A PROPOSAL FOR A NEW WELD CLASS SYSTEM

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Abstract Complex welded structures, such as those in construction equipment, are exposed to tough spectrum loading during their service life. 70-80 % of the main structure are steel structures welded together in highly automated production units. This combination will sooner or later lead to fatigue failures in critical points in the welds. The task for a producer of these vehicles is thus to optimize the design, so that the welds have an adequate quality to withstand the loads during the economic life. The quality systems for welds are described in so called 'weld class systems', such as ISO 5817, where acceptance limits are given for different quality levels. The problem with these systems is an inheritance from old rules and nominal stress based methods, when designers used hand formulas in design, and can be described as being inconsistent, subjective and not well connected to fatigue life. A proposal for a new weld class system, where these problems are removed, is described in this paper. Here three quality levels for fatigue are suggested, where 'as welded' conditions have two levels and post treated welds have one. It contains acceptance limits which are consistent with the expected fatigue life and which can handle revision situations in a more objective way. Furthermore, they can handle not only nominal stress based methods, but also local based ones, such as the effective notch method. The purpose with this new proposal for a weld class system is that it should be able to strengthen the process for welds in a company from the drawing and analysis to the production and final control.

INTRODUCTION

The purpose of having a weld class system, as ISO 5817, ref [10] or Volvo's STD 5605, ref [9], is to define rules for the quality of the welds. The current rules, however, are not well reflecting the fatigue life of the weld geometry. Investigations made, ref [1], indicate that some defects or error types are very important, while others are not. This implies that for a certain quality level the fatigue life can vary one or two magnitudes depending on what kind of error is present. Also, if the quality level is raised, say from D to C in a weld, one can not be certain that the fatigue life will be increased. Another example is the so called "even transition" condition, an important demand often used in the weld class system. This term expresses a requirement of the transition area between the weld toe and the plate surface. The problem is that the control is made visually by the eye and is thus a very subjective method. Here is a clear need of a more objective measure obvious.

Another close related problem is the design of the weld root. The weld classes are within Volvo's system related to the stress levels through a so called Kx-factor (equivalent to FAT-values) and this relation only concerns the toe side of the weld since nominal stresses are being used. This view has the drawback that the root side is neglected and not taken into account. Most of the failures in the supporting structures during the last decades concern the root side of welds and one reason is this described problem. One has to bear in mind that the only important measure for the root side is the size of the root defect that may be present if full penetration is not at hand.

PRINCIPLES FOR A NEW SYSTEM

Current weld classes are inherited from older rules, when analysis mostly was made using hand formulas (nominal methods) Also, the acceptance limits were in many cases set from a production point of view. This lead to the weak relation we see today between quality rules and fatigue life and a new system should therefore avoid the above described problems.

The new proposed system is divided into three different quality levels (VD, VC, VB) for fatigue loaded structures and one for static loaded structures (VS). The two first classes stand for the 'as welded condition', normal quality (VD) and high quality (VC). The last and highest class (VB) stands for 'post treated welds' regardless of kind of treatment.

The different types of occurring errors and defects can be divided into three categories: outer defects (toe side), inner defects (root side) and invisible defects (like inner pores), see figure 1. These are treated differently, so that the weld class system defines rules for the toe side and for the invisible types, since occurring defects here are statistically distributed. The root side, however, has a fatigue life governed mainly or only by the size of the root defect, which normally is the same along the weld. This means that a demand as a measure on the drawing works best, implying that the root side should not be a part of the weld class system at all.

The acceptance limits for occurring errors (on the toe side and for invisible types) should be describing only those having an impact on the fatigue life. One important target in the new weld classes regarding these errors, is that the acceptance limits should reflect a fatigue life, which is the same for different types of errors in one weld class (quality level). Also, if the quality level is increased one step, the fatigue life should be expected to increase a factor of 2 or alternatively the stress could be raised by 25%. In general, the acceptance limits are positioned two standard deviations (2S) away from the median FAT-level. Using an ordinary assumption on S this gives a factor of 1,3 in stress range. A design of a weld can thus connect the analysis to the weld classes on the drawing. Other error types, which have a small impact on the fatigue life, are left out from the weld classes unless other reasons require their presence. Most important for the fatigue life among the outside (toe) features is the transition area, where current systems have the requirement 'even'. In the new system, the term 'even' is replaced by a requirement on the radius, which is more objective and more important: it can be measured.

COLD LAPS

Cold laps are a type of error occurring when melted material has not been merged with the cold plate surface. This produces a crack like defect, often very small, which is parallel to the plate, se figure 2. It can be produced from spatter, forming local rounded laps (a/c=1), or from too high welding speed, when line cold laps (a/c=0) are formed. The latter case can be studied in a 2D model, see figure 3, using fracture mechanics (ref [2]). In the result one can see that the cold lap has a mixed mode at start, with a big influence from mode K_{II}. This gives arise to a kink angle of around 50 degrees at the first step and very quickly, the cold lap is transformed to a sharp vertical crack, now in mode K_I. In fact, after the first steps of crack growth, the stress intensity tends to be somewhat *higher* for *smaller* starting cold laps, see figure 4. The overall result is that the fatigue life for different cold lap sizes tends to be more or less constant for cold lap sizes over a certain value, see figure 5, depending on the geometry of the toe transition area. For a weld in 'high quality' one can see that the cold lap size need to be very small, (< 0,1 mm) in order to reach 2 million cycles, but for 'normal quality', the requirements is easier, cold laps < approximately 1 mm. These results are valid for line cold laps, but if spatter produced cold laps are at hand, then one could expect to have a/c=1, requiring a 3D-analysis, see figure 6. The result shows that the cold lap behaves differently along the crack front. At the top, the mixed mode is very similar to the 2D case with a great kink angle influenced by K_{II}. At the edge, however, the mixed mode is K_{III}, resulting in a small kink angle. The cold lap having a/c=1 at the beginning, now grows towards a line cold lap (a/c=0) and all together this results in a 2-3 times longer fatigue life. However, the acceptance limits, are set according to line cold laps.

LACK OF FUSION

When the weld process for some reason is not right, the result often is lack of fusion. The position could be anywhere from the root to the surface or even between layers. Lack of fusion is a kind of defect that should not be present at all. The analysis of these defects is rather straight forward using fracture mechanics and if there positions are 'right' (say for instance in the middle the weld, as in figure 7), it is quite possible to reach an adequate fatigue life. However, if they are close to the root side or close to the surface or toe area, then the size of the error becomes very sensitive. This means that in the weld class system one cannot generally allow these defects in any class. On the other hand, if lack of fusion is found in production it is possible to perform a fracture mechanics analysis and find that the component can be used without any repairs.

TRANSITION RADIUS

One of the most important measures of the weld regarding fatigue is the transition area between the weld toe and the plate. In current weld class system there is a requirement stating that 'even' transition should be met. This is however not a technically quantified term, since it can not be measured and since revision is made visually, it also leads to a subjective result. A better approach, which is used in the new weld class system, is to base the result on stress concentration factors. This could then be translated into geometric measures leading to a more objective method in the revisions. In the new proposal for weld classes the radius alone is being used, see figure 8, where Kt=2,5 equivalent to R=1 mm is shown. The approach does not involve the angle and the thickness due to simplicity. As seen from figure 9, ref [3], the radius should be > 1 mm for a high quality weld.
The normal quality level of welds does not require the same size of the radius. One way to study the requirements for this case is to set the radius when the stress concentration (Kt) shifts from blunt to sharp. An elliptical notch has a stress concentration $Kt = 1+2\sqrt{(D/R)}$ with blunt to sharp transition for $Kt = \sqrt{(D/a0)}$, where D=depth, R=radius and $a0 = (\Delta Kth/2\Delta\sigma u)^2$, see ref [4]. Using an analogy with the toe transition $Kt = 1+\sqrt{(t/R)}/2$, where t=thickness, this results in t=16D. Inserting this in the blunt to sharp transition one gets $\Delta\sigma u = 2Kt*\Delta Kth/\sqrt{t}$. For typical values of the threshold (ΔKth = 2-5 Mpa$\sqrt{m}$) and the fatigue limit range ($\Delta\sigma u$ = 300-600 Mpa) one reaches a value Kt > 5. This implies that the toe radius shifts to a sharp transition for R < 0,1-0,3 mm see figure 10.

The same size can be found by studying the formulas for Kt = $1+0,5\sqrt{(t/R)}$ together with Kf = 1+q(Kt-1), where q = the notch sensitivity = 1/(1+A/R) and A is a material parameter of the ultimate strength, see ref [5,6]. This leads to the expression Kf = $1+(0,5\sqrt{(t/R)}) / (1+A/R)$, see figure 11. As seen this expression has a maximum at R=A and if this is interpreted as a transition from blunt to sharp Kt it results in a radius R ≈ 0,25 mm for typical materials.

UNDERCUTS

If the welding parameters are not optimal, one example is too low speed, it can lead to undercuts along the weld. This type of error can be analyzed using the effective notch method, where the real radius is replaced by an effective R=1 mm. Studying a fillet weld, see fig 12, the result shows an influence from the size of the undercut. When setting the acceptance limits, the idea is that the normal weld is free from undercuts and the worst acceptable undercut is positioned two standard deviations from this level. This gives a limit in the studied case = 0,6 mm or in relation to the thickness t=10 mm expressed as 0,06t. If, on the other hand, a butt weld is studied in the same way, a lower limit is reached, see figure 13. Here the acceptance limits points at 0,35 mm or in relation to the thickness 0,035t. It might be possible to have different values for fillet welds and butt welds, but since many welds are a mix of these two it can lead to difficulties in the revision. To avoid these problems and have a simple tool, the average of these two results is being used. This leads to an acceptance limit of 0,05t and this is well in line with IIW's recommendations, ref [7].

THROAT SIZE

The throat size (a) concerns only fillet welds. There are different methods to define the throat size and the one used here is: a = the height of the greatest inscribed triangle having equal leg length. A too small throat can be assumed to have an impact on both the toe side and the root side. The toe side can easily be analyzed using the effective notch method and for a fillet in an as welded condition, normal quality, the result is shown in figure 14. As seen, the stress level is more or less independent of the throat size. The only influence comes from the thickness, where t=15 mm seems to fit the FAT 225 value and the curves also seem to fit the standard correction $S = S0 * (t/t0)^n$ well with an exponent n ≈ 0,2-0,3.
The root side of the weld is influenced by the throat size for load carrying welds. Studying this case there are two methods: fracture mechanics and notch method. A comparison between these two methods has been made, see figure 15-17. As seen in figure 17, the calculated life coincides well for the two methods even for high Kt (large root defects). This is being used when the acceptance limits have been set for the root side. If no penetration is assumed, the worst and designing case is at hand. Assuming a typical throat size as the median level and position the acceptance limits two standard deviation away, see figure 18, one gets a result of 0,7a. The acceptance limit of the throat size should thus not be less than -0,3a.

MISALIGNMENTS

If two plates are welded together either in a fillet or in a butt weld and these are not met in the right position or in the right angle, then misalignments are at hand. These can thus be of two kind: axial or angular, see figure 19. When tension loads are applied to the joint, secondary bending moments occur and this can have a great influence on the fatigue life. The stress raising effect can be expressed as a factor Km and in IIW's recommendations, see ref [7], formulas are given for different cases. One of the parameters in these formulas (λ) reflects the restraint of the joint, which is illustrated in figure 20. Assuming unrestrained case, symmetrical lengths of the plates and neglecting the influence of straightening from the loads one can deduce all cases into one simple formula: Km = 1 + 3e/t, where e = misalignment and t = thickness. Identifying the median level as no misalignment and the acceptance limits as two standard deviation away (1,3 in stresses) this leads to 1+3e/t=1,3 or e/t=0,1. So for both butt welds and fillet welds and also for both axial and angular misalignment the acceptance limits is e/t < 0,1.
The case when two different thicknesses meet, having one of the plate surfaces in plane, automatically leads to a misalignment, since the middle lines are not coincident. However, if this case is treated under misalignment then thickness changes above 10% would be prohibited. This implies that thickness changes should not be treated as misalignment in the weld class system, on the contrary, a thickness change should be analysed and designed to withstand the loads.

PORES

Welding often produces different kinds of pores. Most of them are spherical but other forms can exist. The current weld class systems have many different cases and the impression is that they should be simplified. There are two kinds of acceptance limits: single pores and clustered pores with acceptance limits either expressed as a relation to thickness or throat size or as a percentage of a measured area.
For a single inner pore of size D one could assume an equivalent semi elliptical crack (a/c=1) positioned in a typical weld area of $10*10$ mm^2. The stress level depends on the position of the pore, but a reasonable assumption is to use

nominal values. Using fracture mechanics in Afgrow, ref [8], see figure 21, one can define acceptance limits at 2 million cycles as 2,3 and 4 mm for the three different classes, see figure 22. If a pore is positioned at the surface one can assume a surface breaking semi elliptical crack having a/c=2. Analysis in the same way then results in somewhat lower acceptance limits 1,2 and 3 mm respectively.
The analysis above do not take into account pores having a/c>1 or pores close to each other. So rules for these cases must be formulated. If a is assumed constant and a/c > 1, then a longer life than a/c=1 is reached. This implies that the size of pore should be taken as its greatest extension. If two pores (of perhaps different sizes) are close to each other, a stress raising factor is at hand. Studying the stress concentration (Kt) and plotting the results with different relative distances one can see that it is the biggest pore size that governs Kt, see figure 23-24. If Kt is plotted as function of distance related to the biggest pore size, then the curves coincide and this leads to the following rule: if the distance between two pores is less than the *biggest* pore size, then they should be regarded as one single pore. In ISO 5817, the opposite is stated and this seems not right.

DISCUSSION

The current weld classes, as stated in the international ISO 5817 or in Volvo's STD 5605, have been shown to have a weak relation to fatigue. This is unsatisfactory and leads to a difficult situation especially when the design processes of today drive towards higher performance and optimized geometries. If the process from drawing, analysis, production and control of the welds lack a stable platform (the weld classes) then there is a risk of failures. Especially the use of high strength steel in welded structures, that require high quality welds, will be suffering from weaknesses in the current weld classification systems.
The new weld classes define three levels of quality, two as welded and one post treated. Apart from these three there is also one class for static cases, since the demands on these differs considerably. Some principles have been set before the definition of the acceptance limits were made. First of all, error types in one weld class level should have the same life and second, a shift from one weld class level to a higher, should reflect either twice the fatigue life or an increase of 25% in allowed stress level. Apart from these principles, only error types important for fatigue life are defined in the different classes, other types of errors have the same limits for all classes.
Most important points regarding the fatigue in welds are the toe area and the root area. The new weld class system, as described above, has divided these two points and they are thus treated quite separately. The root side, if not fully penetrated, may serve as starting defect, the greater defect the shorter life. Designing against fatigue is thus depending on the needed penetration. This means that the root side should not be a part of the weld class system at all. Instead, the best way is to define the root side as a measure on the drawing and support the value through analysis. The toe side on the other hand has most of the fatigue failures from the transition area between the weld and the plate. Here the local geometry is the most important factor, especially in form of a too small radius or other defects. This is therefore the main purpose of the new weld class system: define acceptance limits for radius, cold laps and undercuts in order get a fatigue life well related to the expected life. Error types inside the material such as pores etc are also treated in the weld class system since they may serve as starting point for fatigue failures.

CONCLUSIONS

In conclusion the following can be stated about current weld class systems:

- the relation between acceptance limits and fatigue life is weak
- within one class (quality level) some error types have a short life and some a long life
- some error types show no influence on the fatigue life
- the 'even transition' condition is subjective and cannot be measured
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A new weld class system has been proposed since the current ones are not well reflecting fatigue life phenomena. The new system has three quality levels VD and VC for 'as welded' condition and VB for 'post treated' welds and is built according to the following principles:

- weld classes governs the toe side and invisible defects (like inner pores)
- the root side is governed by measures on the drawing is *not* a part of the weld classes
- only error types important for fatigue loads are described
- different error types within one class (one quality level) have the same fatigue life
- if the weld class is increased one step, twice the fatigue life or 25% higher stress can be expected
- static loaded welds have one class itself (VS)
- the old 'even transition' is replaced by demands on the toe radius

The system is proposed to be Volvo's new standard and will be remitted by the end of year 2007.

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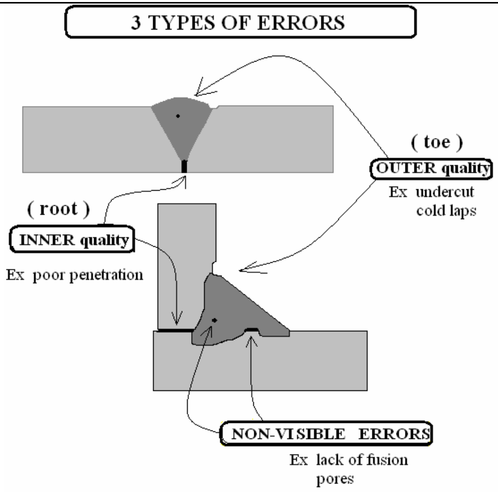

Figure 1 Three different categories of errors. Outer quality and non visible errors are treated in the new weld class system, inner quality is not.

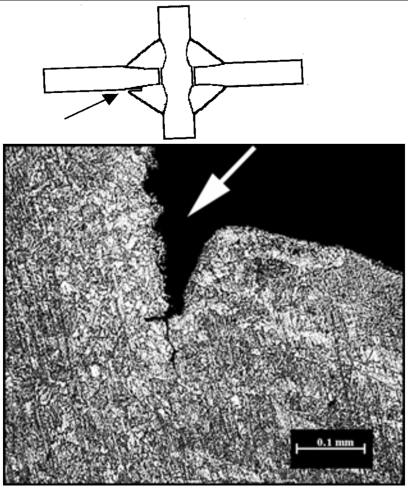

Figure 2 A cold lap with a size of 0,1-0,2 mm.

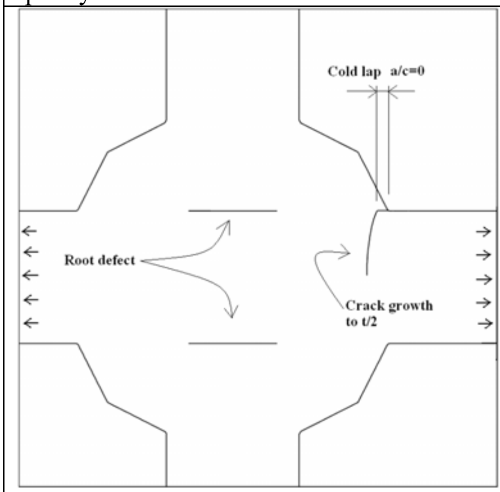

Figure 3 Non load carrying cruciform joint with a cold lap.

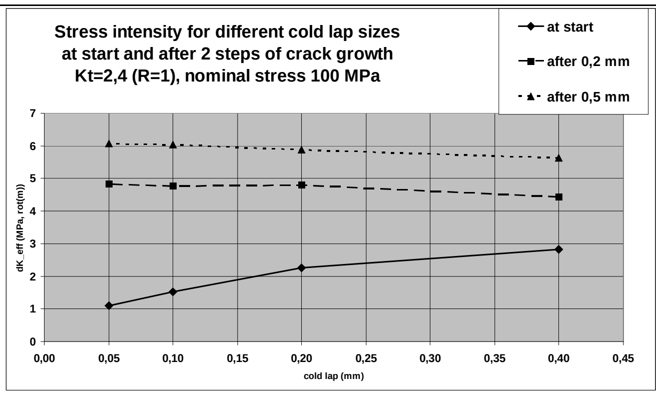

Figure 4 Stress intensities for different starting cold lap sizes. Note that the stress intensities after the first steps of growth tends to be somewhat lower for bigger cold laps

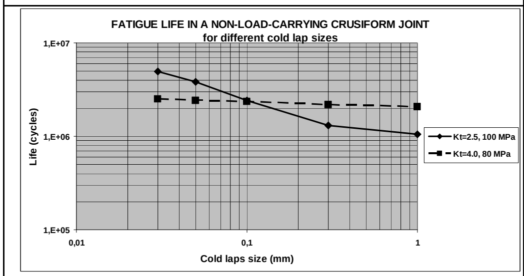

Figure 5 Life in a cruciform joint with different toe geometries and having different starting cold lap sizes 2D analysis).

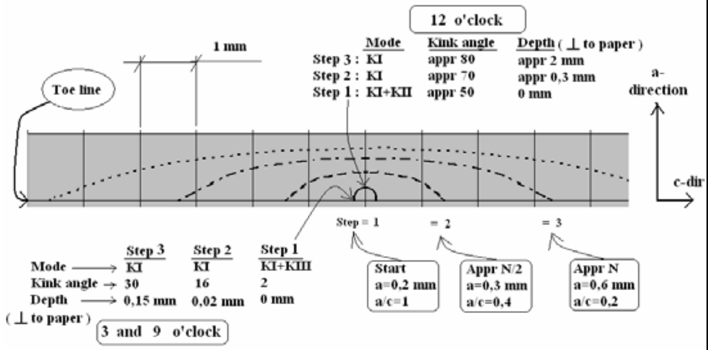

Figure 6 3D crack growth for a spatter induced cold lap. View is seen from above showing the crack front and its shape. As seen the result at 12 o'clock has a great kink angle (≈2D) and at 3 and 9 o'clock the kink angle is small (mixed mode K_{III} at step 1).

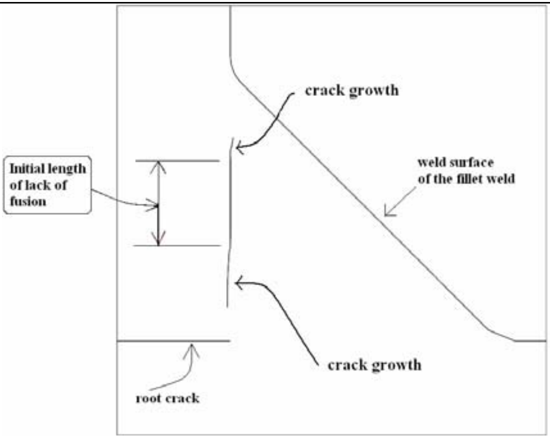

Figure 7 Lack of fusion positioned in the middle of the side of a fillet weld. In this case, if non load carrying situation is assumed, a rather long fatigue life could be expected.

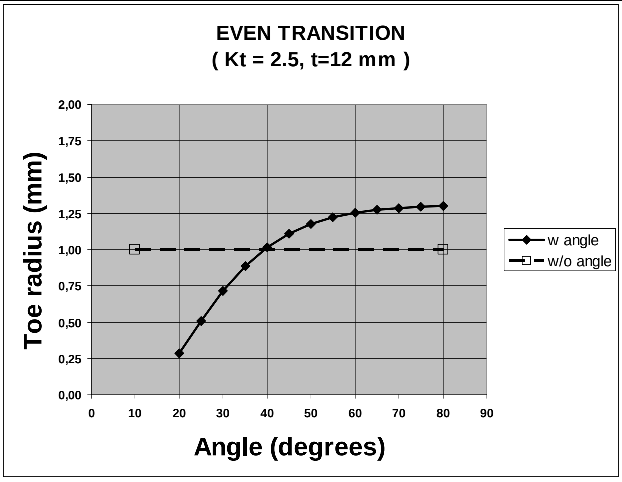

Figure 8 Stress concentration in the toe transition in a fillet weld using the toe radius and with or without the angle.

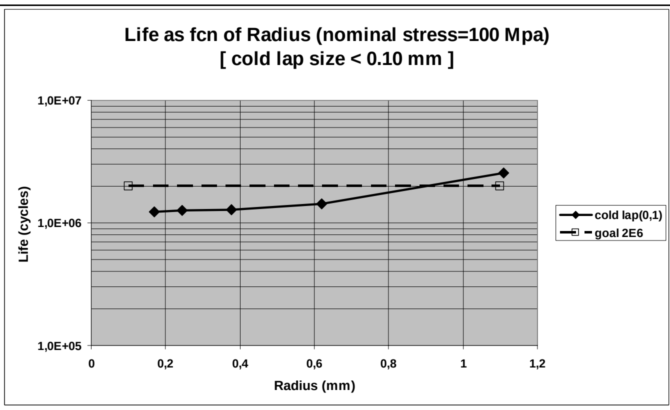

Figure 9 Calculated fatigue life in a crusiform joint. Life of 2E6 cycles is reached when radius ≈ 1 mm.

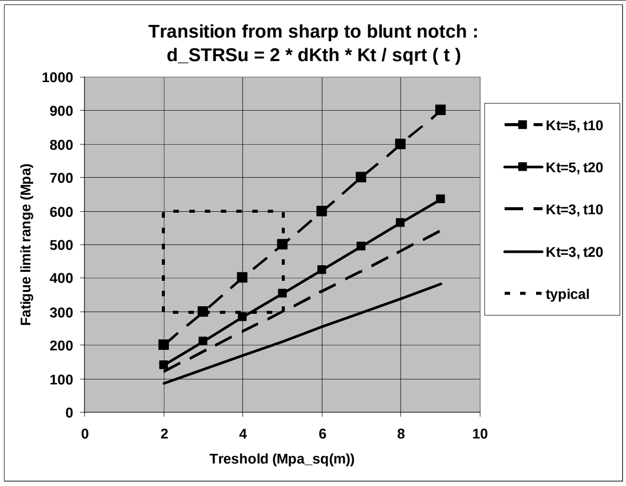

Figure 10 Transition from a blunt to a sharp stress concentration in a weld toe can be determined to at least Kt > 5.

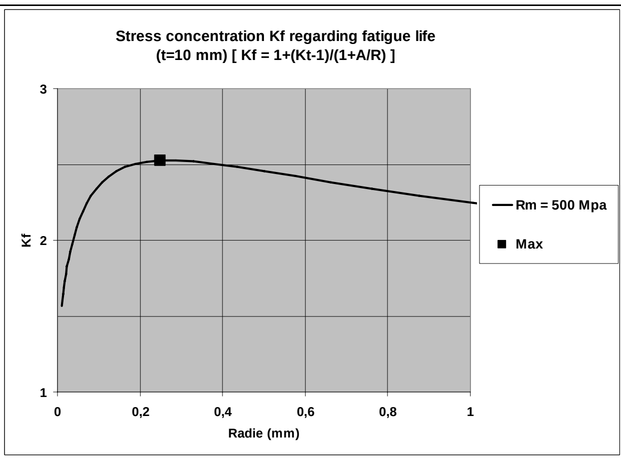

Figure 11 Stress concentration Kf as fcn of weld toe radius.

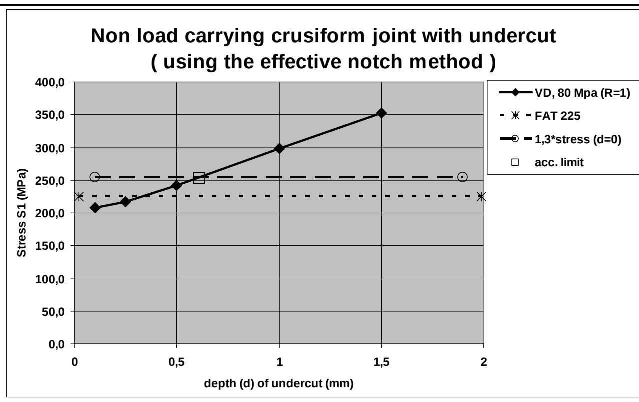

Figure 12 Stress levels in a fillet weld having an undercut. Acceptance limit is taken as the stress level 2 standard deviations above a fillet weld without undercut.

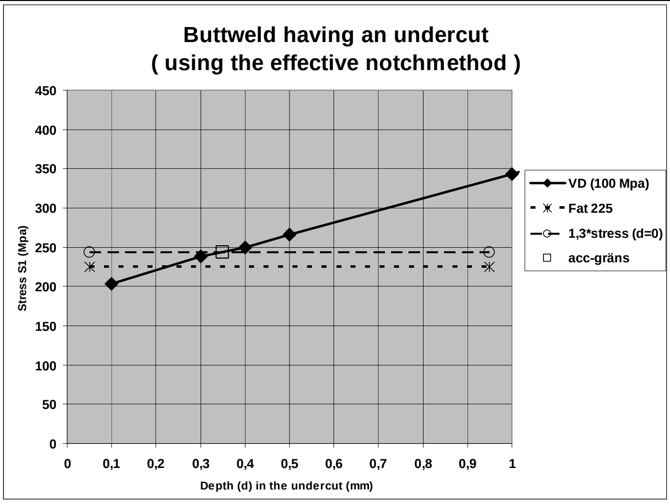

Figure 13 Stress levels in a butt weld having an undercut. Acceptance limit is taken as the stress level 2 standard deviations above a butt weld without undercut.

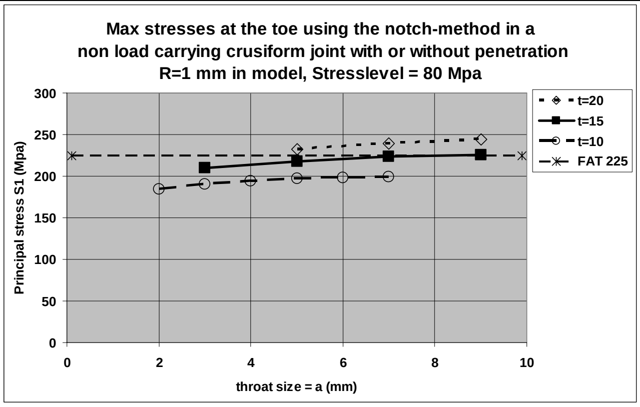

Figure 14 Stresses in the weld toe as function of the throat size a for different thicknesses.

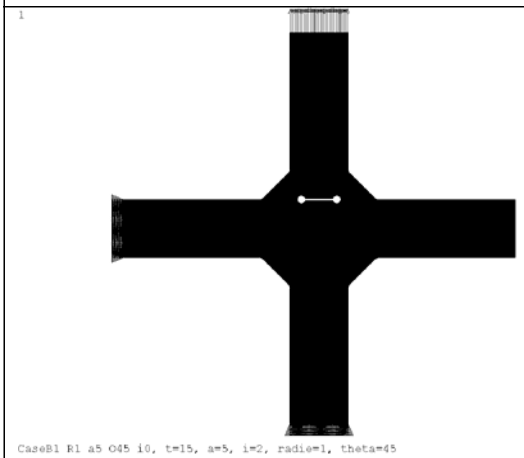

Figure 15 Influence from throat size on the root side, model built using the effective notch method (Ansys).

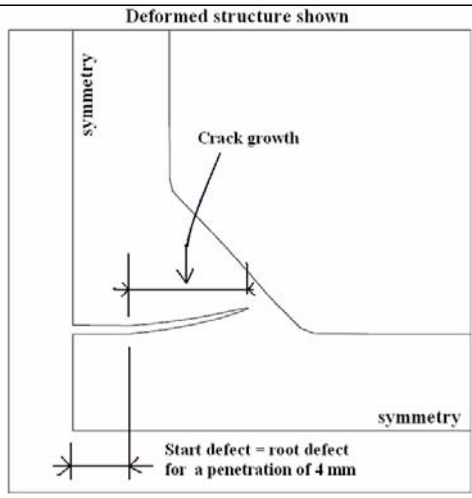

Figure 16 Influence from throat size on the root side, model built using fracture mechanics (Franc2D).

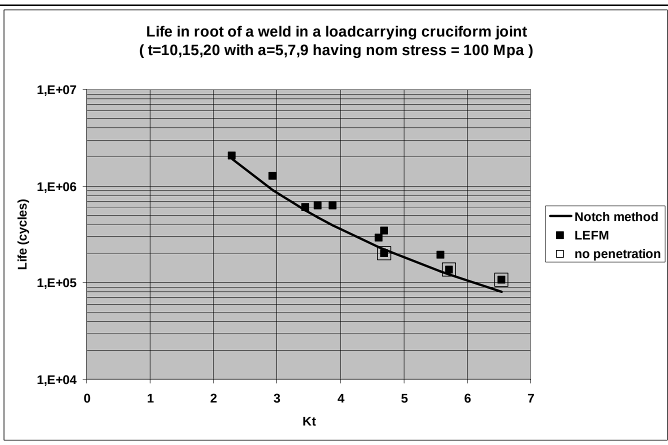

Figure 17 Comparison between the effective notch method and linear fracture mechanics as a function of Kt in the root of a weld.

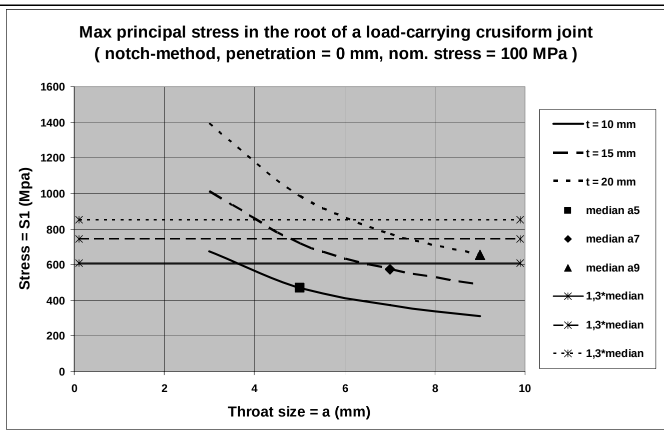

Figure 18 Influence from throat size on the stresses in the root. Horizontal lines indicate which throat size is equivalent to 1,3*median stress level.

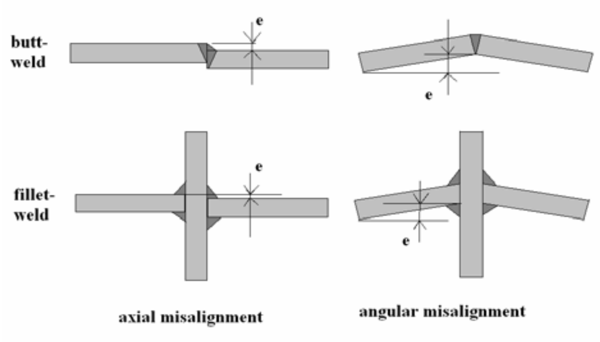

Figure 19 Misalignments in fillet and butt welds.

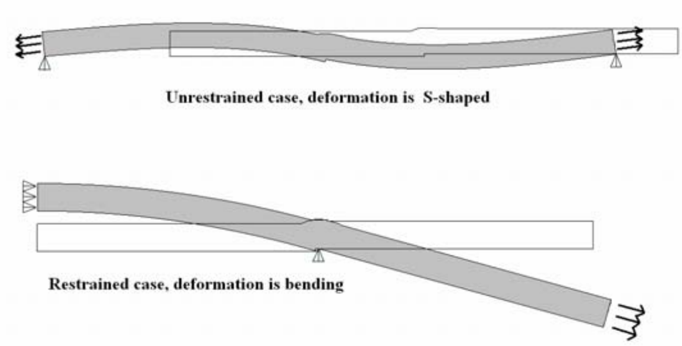

Figure 20 Axial misalignment in a butt weld with different types of boundary conditions. Analysis made in Ansys (2D). Restrained case gives higher stresses. Deformation is highly exaggerated

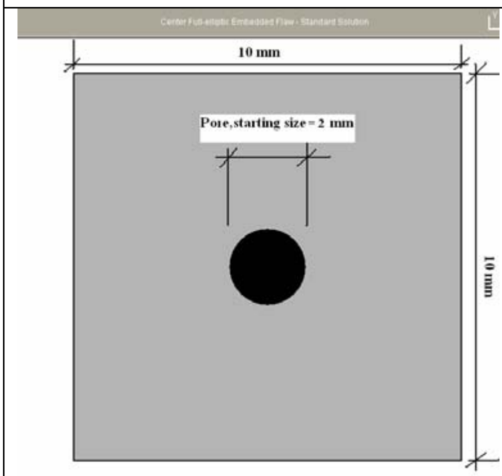

Figure 21 Semi elliptical crack in a square section equivalent to a pore in a weld (Afgrow model). Stresses are perpendicular to the paper.

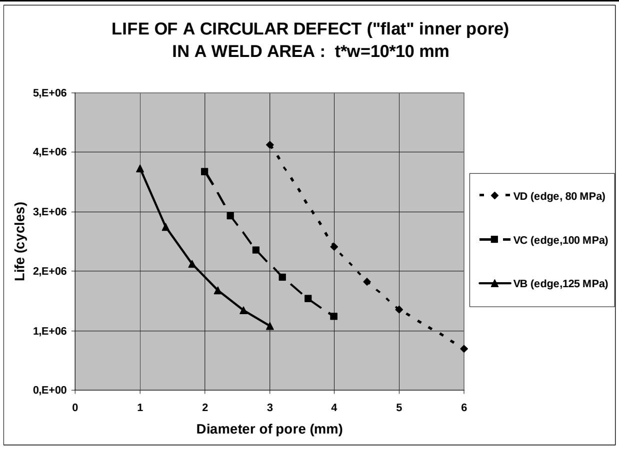

Figure 22 Life of an inner pore calculated with fracture mechanics.

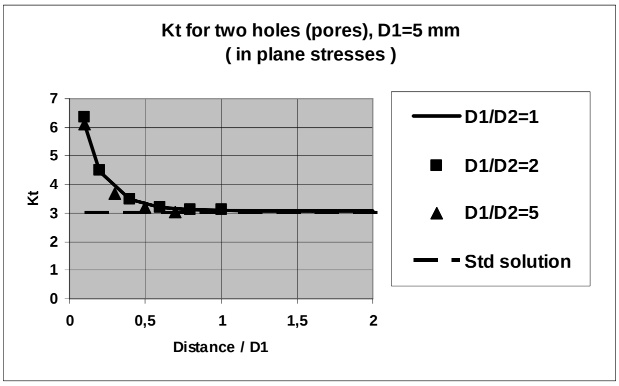

Figure 23 Stress concentration Kt plotted against relative distance to D1. Note that the curves coincide.

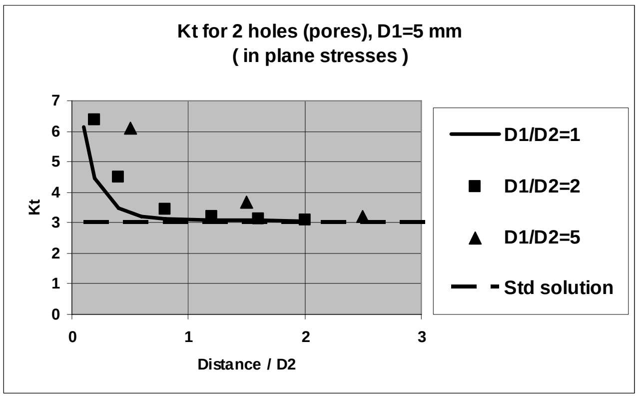

Figure 24 Stress concentration Kt plotted against relative distance to D2. Note that the curves do not coincide.