting fluid leakage is sufficiently great to ensure its detection before it can develop into a guillotine failure.

To these I would personally add a third requirement,

(c) That the fluid leakage is tolerable within the safety case.

Hence, whilst (b) requires the leakage to be greater than some detectable limit, (c) also requires that the leakage be less than some tolerable limit. The tolerable limit might be due to the effect of (say) hot gas or moisture on nearby equipment, or the effect of toxic gas on personnel, etc.

Qu.: Of what does a full LbB assessment consist?

There are several distinct steps in an LbB assessment:-

(i) Determine the size, shape, orientation and location of the *starter* crack;

(ii) Calculate the growth of the crack, in both length and depth, up to the point at which the crack becomes through-thickness due to ligament failure (“snap-through”);

(iii) For the purposes of assessing through-crack stability, re-characterise the through-crack at snap-through using the rules of R6 Section II.3.5.2;

(iv) Calculate the crack opening area and hence the fluid leakage rate (for this purpose a different form of re-characterisation may be required – see below);

(v) Calculate the critical through-crack length;

(vi) Calculate the time for the crack to grow from its re-characterised length at snap-through to the critical length;

(vii) Determine, (a)if the leakage rate is sufficiently great to be detectable, and, (b)if arrangements on plant ensured its detection prior to instability, as calculated in (vi).

To these R6 requirements I would personally add,

(viii) Ensure that the leakage remains tolerable within the safety case prior to detection.

Qu.: What loads are assumed in the assessments?

Crack growth assessments will use representative normal operating conditions. Ligament failure resulting in snap-through should be based on fault loadings and lower bound materials properties (noting that a part-penetrating defect might snap-through *because of* some fault loading).

The critical through-crack assessments must also be based on fault loadings and lower bound materials properties.

Qu.: What does "re-characterisation" of the crack at snap-through mean?

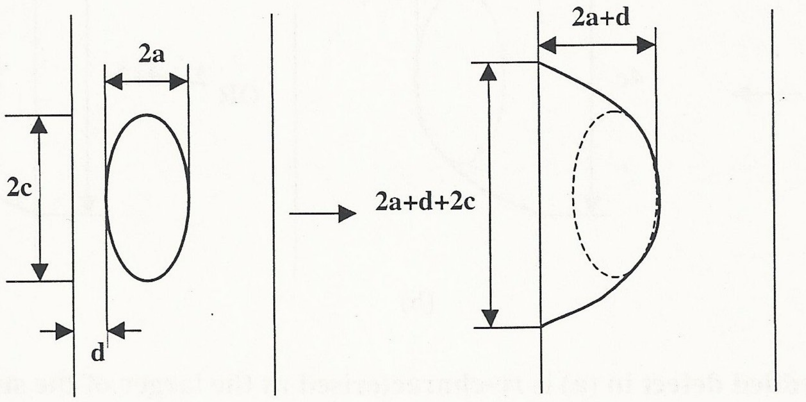
There are three distinct re-characterisation procedures:-

(A) When calculating the critical crack length

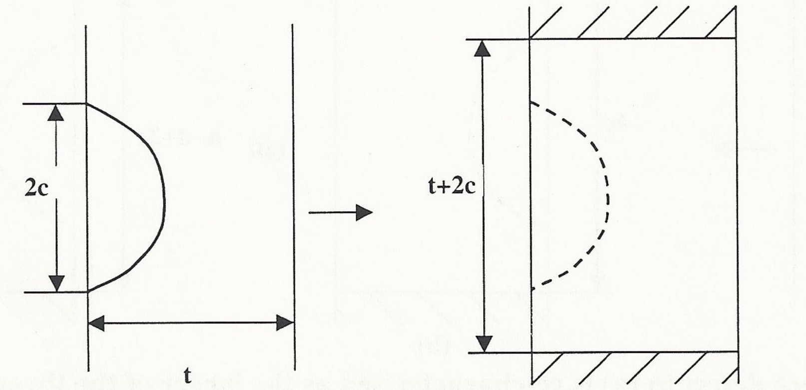
Under the main procedure of R6 the length of the through-crack must be assessed as being greater than the length of the part-penetrating crack immediately before it snaps-through. The rules for this re-characterisation are defined in R6 Section II.3.5.2 and in Figures II.3.4 (brittle materials) and II.3.5 (ductile materials), the latter being reproduced below.

Figure 1 Re-Characterisation for ductile behaviour to be used for the calculation of the critical crack length

(NB: R6 has distinct rules for brittle behaviour)



(i) Embedded defect



(ii) Surface defect

(B) When calculating lower bound leakage rates to underwrite detectability

When a semi-elliptic defect snaps-through it does not immediately become a parallel-sided 'letterbox' crack like that shown in Figure 1(ii). The defect length on the back surface ($2c_2$) will initially be much shorter than on the surface from which the crack has grown ($2c_1$). This means that the leakage rate will be strongly throttled by this smaller length, and hence the leakage would be over-estimated if the geometry of Figure 1(ii) were assumed. This is discussed in R6 Section III.11.6.3. The re-characterisation rules in this case are,

(i)For stresses below yield with no stable tearing

After snap-through the 'front' surface length is assumed unchanged at $2c_1$ whereas the back surface length ($2c_2$) is defined as the smaller of twice the thickness and $c_1 / 2$. The latter would mean the length on the back surface were ¼ of the front surface length.

(ii) For stresses above yield with stable tearing

The re-characterisation rule is given by R6 Figure III.11.7, reproduced below as Figure 2.

(C) When calculating upper bound leakage rates to underwrite tolerability

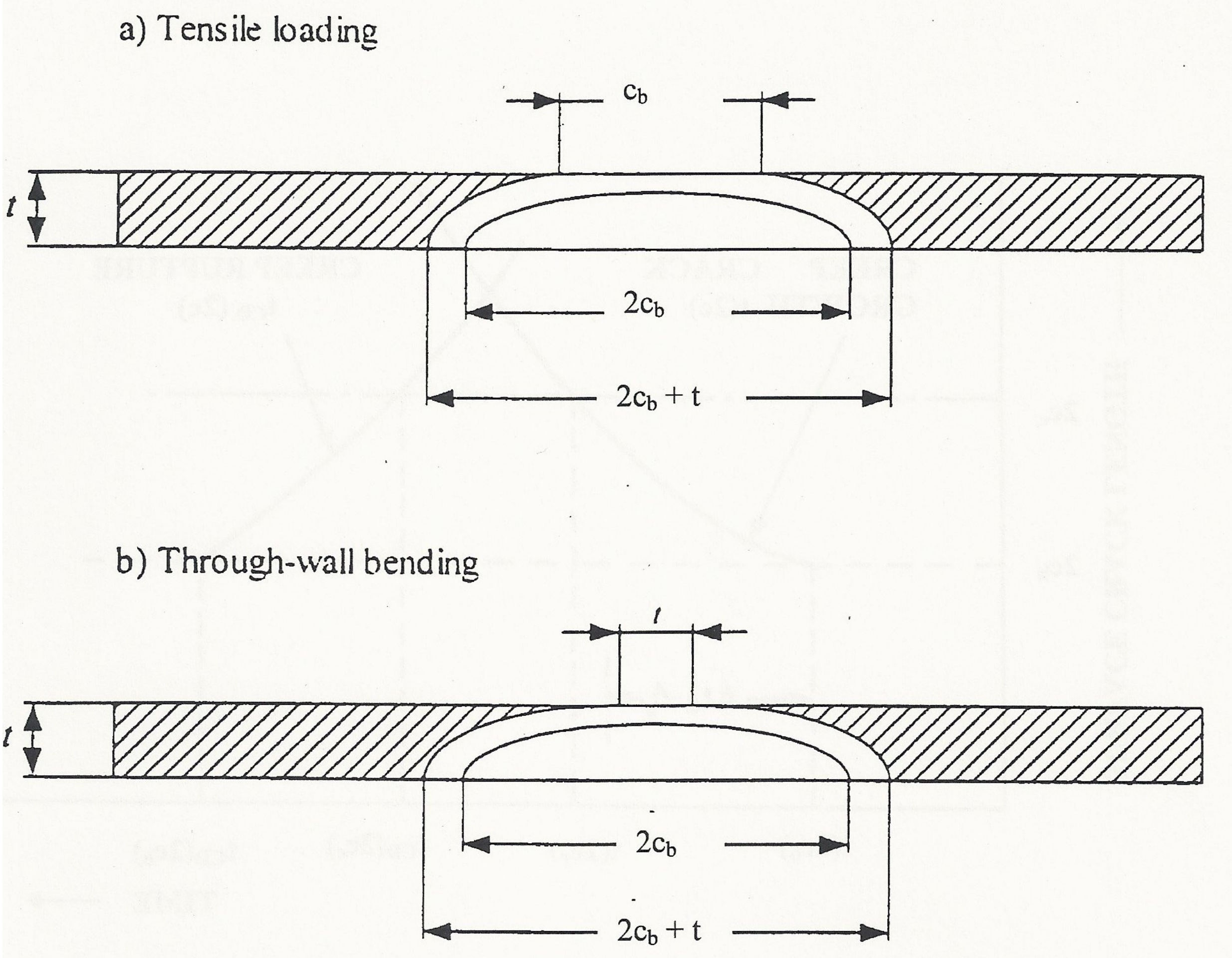
This is not covered explicitly in R6. My advice is to attempt one of the following,

(a) Calculate the development of the crack initially re-characterised as in (B). In particular the length of the crack on the back surface is needed at the latest detection time.

(b) Since (a) is difficult, it may be better to use plant experience of leaking cracks to gauge a suitable crack length and shape. This option is only available if there have been leaks from the plant items in question. This will often be the case for boiler tubes.

(c) Failing (a) and (b) the conservative course is to assume the re-characterisation rule of (A), e.g., Figure 1(ii).

Figure 2 **Re-Characterisation for ductile behaviour to be used for the calculation of leakage rates for stresses in excess of yield and defects subject to stable tearing**



Qu.: Are full LbB assessments common?

No. They are extremely rare. In fact, I've never seen one.

Qu.: Why?

The main reasons are,

- The size of the starter crack must be known (but generally isn't);
- Moreover if the starter crack has to be assumed fully circumferential then LbB is going to be impossible to argue;
- Calculating crack growth all the way to snap-through is challenging – especially as regards the development of the crack length, which is crucial in a LbB claim.
- The calculated crack growth predicts that snap-through will not occur in the life of the plant.

Qu.: What mechanisms need to be considered in the crack growth calculation?

All mechanisms leading to crack growth must be assessed. This will usually be creep and fatigue, but if a corrosion mechanism is active then this must be quantified. This may be tricky. SCC growth rates are very uncertain, for example.

Qu.: Is corrosion a specific difficulty?

Yes.

In addition to the uncertainty in crack growth rates due to corrosion there is also the issue of general wall thinning. Widespread wall thinning is a greater threat to guillotine failure than a single crack. Consequently if substantial wall reduction due to corrosion mechanisms are likely then a LbB case may not be credible – at least one argued based on structural analysis. OPEX may, or may not, provide support for LbB in practice.

In EDF Energy those cases in which we have had guillotine pipe failures (or very large breaches due to sections blowing out) have been from CW systems suffering from widespread corrosion. We have never had a guillotine failure of a boiler tube or of any of the main steam & feed pipework systems. (These remarks are made from memory – I haven't checked).

Similarly, worldwide OPEX from plant performance during severe earthquakes indicates that pipe breaks tend to occur only in systems suffering widespread corrosion metal losses, Ref.[1].

Qu.: What about erosion?

If the fluid flowing through the crack can cause erosion then this could undermine arguments based only on crack growth. I don't have any knowledge of this really, but I have suspicion that steam leaks may be more vulnerable to accelerating due to erosion than we sometimes appreciate. This is based on cases of steam lancing. Where superheated steam from a tube leak plays onto structural steelwork it can eat away great chunks of steel.

Qu.: What if the crack growth assessment implies no leak?

It may be that the assessed crack growth rate is so slow that snap-through from the starter defect is predicted never to occur in plant life. This prevents a full LbB case from being made. On the other hand, it obviously represents a more benign situation than if snap-through *were* predicted. In this case the cut-down "detectable leakage" argument (see below) can be used to provide an additional leg in a safety case, despite the full LbB case not being applicable.

Qu.: What is the OPEX on LbB?

The OPEX on LbB in power plant is extremely good for systems which do not suffer widespread corrosion. LbB is the expected failure mode both for boiler tubes and for the major steam & feed pipework systems. (On the other hand guillotine failures are more likely on CW systems, where brittle materials have been used, or on condensate systems which have been subject to extensive metal loss due to FAC).

- There have been ~100 boiler tube leaks in AGRs and all have been leaks – no guillotine failures.
- On Magnox power stations there were ~400 boiler tubes leaks, again with no guillotine failures (though one or two may have been rather large leaks).

- Leaks from our (AGR) major piping systems are fairly uncommon, but do happen. When they occur they are generally from small or medium bore branches rather than the main pipe (e.g., small bore thermal fatigue and drain pots), or else from bolted flanges on feed systems, which do not concern us here.
- In contrast there have been many leaks from the main pipe runs on conventional power plant with similar pipework due to poor control of Type IV cracking and TTIBC. My knowledge of the OPEX here is poor but certainly LbB generally occurs (though I can't say for sure that there have never been any guillotine failures). Lamentably it appears that detailed OPEX from conventional plant is not available.
- The above experience of LbB is, however, limited to leaks occurring from normal operation. R6 and safety cases require that LbB be demonstrated under fault loading. Some OPEX on this also exists, in relation to seismic events, see Ref.[1]. The broad picture is that well designed pipework systems in power plant are robust against even severe earthquakes (up to ~0.6g) unless corrosion mechanisms such as FAC have caused extensive thinning before the event.

Qu.: How is LbB argued for boilers?

I can't be definitive about all cases. However, in the context of AGR boilers the LbB case has often been argued based on the OPEX evidence rather than on a structural analysis based formal LbB or detectable leakage claim. Hence Ref.[1] has been deployed as support.

Boiler tube failure cases are probabilistic. Tube leaks do occur. Boiler tube failure is generally in the "frequent" or "infrequent" tolerability category. The threat to the reactor is, (a) over-pressurisation due to steam ingress into the coolant gas, and, (b) the challenge to the gas circulators (and hence core cooling) due to the effects of moisture on the motors. So the issues are, (i)how frequently leaks occur, (ii)the probability of a guillotine failure and its associated leakage rate, and, (iii)whether a number of simultaneous guillotine failures is credible. So Ref.[1] has been used, for example, to support the claim that no more than 1-in-10 boiler tube leaks at HPB/HNB will be guillotine failures even under a severe seismic event.

Qu.: What is a "detectable leakage" argument?

A "detectable leakage" argument is a type of cut-down LbB argument. It is the type of argument which is generally used.

Note that other procedures, e.g., NUREG-1061, may refer to this cut-down type of argument as leak-before-break. Only R6 distinguishes clearly between full LbB and merely a detectable leakage case.

Qu.: Of what does a detectable leakage claim consist?

(i) Calculate the critical through-crack length (under fault loading and with lower bound materials data);

(ii) Calculate the crack opening area, and hence the fluid leakage rate through the critical crack, and hence confirm that the leakage rate is sufficiently great to be detectable.

To these R6 requirements I would personally add,

(iii) Confirm that the leakage rate through the critical crack is tolerable in the safety case.

R6 specifies (i) and (ii) slightly differently, calling for the length of the through-crack which corresponds to the minimum detectable leakage to be calculated. This has the advantage that a reserve factor on crack size can then be derived (which is required in, for example, NUREG-1061).

Allowance for the time taken to detect the defect can also be included by increasing the smallest detectable crack size to account for crack growth over this period.

Qu.: How does a detectable leakage argument differ from full LbB?

The main difference is that a detectable leakage argument does not require knowledge of the initial defect nor does it require the development of the part-penetrating defect to be calculated. Moreover, the argument can be deployed even if a crack growth calculation would not result in leakage. This eliminates the main problematical features of a full LbB case.

However, a detectable leakage argument is not really logically complete. If the starter defect exceeds the through-crack critical length then it will be unstable on snap-through. This possibility is simply ignored.

Qu.: What does “conservative” mean in LbB or detectable leakage arguments?

The term “conservative” can be ambiguous in the context of LbB type arguments. In order to demonstrate detectable leakage it is conservative to under-estimate the leakage. But in demonstrating that the leakage is tolerable it is conservative to over-estimate the leakage. Consequently it is likely (in my opinion) that you will need to do the leakage calculation twice, with these two different aims in mind.

R6 concentrates entirely on detectablity, rather than tolerability, and hence uses the term “conservative” to mean under-estimating the leakage rate. This is rather misleading in my view.

Factors which affect whether the calculated leakage is upper or lower bound include,

- The through-crack shape / re-characterisation rule employed;
- The material properties used to calculate the critical crack length;
- The loading assumed (i.e., normal operating versus fault loading);
- The details of the calculation of crack opening area (e.g., the amount of plasticity assumed);
- The details of the leakage rate calculation, e.g., whether an upper or lower bound friction factor is assumed, and the degree of crack divergence, crack taper, etc.

Qu.: How are crack opening areas calculated?

For plates, cylinders and spheres, and for linearised stresses, R6 gives advice on sources of crack opening solutions, see R6 Section III.11.6.4 and Table III.11.4. For other geometries or loadings you may have to do your own analysis (FEA).

However R6 includes a formula for any thin shell under membrane loading, see R6 Equ.(III.11.1). This formula is claimed to give a *lower bound* opening area.

Note that the effects of plasticity may be important in increasing the leakage area. This is important if claiming tolerability of the leak.

Qu.: What effect do wall-bending stresses have on LbB claims?

Wall bending stress will result in the crack opening being smaller on one surface than the other. Hence the opening, w_0, on the inner surface may differ from the opening, w_{ex}, on the external surface. The leakage rate will depend both upon the average opening, $w=\left(w_0+w_{ex}\right)/2$, and also upon the “crack divergence parameter” defined as $d=\left(w_0-w_{ex}\right)/2w$. The crack divergence parameter may be positive or negative, corresponding to flow being choked at the external or internal surface respectively. Equal and opposite values for d can result in different leakage rates.

Qu.: Can large wall bending stress undermine a LbB claim?

Yes.

If the wall bending stress exceeds the membrane stress sufficiently then crack closure may be predicted on one surface. In other words $|d|\geq 1$ means crack closure. In this case there may be no leakage – or at least the leakage becomes impossible to calculate. Such a situation is fatal to a LbB or detectable leakage claim.

These cases are common. For example residual stresses will often prevent a LbB claim, as might large bending stresses at structural discontinuities.

The phenomenon of crack closure by bending stresses is not merely academic. There have been cases of valve bodies being found to have through-wall *original sin* cracks (casting defects) which have been in service without leaking – due presumably to being closed by bending stresses under load.

Qu.: How is leakage rate calculated?

Assuming the crack opening, and divergence, has already been calculated, the leakage rate calculation depends upon the flow regime,

- Single Phase Flow, e.g., primary coolant leakage from AGRs, can be calculated using the program DAFCAT. Alternatively calculations essentially equivalent to DAFTCAT can be done quite simply by hand using the formulae given in R6 III.11.6.5.1.
- Two-Phase Flow, e.g., wet steam, can be calculated using the programs SQUIRT or PICEP. The methodology and equations underlying SQUIRT are given in R6 III.11.6.5.2, but are much more complicated than for single phase and the User is likely to opt to employ the programme rather than hand calculation.

Are these programs now within RCODE?

As well as the crack opening area, the leakage rate will depend upon the crack taper/convergence/divergence and upon the friction factor (which depends upon the crack surface roughness). In the case of two-phase flow certain thermodynamic properties of the fluids may be required (entropies).

Qu.: What is a Proof Test Argument?

A proof test argument is an attempt to underwrite the integrity of a structure (usually a pressure vessel) against the possibility of defects being present but without the benefit of inspection evidence. It is potentially applicable only if the structure had an initial proof test of a greater severity than any loading that will be seen in service, including the most severe fault loading that must be addressed.

Qu.: What are the key steps in a Proof Test Argument?

We shall assume that we are dealing with a pressure vessel. The key steps are,

[1] Determine, via R6 assessment, the largest defect that would just survive the proof pressure test;

[2] Determine the crack growth over the desired service life due to creep, fatigue and any other mechanism which might be active;

[3] Determine whether material properties will have changed due to service exposure (e.g., thermal ageing effects);

[4] Determine, by R6 assessment, if the vessel with the crack derived as above will survive the worst required fault condition. If so the integrity of the vessel is assured by the proof test argument.

Qu.: Are Proof Test Arguments used in practice?

I am not aware of proof tests arguments having been used for AGR plant or PWR plant – can anyone think of any examples?

However, proof test arguments formed the main structural integrity argument underpinning the safety cases of the Magnox reactor pressure vessels (those with steel RPVs, that is). So historically the proof test argument was extremely important – bearing in mind that Magnox stations had no containment beyond the RPV.

Qu.: How large are the reserve factors from a proof test argument?

One does not expect a large reserve factor from a proof test argument. The reason is that the deepest defect surviving the proof test is generally very deep indeed. This is simply because the vessel will normally be made of ductile material. But the large assumed crack size means that the assessed crack growth could be large – at least in comparison with the small remaining ligament. Consequently the tolerable load at the end of life may be (theoretically) much reduced compared with the proof pressure test. Because of the extreme pessimism of assuming such a large defect at start of life, any positive proof test margin at all would usually be considered as providing assurance.

Qu.: How convincing is a proof test argument?

(i) The proof test defect is often very deep indeed , e.g., 90% of the section, and subsequent growth may take that to (say) 95% deep. This is intrinsically a fragile regime for fracture mechanics calculations (and will be completely impossible if the SIF solution extends only to, say, 70% of the wall).

(ii) Most commonly a PTA would employ best estimate material properties at both the proof test and in operation. An overtly conservative assessment would use upper bound properties during the proof test (to maximise the defect size) but lower bound properties in service. However the scatter in the material properties would most likely eliminate any chance of a positive margin being demonstrated.

(iii) Is it valid to assume that the material properties are at the same position in the scatter band before and after service? It may seem so – but what if the crack grows from one material zone (say a tough weld material) into a weaker zone (say a relatively low toughness HAZ)?

(iv) There is a similar dichotomy as regards crack growth – but usually there is an assumption of upper bound growth rates.

(v) Stable tearing is a phenomenon which usually increases the reserve margin. However, the effect of stable tearing during the proof test is to increase the size of the crack which would survive – and hence increase crack growth rates – and hence will generally reduce the proof test margin. But just how much tearing should be included?

Actually it seems to me that the proof test argument cries out for a probabilistic treatment, but I suspect this is not usually done.

Qu.: What is a “strength mismatch” fracture assessment?

Most assessments are of weldments, and most weldments involve several material zones, often of substantially differing strength. The main procedure of R6 will guide you to use the weakest strength data for material in the vicinity. In contrast, a strength mismatch assessment includes a more realistic (less conservative) allowance for the strengthening effect of neighbouring material.

Qu.: Where is the strength mismatch fracture assessment procedure?

It is in R6 Chapter III Section 8, with associated limit load solutions for inhomogeneous materials being given in R6 Chapter IV Section IV.2.

Qu.: What are the key elements of a strength mismatch fracture assessment?

The part of the assessment which is changed is the collapse load, and hence Lr. You can read the detailed procedure in R6 III.8, but the essence of it is that you need to calculate the collapse load for the inhomogeneous structure.

Qu.: How is the inhomogeneous collapse load calculated?

Well, you can calculate the limit load in the usual ways…

- Using the lower bound theorem, but now with a yield strength which is different at different places, or,
- Elastic-plastic FEA.

But R6 III.8 is really designed to be used in conjunction with the compendium of inhomogeneous collapse solutions of R6 IV.2.

Qu.: How is Kr calculated in a mismatch assessment?

The elastic SIF is calculated just as for the homogeneous assessment.

The toughness used should be the toughness of the material at the crack tip. However if crack growth is possible this may require consideration of the toughness of the material into which the crack tip moves.

Qu.: Why does mismatch affect Lr but not Kr?

The SIF is unaffected because it is calculated elastically, and hence unaffected by the material strength. Also, fracture is a response local to the crack tip, so the toughness is a local (crack tip) property.

In contrast, plastic collapse is a response of the whole structure. Stress redistribution is the mechanism by which material around the crack/ligament becomes involved. Hence mismatch affects Lr significantly.

Qu.: What is “crack arrest”

In certain circumstances a crack which has started to run (fracture) may arrest. This can happen for the following reasons.

- EITHER the crack runs into a region of higher toughness…
    - …because it encounters different material
    - …or because it encounters increased temperature
    - …or because it runs into a region of lower neutron dose.
- OR the stress intensity factor reduces as the crack grows…
    - …because the nominal stress is reducing, possibly becoming compressive,
    - …or because the load is dynamic and reduces over the timescale of crack propagation.

The procedure for crack arrest assessment can be found in R6 Chapter III Section III.12. Personally I would be very reticent about using it for a safety critical application, though it may be important if you wish to calculate when a running pipeline crack might stop. The drawback is that you require special crack arrest toughness data.

References

[1] Dennis Leigh, “Leak versus guillotine failure in superheater bifurcations and upper transition joints”, E/REP/BBAB/0007/AGR/08, January 2009.