Brittle fracture: selection of sub-grade for 'quasi-static' structures

Selection of steel sub-grade is an important responsibility for all steel designers, to manage the risk of brittle fracture. David Brown of the SCI discusses a new publication (P419[1]) which presents steel thickness limits which may be used in buildings where fatigue is not a design consideration.

The Eurocode basis

Designers familiar with BS EN 1993-1-10 or PD 6695-1-10 will know that the selection of a steel sub-grade depends on the stress level, the type of detail, the service temperature and the material thickness. BS EN 1993-1-10 presents (in Table 2.1) limiting thicknesses for steel sub-grades, depending on the so-called reference temperature. The reference temperature is the service temperature, but then subject to various adjustments.

In the UK, significant modifications are made to the 'core' Eurocode, via the National Annex. The effect of the UK NA is accounted for in the thickness limits presented in PD 6695-1-10, which contains look-up tables for steel in buildings (internal and external) and bridges. Worked examples showing how to select a steel sub-grade using the Eurocode, PD and UK NA were presented in NSC, October 2016[2].

A JRC publication[3] provides comprehensive background on how the thickness limits in BS EN 1993-1-10 were derived. The background document is not easy to digest, but after the various formulae have been committed to a spreadsheet, it is possible to replicate the values found in Table 2.1 of the Standard. For anyone rising to that challenge, there is some (variable) degree of rounding in the printed table.

The effect of fatigue

The Eurocode states in the Note to clause 2.1(2):

"For elements not subject to tension, welding or fatigue, the rules can be conservative. In such cases evaluation using fracture mechanics may be appropriate, see 2.4 (of the Standard). Fracture toughness need not be specified for elements only in compression."

The JRC background document is clear in paragraph 1.4.3(2) that Section 2 of the Eurocode was developed for structures subject to fatigue (such) as bridges, crane runways or masts subject to vortex induced vibrations. The background document goes on to say:

"its use for buildings where fatigue plays a minor role would be extremely safe-sided"

The effect of fatigue is to cause an initial crack to grow to a much larger design crack. The assessment of sub-grade is then carried out on the basis of the design crack. The initial crack size is related to the thickness of the element, as shown in Figure 1.

The size of the initial crack assumed in the Eurocode is one that might be missed during inspection after fabrication. The JRC background document demonstrates that the minimum crack width detectable by inspection methods after fabrication is smaller than the assumed crack width, implying that the assumed crack sizes should be detected. It is assumed that the steelwork is fabricated, welded and inspected in accordance with the requirements of BS EN 1090-2.

The effect of fatigue is to grow the initial crack to a much larger defect, as shown in Figure 2 (over page). The curve is a representation of the expression given in the JRC background document.

The design crack depth a_d is expressed as:

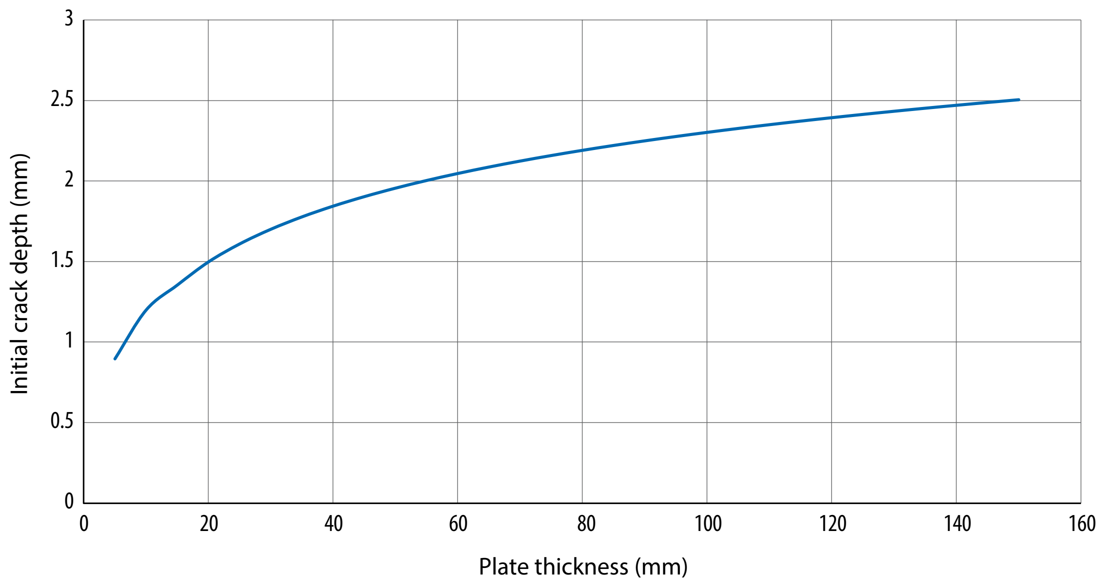
$a_d = 2 \times 10^{-6}\, t^3 + 6 \times 10^{-4}\, t^2 + 0.1341t + 0.6349$

where:

t is the plate thickness.

▶28

Figure 1: Initial crack size



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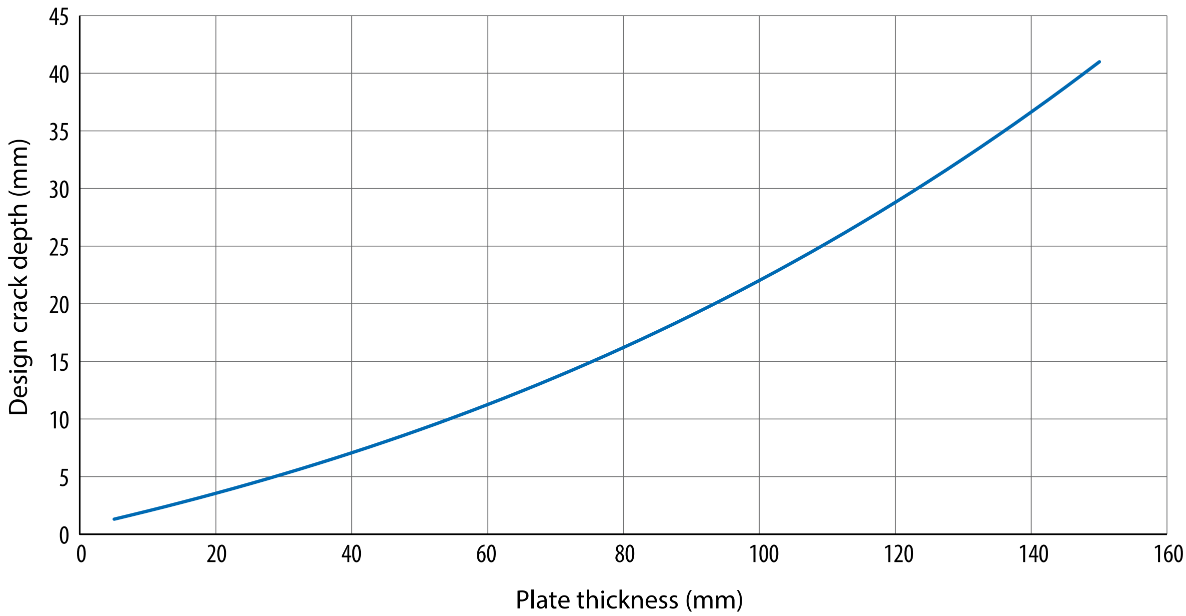

Figure 2: Design crack size

It is interesting (and possibly sobering) to note that the Standard is based on 0.5 million cycles, equivalent to a 25 year life. Usually, 2 million cycles are assumed for a 100 year life. The Eurocode approach therefore anticipates inspection of a fatigue-sensitive structure at 25 year intervals, and repair if necessary to reinstate the original conditions. Such inspection would be normal in bridges.

The new publication

The new guide reduces the growth due to fatigue. The word "reduces" has been used, since to assume no growth at all would be to eliminate the effect of fatigue altogether. After consultation, it was decided that some fatigue should be allowed for even though for the structures within the intended scope, fatigue would not be a design consideration. Based on indicative guidance from a DIN Standard, 20,000 cycles was chosen to allow for some fatigue in structures where fatigue is not a design consideration – most buildings. The term "quasi-static" would cover such structures – in reality that there may be some limited cycling of load, but that would not normally be considered – the design approach is to consider all loads as static.

The key to the new approach is the formula to express the crack growth under 20,000 cycles. Experts at the University of Aachen (who were also deeply involved with the development of the Eurocode) provided this all-important expression.

For structures where fatigue is not a design consideration, the new expression for crack growth is given by:

$$a_d = 3.6258 \times 10^{-11}\, t^5 - 2.2316 \times 10^{-8}\, t^4 + 5.3365 \times 10^{-6}\, t^3 + 6.3837 \times 10^{-4}\, t^2 + 0.045124\, t + 0.82483$$

The resulting design crack depth is only a little larger than the initial crack depth, as can be seen in Figure 3. The ratio (design crack depth)/(initial crack depth) is plotted on the right hand axis.

Based on the revised design crack size, limiting thicknesses are determined and presented in the new publication, including an equivalent Table 2.1 from the Eurocode, and equivalent look-up tables from PD 6695-1-10 for use in the UK.

Additional modifications

The title of this section is deliberately misleading. Apart from the revised crack growth, there are no other modifications to the process described in the background document. All the assumptions made in developing Table 2.1 of the Eurocode are followed, without exception.

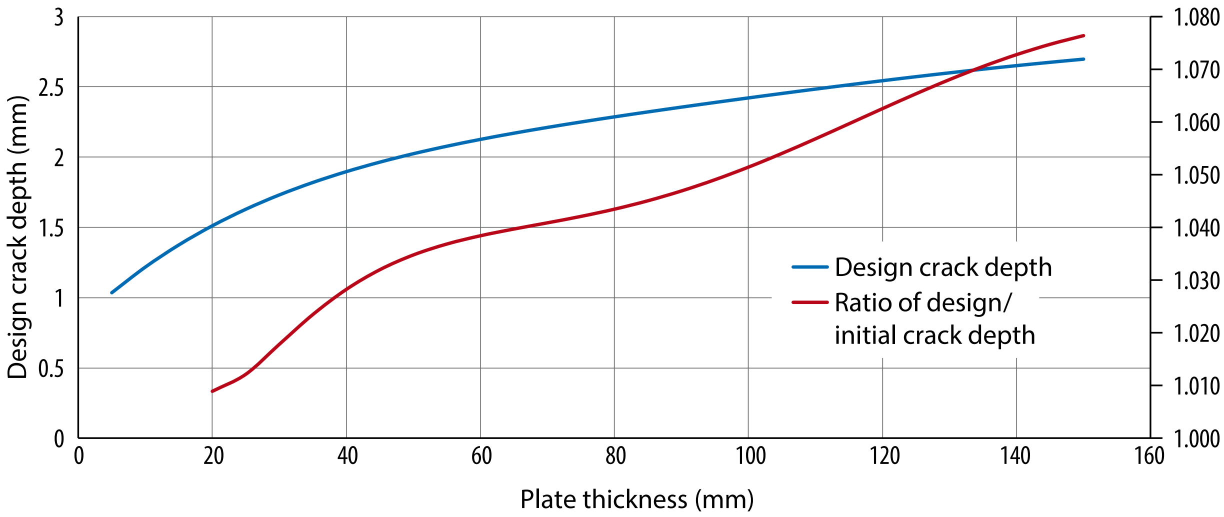

Figure 3:
Initial and design crack depths (20,000 cycles)

The provisions of the UK NA have also been followed, without exception. These include:

- The adjustment for detail type, described in NA.2.1.1.2;
- The adjustment for the Charpy test temperature, described in NA.2.1.1.4;
- The adjustment for the applied stress, described in NA.2.1.1.5, which means that the limiting thickness values are based on an applied stress of 75% of the yield strength;
- The adjustment for the steel strength grade, as described in NA.2.1.1.6.

These provisions of the UK NA are listed simply to emphasise that they have been properly observed in developing the tables presented in the new publication. The publication does not allow for impact or cold forming; in these cases the limiting thicknesses can be calculated from the tabulated data provided.

Revised thickness limits

The effect of much reduced crack growth is very significant. The limiting thicknesses are much larger than those in PD 6695-1-10, which allowed for crack growth under 0.5 million cycles. Table 1 presents a comparison for external S355 J0 material, covering combinations 4 to 10 (the welded detail types).

Scope of the new publication

Firstly, if the structure under consideration is subject to fatigue, the tables in the new publication should not be used; The Eurocode, NA and PD 6695-1-10 must be followed in the UK. For structures where fatigue is not a design consideration, the new publication presents less onerous thickness limits. For structures outside the UK and not subject to fatigue, the new publication provides an equivalent to Table 2.1 of the Eurocode which may be used as a basis for steel sub-grade selection.

References

1 *Brittle fracture: selection of steel subgrade to BS EN 1993-1-10* Brown, D. and Cosgrove, T. SCI, 2017
2 *The selection of steel-subgrade* Henderson, J. R., NSC, October 2016
3 *Commentary and worked examples to EN 1993-1-10 "Material toughness and through thickness properties" and other toughness oriented rules in EN 1993* Sedlacek, G. et al, JRC, 2008

Detail type	Tensile stress level $\sigma_{Ed}/f_y(t)$						
Welded - moderate	≤ 0	0.15	0.3	≥ 0.5			
Welded - severe			≤ 0	0.15	0.3	≥ 0.5	
Welded - very severe				≤ 0	0.15	0.3	≥ 0.5
	Maximum thickness (mm)						
	Comb.4	Comb.5	Comb.6	Comb.7	Comb.8	Comb.9	Comb.10
PD6695-1-10	67.5	55	45	37.5	30	22.5	17.5
P419	200	200	200	188.5	145.5	95.5	65.5

Table 1: Limiting thicknesses for external S355 J0 steel