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Course on fatigue and fracture mechanics

Influence of residual stresses and post-welding improvement methods

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Preface

This chapter of the course on fatigue and fracture mechanics contains some repetitions of previously taught material in order to be self-standing whenever necessary. The sections concerned are section 1 (introduction, for a large part), as well as sections 3.1, 3.2 and 4.1. These do not need to be presented again in class but however will help the students better understand the concepts presented.

Regarding the bibliography and further reading, the student will find all sources cited within this chapter at the end, but he will also find a supplementary table with a list of selected books on fracture mechanics and fatigue of structures.

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1. Introduction

To explain why the fatigue resistance is not « a priori » linked to the tensile strength, one can take advantage of the analytical modeling of fatigue failure. Fatigue life, expressed as number of cycles to failure, N, can be separated in the following three different phases (see Figure 1):

1) Crack initiation: depending upon the material and stress level, various mechanisms take place to create voids and micro-cracks in the material. These micro-cracks progress through the material grains. Once the size of a micro-crack becomes important and that it grows in a preferential direction, it will develop in a preferential way, unloading the other micro-cracks. In a steel structure, characteristic crack lengths in the range of a_0 = 0.1 to 1 mm are usually considered.
2) Stable crack propagation: the presence of the crack creates a stress concentration and local plastification at the crack front. The opening and closure of the crack corresponding to each stress cycle gives rise to large plastic slips which form striations on the fracture surface. The crack size increases with each stress cycle in a stable manner.
3) Unstable crack propagation : the crack propagation rate increases exponentially until a critical size, a_{cr}, corresponding to the instability of the cracked element, is reached and failure occurs.

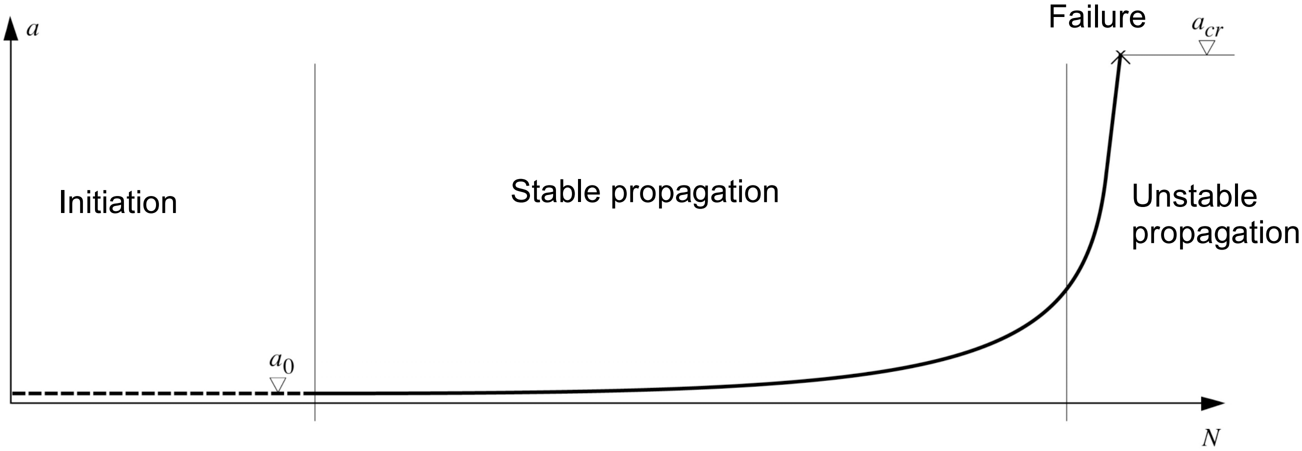


Figure 1 : Stages of crack developpment and fatigue life [Hirt et al. 2006]

Crack initiation fatigue life is highly dependant upon material characteristics, as shown for example by the parameters in the well-established Manson-Coffin relationship [Manson 1954, Coffin 1954] :

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma'_f - \sigma_m}{E} \cdot \left(2N_f\right)^b + \varepsilon'_f \cdot \left(2N_f\right)^c \qquad (1)$$

Where :

ε'_f ; σ'_f	ductility and strength coefficients of the material in fatigue ;
σ_m	local mean stress ;
$\Delta\varepsilon$	total, or elastic-plastic, strain range ;
E	Young's modulus ;
b ; c	ductility and strength exponent of the material in fatigue ;
$2N_f$	number of load reversals until failure of a smooth specimen.

All other things kept the same, crack initiation fatigue life in steels increases with tensile strength. On the opposite, crack propagation fatigue life in steels, particularly C-Mn steels used in structural engineering, is independent of mechanical properties, see for example [Rolfe & Barsom 2000]. Thus, total fatigue life and the relative importance of the initiation versus the propagation fatigue life depends on the presence of imperfections (also called in literature flaws, defects) which, according to their size and shape, reduce or suppress the initiation period.

In machined steel parts, as illustrated in Figure 2 [Maddox, 1991], it is common to say that the higher the steel grade, the better its fatigue strength since the initiation period is the largest part of the total fatigue life. For welded structures, on the contrary, the effects of notches, defects, and corrosion reduce the fatigue strength, by reducing the number of cycles needed to initiate a fatigue crack. That is, the largest part of the fatigue life comes then from the crack propagation period. As a consequence, the fatigue strength of welded structures made out of high steel grades is not higher than that of mild steel (when both have the same defects), as can be seen in Figure 2. This is reflected in most structural codes, for example Eurocode 3 [EN1993-1-9 : 2005].

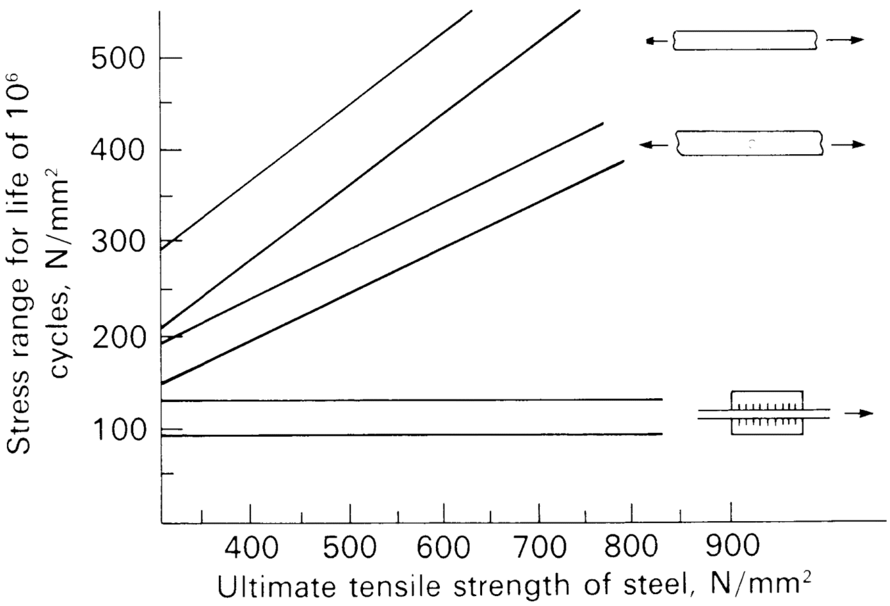


Figure 2 : Effect of steel strength on fatigue strength [Maddox 1991]

This last affirmation is however still a point of controversy. Some studies show there may even be an inverse material dependency, i.e. welded elements using high strength steels may have a lower fatigue strength in the high cycle region [Miki, Homa et al. 2002]. But it can be argued that the welding of high strength steels requires more skilled fabricators. As modern welding procedures and good workmanship results in better weld geometry and fewer defects, it comes not as a surprise that other studies, for example [Mang, Bucak et al. 1991], show a better fatigue resistance for welded high strength steels elements. Thus, fatigue resistance modeling is not in question in this debate, but the presence/absence of a crack initiation phase is.

In modern structures, more high strength steels are used to create lighter and more slender structures, but which are subjected to high stress levels. As the design stress level is increased to take advantage of the high strength, so does the ratio between variable and permanent loads and thus the magnitude of the stress variations. In welded structures, in order to keep a balance between static and fatigue design, more emphasis has to be put on the latter since fatigue resistance does not increase in the same manner as steel tensile strength. For the details located in the critical sections, i.e. that cannot fulfill the fatigue safety criteria, the solution can be:

- New or modified detailing, displacement of details in less stressed sections,
- Improved welding procedures, better workmanship,
- Post-weld improvement methods.

The above mentioned solutions are developed in chapter 3. However, this part of the course puts an emphasis on post-weld improvement methods. The objective is to give the basis as well as practical information on these methods. In order to fully understand the fatigue behavior of welded structures, one first needs to present what are residual stresses and their influence on fatigue.

2. Residual stresses in welded structures

Residual stresses, or self-equilibrating stresses, are the stresses that exist in a structure or a component without the application of any external load. Manufacturing processes such as forming, rolling, welding, machining, etc. are the most common causes of residual stresses. In some instances, residual stresses may also be induced or modified later in the life of a component by imperfect fit-up, assembly procedures, erection, service loads, occasional overloads, by in-service repair or modification. Residual stresses are an important factor influencing the structural behavior in all instability failures, as well as in fatigue crack initiation and propagation when cyclic service stresses are superposed onto the residual stresses. Residual stresses may sometimes be seen indirectly when looking at the mill scale cracking after welding. An example is shown on Figure 3 for an I girder with stiffeners and gusset plates welded onto it. From the pictures, one can note that tensile residual stresses up to yield exist perpendicular to the yield lines and that the fatigue crack directions are parallel to these yield lines (i.e. welding residual stresses will open any imperfection, or micro-crack present, that is in the direction of the yield lines).

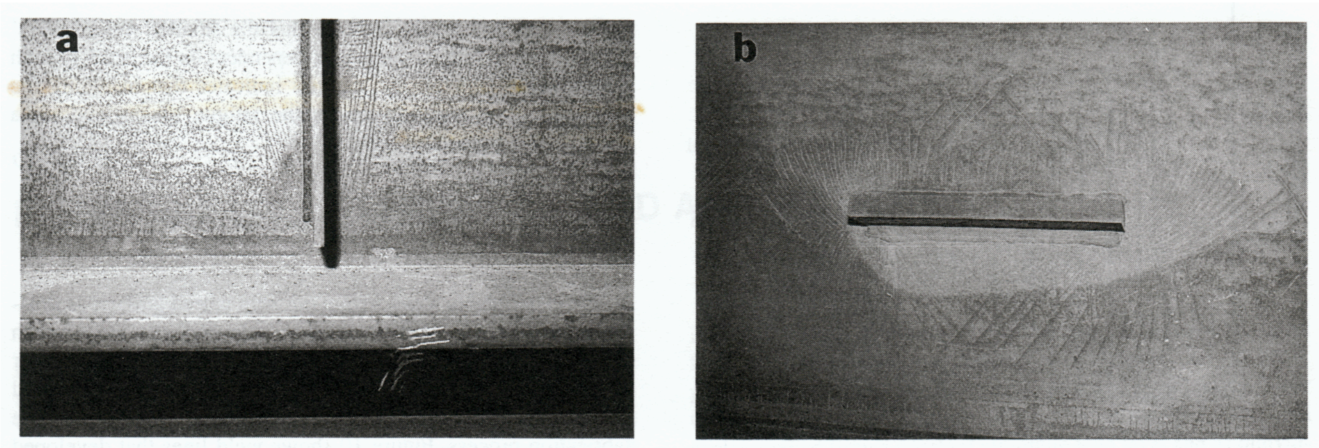


Figure 3 : Yield lines in mill scale adjacent to welded details confirm existence of residual stresses. (a) stiffener detail showing yield lines after welding (b) Web gusset detail showing yield lines after welding [Fisher et al. 1993]

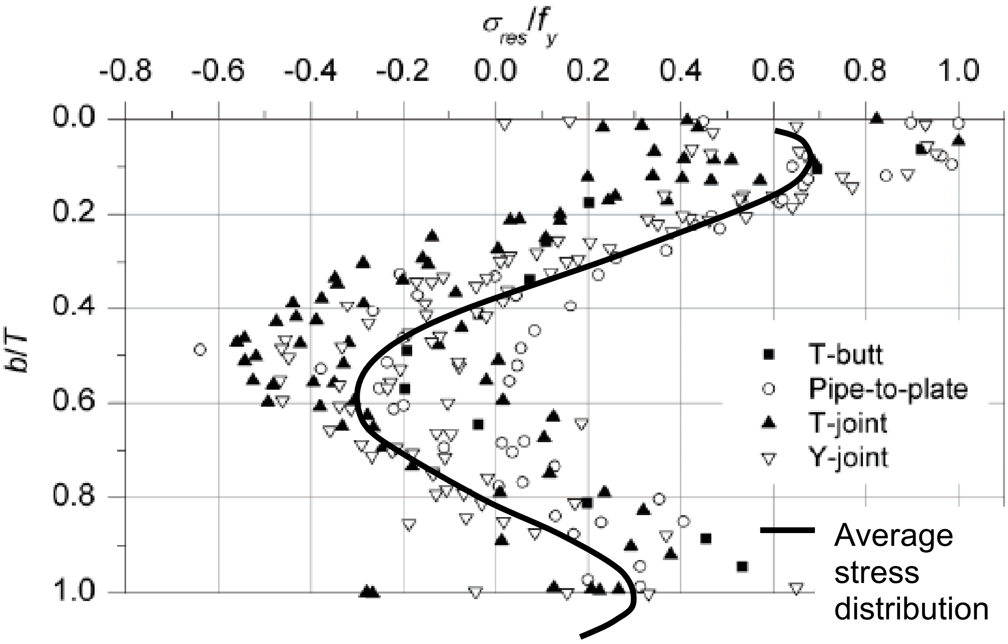


Figure 4 : Transverse welding residual stresses [reported in Stacey et al. 2000]

Effectively, welding in particular introduces tensile residual stresses in the vicinity of the welds, which modify the mean stress experienced by the welded joint under fatigue loading. Figure 4 illustrates, for different welded details, the welding residual stresses present at the weld toe location, from the surface down to through the thickness T. It is generally, and conservatively, assumed in design that tensile residual stresses up to the proof strength of the material will be present in a welded structure. Its fatigue life will be thus independent of mean stress :

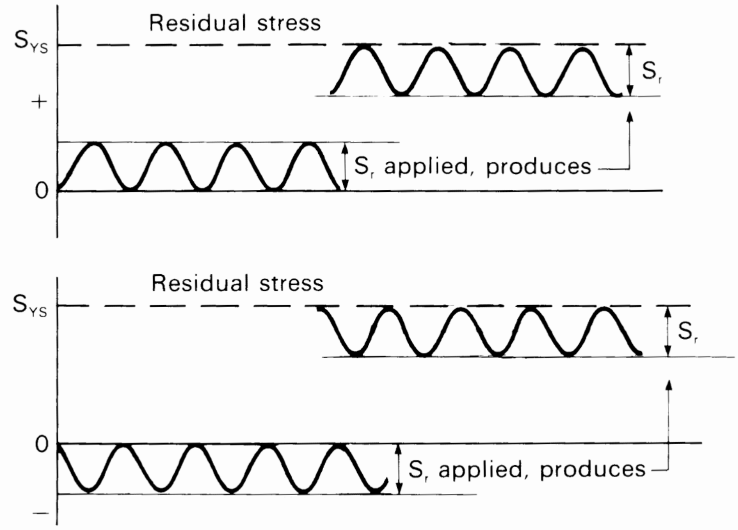
$$\sigma_{mean} = \frac{\sigma_{\min} + \sigma_{\max}}{2} \tag{2}$$

where σ_{min} = minimum nominal algebraic value of the stress in the cycle;
σ_{max} = maximum nominal algebraic value of the stress in the cycle (by convention : tension is positive, compression is negative).

Fatigue life of a welded structure will thus only depend on the applied stress range, $\Delta\sigma$, even if it is compressive [Gurney 1979]. An example of this behavior is presented in Figure 5 for a transverse fillet welded attachment [Maddox 1991], where R is known as the stress ratio and defined as follows :

$$R = \frac{\sigma_{\min}}{\sigma_{\max}} \tag{3}$$

In the top part of figure 4, two cases are presented with the applied stress range from the loading being in one case in tension and in the other in compression. With the addition of the high tensile residual stresses, one sees that for the same range of applied stress, the stress conditions produced at the weld are the same for both tensile and compressive applied loading. If this is correct, then the fatigue strength should thus be independent of the mean stress or the stress ratio. This is confirmed in Figure 5, lower part, by test results under different stress ratios, plotted on a double-log scale : number of cycles to failure N versus stress range S. One sees that all test results fall within the same scatter band. Consequently, all the fatigue design specifications are based on the use of full stress range regardless of whether it is tensile or compressive [Manteghi & Maddox 2004]. Linked with the parameters involved, fatigue strength or resistance curves are also often called S-N curves.



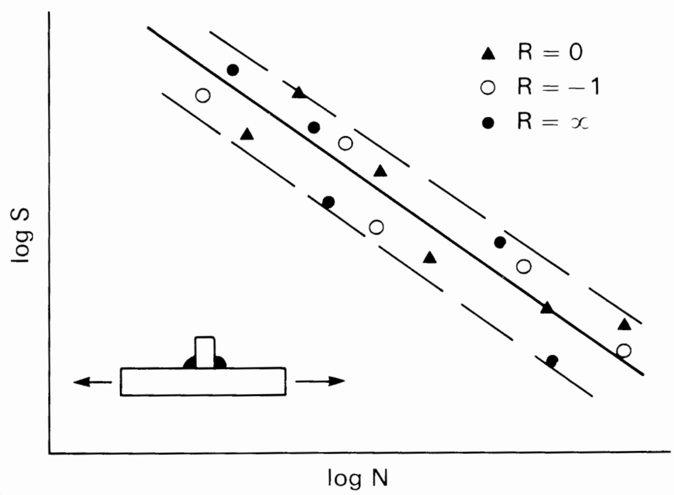


Figure 5 : Fatigue test results for steel fillet welded joints containing high tensile residual stresses [Maddox 1991]

Furthermore, regarding the importance of the residual stress field on the fatigue life of welded details, it was long ago recognized [Gurney, 1979] that fatigue strength decreases when testing larger welded components compared to small welded specimens (with the same welded detail). In Figure 6, the fatigue strength curves obtained with small welded specimens at a low stress ratio are compared with the data points obtained on a large welded beam. One sees that the data points are remarkably lower than strength curves beams [Otha et al. 1996]. That is, the fatigue strength for a welded beam does not vary with the stress ratio, as the tensile stress reaches the yield strength of the material in the welded beam and the maximum stress tends to the yield strength by shakedown in spite of the stress ratio [Gurney, 1979]. This fatigue strength, which is not affected by the stress ratio, is defined as the basic fatigue strength of a welded joint. However, the residual stresses in a small welded specimen are usually low and the maximum stress increases with the increase in the stress ratio. Therefore, as illustrated in Figure 6 the fatigue strength for a small welded specimen decreases with increasing stress ratio.

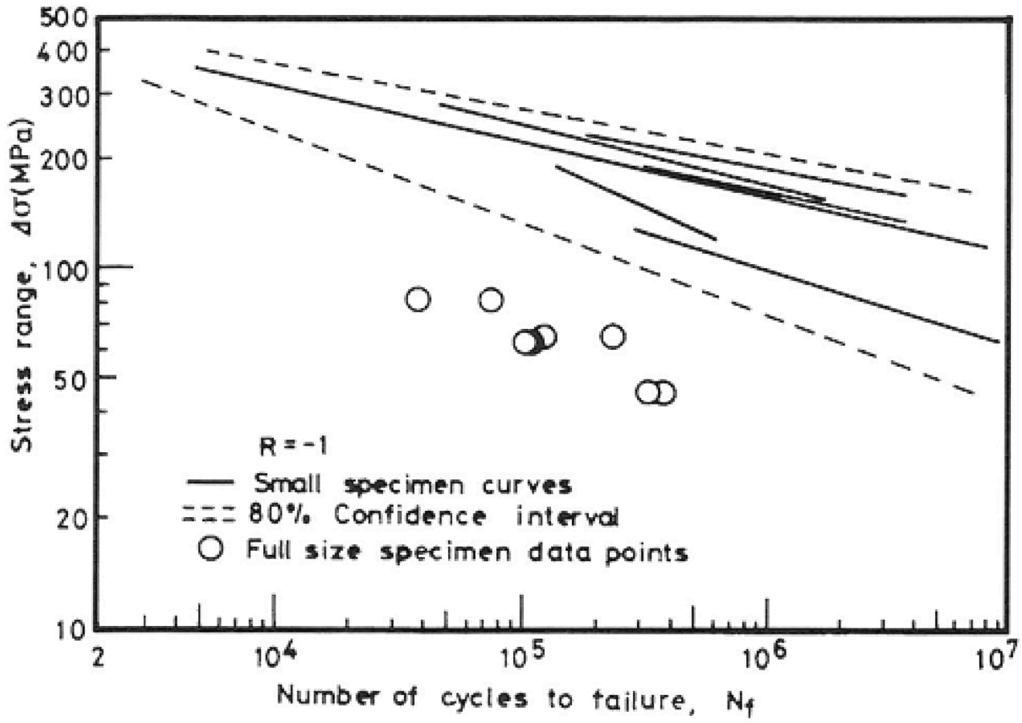


Figure 6 : Difference of fatigue strength between small welded specimens and large welded beams, all in aluminum alloys [Otha et al. 1996]

The consequence is that one needs to test « large-scale » specimens in order to account for the complete welding residual stress field. As well, to have a lower bound for the design fatigue resistance curves contained in design codes such as Eurocode 3, part 1-9 [EN 1993-1-9: 2005], only « large-scale » tests were included in the fatigue database used to define them.

3. Solutions to improve fatigue strength

3.1. Detailing

Stress concentrations depend on the shape of the component and on the manufacturing process. They occur at corners, loading positions, abrupt section changes, etc. Indications for good fatigue resistant design are given for example in an ECCS publication [ECCS 2001]. In order to get better fatigue strength, in particular with high strength steels, it is essential to follow the precautions given below :

- Avoid structural discontinuities in highly stressed regions.
- Put welds and details in zones near the neutral axis or where the mean stress is compressive.
- Design details where bending moment is minimized, for instance by avoiding misalignment or offset, which causes secondary bending stresses (example: converging axes of truss diagonals and chords).
- Avoid the combination of several stress concentrations in the same region, like welds in zones affected by holes, tapering, attachments, etc., as this increases further the stress concentration factor.
- Preferably use high performance steels, such as thermo-mechanical steels, see [EN 10025 : 2004, SED n° 8 2004].
- Do not use fillet or partial penetration welds in load carrying welded joints but full penetration welds.
- For welds made from one side only (root not accessible), use a backing strip to ensure better root weld.

- Avoid using stiffeners, except at supports, if the self-weight increase of the panel without stiffeners is only 10 to 15 % more than the weight of the original stiffened panel (web and flanges) ; this design will, in the end, be more economical and fatigue resistant.
- Change detail from a welded to a bolted shear connection.
- Ensure that support stiffeners are at the axes of the supports.

3.2. Welding procedures and workmanship

The requirements (steel fabricator, supervisor, welder) for welding structures subjected to cycling loadings are set higher, but it is not sufficient to ensure proper fatigue strength. It also requires state of the art production processes, see for example publication [SED n° 8 2004]. Manual arc welding for example should preferably not be used and, for at least longitudinal welds, automatic welding machines should be used. With fine grain steels, since they are very sensitive to welding parameters, it is very important to follow the rules given in EN1011-2 [EN1011-2 : 2001] for pre- and post-heating temperatures, etc. to avoid the forming of large grains and martensite. In addition, a couple of precautions about the fabrication procedure such as the systematic use of backing strips were already mentioned in the previous paragraph.

In case of welds not meeting the quality requirements, a fitness-for-purpose assessment shall be carried out as a first step, especially for high strength steel welds since a repair may worsen the problem. If it shows that the weld needs to be repaired, the repair procedure must be well though about and approved by a welding engineer. For all steels, most repair welding is made using manual arc welding. The defects created, in particular at the start and stop positions, exceed those from other welding processes and therefore make it difficult to recover the original quality from automatic welding. In the case of high strength steels, this problem is emphasized because the consequences of downgrading the fatigue strength (fatigue class) of a welded detail are larger. In some cases, solutions such as post-weld improvement methods (grinding for example) can be proposed. The latter is the subject of the next paragraph. Some information about good workmanship can be found for example in ECCS recommendations [ECCS 2001]. For improving the fatigue strength, new developments such as low temperature transformation welding material may also be considered, see [SED n° 8 2004].

3.3. Post-weld improvement methods

Most methods consist in treating the **weld toe regions** of a joint after welding, meaning that details with cracking starting from an internal imperfection or from the weld root cannot be improved, as will be further explained later. Only a few methods, not used in civil engineering applications, such as component detensionning may improve the fatigue strength of a component as a whole. Post-weld improvement methods have been studied by various industries, in particular by the automotive and offshore industry [Maddox 1991, Haagensen 1997]. Large databases of test results can be found in the literature, for example [Huther et al. 1996]. These post-weld improvement methods influence beneficially, within certain limits, the fatigue strength of the improved joint, as can be seen in Figure 7.

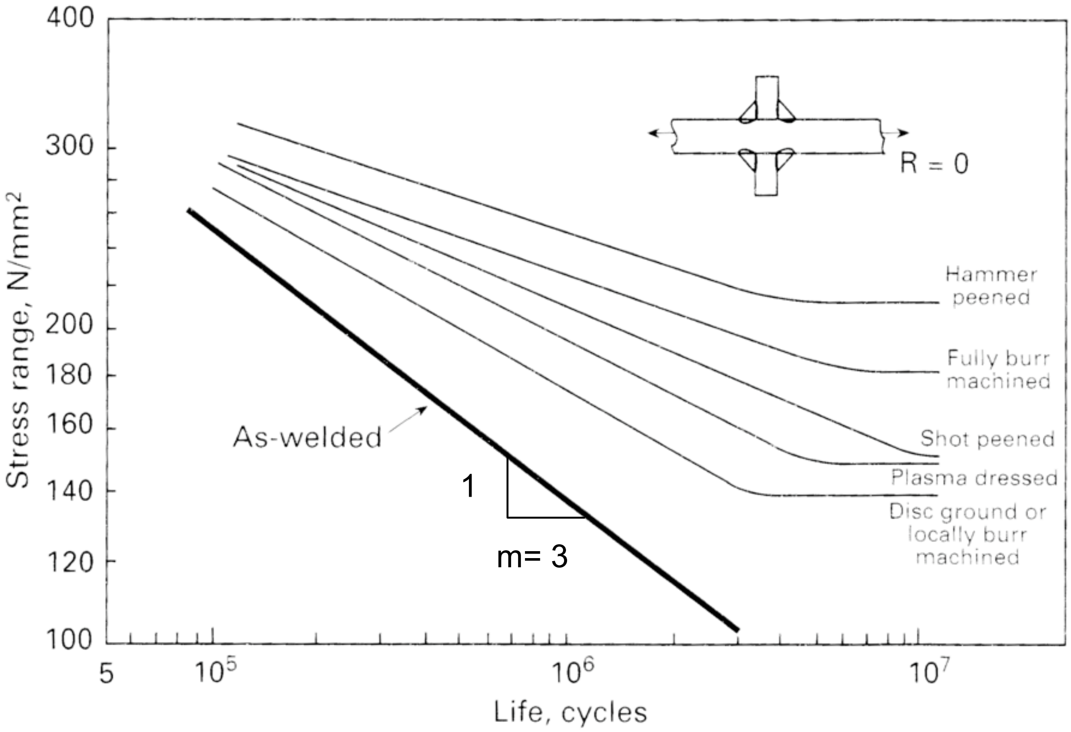


Figure 7 : Typical improvement in fatigue strength of mild steel fillet welds resulting from toe dressing or peening [Maddox 1991]

For the reasons given in the introduction, they are especially efficient in the case of welded structures made out of high strength steels. Numerous improvement methods exist and in this course we will only deal with five of them, which are among the most popular ones, that is (see summary in Figure 13) :

A) Grinding;
B) Tungsten Inert Gas (TIG) dressing of the weld toe;
C) Needle peening;
D) Hammer peening ;
E) Ultrasonic hammering systems (UIT or UP).

The main parameters responsible for the beneficial influence of the improvement methods are the following :

1) Reduction of local stress concentrations, notch radius;
2) Creation of a crack initiation phase;
3) Alteration of the residual stress field of the superficial layer.

Consequently, the improvement methods can be divided into two distinct groups :
- Methods which smoothen the weld bead-base plate transition (parameter 1) and eliminate the surface defects (parameter 2), that is methods A and B;
- Methods which change tensile residual stresses into compressive stresses around locations of potential fatigue cracks (parameter 3), and produce also cold hardening at surface, that is methods C, D and E. Some of these methods, especially the high energy level ones, also smoothen the weld-plate transition but this is not their primary intended goal.

The methods and parameters are summarized in Figure 8 as a table.

Figure 8 : Effects of post-weld improvement methods

Geometrical effect		Mechanical effect
Increase weld bead-base plate transition radius	Eliminate surface defects	Compressive residual stresses and cold hardening
Grinding	**Grinding**	-
TIG-dressing	**TIG-dressing**	-
-	-	**Needle peening**
Hammer peening	Hammer peening	**Hammer peening**
UP/UIT	UP/UIT	**UP/UIT**

The beneficial influence of an improvement method on the fatigue strength can be represented on a standard S-N diagram (for constant amplitude loading) by both a translation and a rotation of the resistance curve, see Figure 9. As can be seen, the fatigue class of the improved detail is raised by both the translation and the rotation.

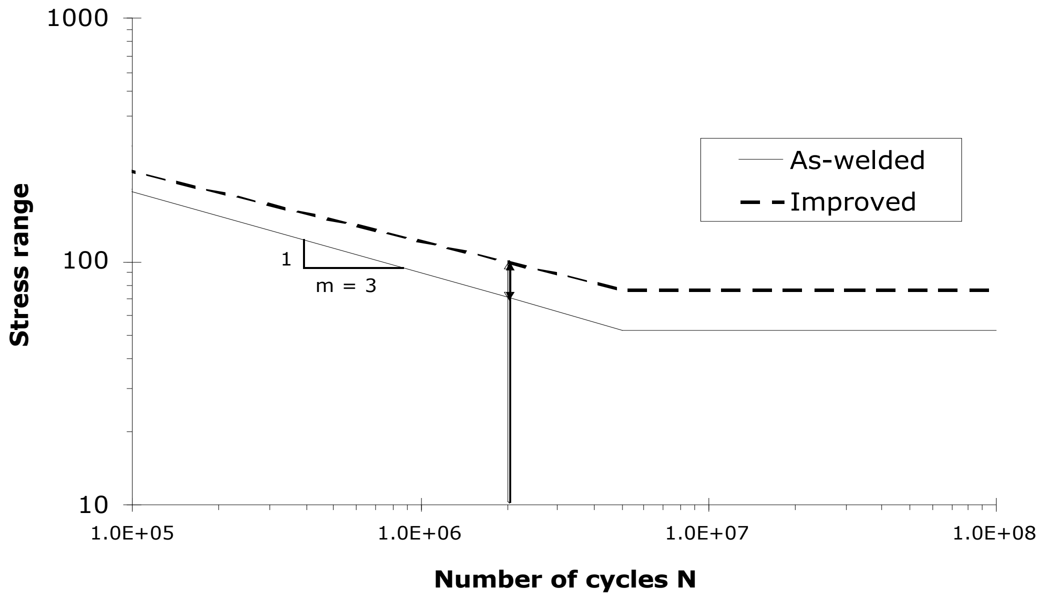


Figure 9: Influence of the use of an improvement method on the S-N curve of a welded joint

Parameter 1 is responsible only for a translation and parameters 2, 3 for both a translation and a rotation. One must be careful because there are several restrictions to the benefits of the improvement methods.

All improvement methods have in common the potential problem that a crack may initiate at another location than the treated area, for example a crack may develop from the root in a cover-plate weld, or from blow-holes in load-carrying fillet welds. In such cases, the benefit obtained may be negligible [Haagensen 1997]. **When considering the use of improvement methods, the possibility of crack initiation at other locations must always be considered**. All the same, successful implementation of these methods depends on the adequate training of operators as well as inspectors.

An example of the influence of peening methods on fatigue resistance is given in Figure 10 [Huther et al. 1996], for transverse attachments. Apart from the results dispersion, typical for fatigue resistance studies, one can notice that the resistance of the peened detail is raised by both the translation and the rotation of the test data set.

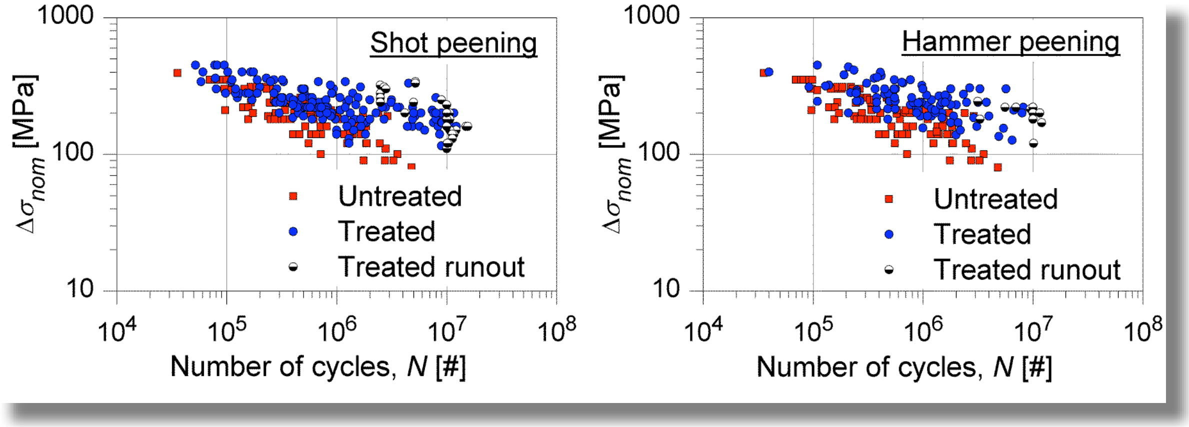


Figure 10 : comparison of S-N data on untreated and treated stiffened plate specimens

Currently no international code contains rules to cover post-weld improvement methods. The only exception is grinding, as it is included in the requirements for a few detail categories (e.g. butt welded joints). Some recommendations do exist however, such as the ones written by Maddox and Haagensen within Commission XIII of the International Institute for Welding [Haagensen & Maddox 2004], the last not yet published version of these recommendations being very recent [Haagensen & Maddox 2008]. These cover steels with yield strength up to 900 MPa, including austenitic steels, and will serve as a basis in the next paragraphs. The student is referred to these recommendations for equipment, procedures, inspection and quality control criteria. In the USA, it was considered including UIT post-weld treatments in the 2007 version of the AASHTO code [AASHTO 2007]. Finally they didn't because of concerns regarding the long-term performance due to, for example, subsequent heat treatments or possible corrosion pitting of the treated zones. Another problem is that the method is properietary, Esonix UIT [Statnikov 2005].

In the following paragraphs, several treatment methods are briefly discussed, a summary of the methods is also given in Figure 13. Further information regarding these methods can be found for example in : [Haagensen 1997, Kirkhope et al. 1999, Haagensen & Maddox 2008].

Grinding methods

Grinding methods are perhaps the most recognized and widely-accepted of all post-weld treatment methods. Simply stated, grinding works by removing material at the surface of the weld toe (or full weld profile), with the goal of eliminating near-surface weld defects and reducing the severity of the geometric discontinuity (i.e. reducing the stress concentration) introduced by the welded detail. Disk grinding and burr (i.e. hemispherical or spherical) grinding tools are available. Disk grinding is considered to be faster than burr grinding, and therefore less costly. Burr grinding, however, is considered to be potentially more effective. The advantages of grinding in comparison with other methods are the reliable improvements possible and the ready availability of the necessary equipment. In the case of disk grinding, the speed of treatment is also considered an asset. The disadvantages in the case of burr grinding are the slower treatment rate and high cost of consumables. In the case of disk grinding, a major disadvantage is the high risk of creating defects or score marks worse, from a fatigue standpoint, than those present in the untreated weld.

Dressing methods

Dressing methods is another, well established and much studied, class of geometry improvement methods, as discussed in [Haagensen 1997]. TIG and plasma dressing methods are discussed in this reference. The first method involves re-melting the weld toe with a welding torch of the type used in TIG (Tungsten Inert Gas) welding (also known as GTAW – Gas Tungsten Arc Welding). Plasma dressing is similar to TIG dressing, but with a higher (approximately double) heat input. This enables an increase in treatment speed and reduces the importance of the electrode position on the success or failure of the method [Kirkhope et al. 1999]. Plasma dressing has the disadvantage of requiring equipment that is less mobile and less readily available. Essentially the goals of dressing are similar to those of grinding, that is: to remove small crack-like defects and reduce the stress concentration at the weld toe. TIG dressing can remove defects up to 6 mm below the weld surface. The main advantages of dressing methods are the large fatigue life improvements possible and the relatively low cost. The main disadvantages are the high level of operator skill required, the need for careful cleaning of the weld, and an apparent risk of over-hardening (cracking) in high carbon steels.

Peening methods

The most commonly used residual stress-based treatment methods involve the peening or impacting of the weld toe to a degree sufficient to cause the plastification of a thin surface layer, which relaxes when the impacting object is removed, resulting in a built-in compressive residual stress near the surface of the treated detail. This stress may be sufficient to slow the crack growth rate or even halt it. Shot, needle, and hammer peening are the classical methods, in increasing order of energy level. Ultrasonic hammering is a high energy level method that has received much attention in recent years.

The level of built-in compressive residual stress may be influenced by the subsequent loadings. If performed in the shop, the treatment efficiency may decease after erection of the structure as the dead load and cyclic loads combination can cause larger shakedown effects in the compressive residual stress layer. Even if done on site, shakedown can occur if the structure is subjected to large compressive overloads. This subject will be further discussed in section .

Hammer peening is carried out using a pneumatic or electric hammer with a single, hemispherical tip 6-18 mm in diameter. In general, four passes of the hammer peening tool are recommended for optimal treatment. A treatment speed of 25 mm/s is recommended in [Kirkhope et al. 1999]. [Haagensen & Maddox 2008] indicate that with a speed of 0.8-1.7 mm/s, a single pass may suffice. Proper hammer peening should result in a smooth dent with a uniform depth of about 0.5 mm along the weld toe.

In the case of needle peening, four passes are generally recommended for optimal treatment, at a treatment rate not exceeding 800 mm/min. (~13 mm/s) [Haagensen & Maddox 2008]. Proper needle peening should result in area uniformly covered with small overlapping indentations. It should not be possible to see any point on the surface that has not been impacted at least once by the peening tool.

Figure 11 presents an example of residual stress measurements due to needle and hammer peening [Bremen 1989, Walbridge 2005]. One can see that compressive residual stress layer induced by the treatment is a few millimeter deep and function of the method (about 1 mm for needle peening vs 3 mm for hammer peening). It also illustrates that some shakedown effects occur due to cycling and are accounted for in the model. Modelling of the residual stress distribution due to post-weld treatment made using peening tools (with the exception of UIT/UP) can be showed to be a function of the imprint diameter, d_p, is of the peening tool and expressed as:

$$\begin{aligned} \sigma_{res} &= -0.5 f_y \qquad if\ b \le 0.1 d_p \\ \sigma_{res} &= f_y \left[5/6 \left(\frac{b}{d_p} \right) - 7/12 \right] \qquad if\ b > 0.1 d_p \end{aligned} \tag{4}$$

In order to model the influence of both the welding residual stresses and the post-weld treatment, one can superpose both cases, that is the residual stresses presented in Figure 4 and Figure 11. The result is illustrated in Figure 12 [Walbridge 2005].

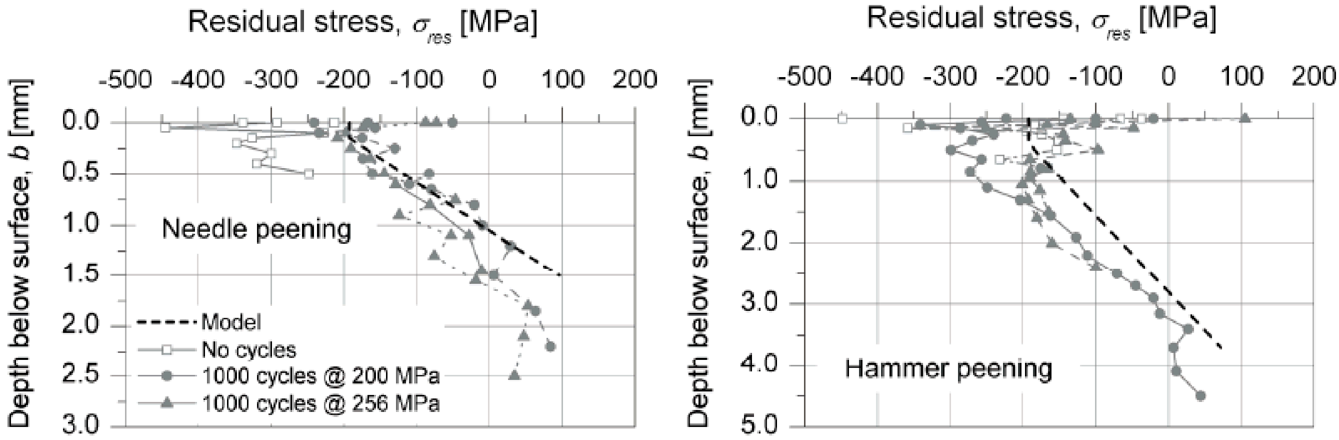


Figure 11 : measured and modelled (equation 4) residual stresses due to needle (left) and hammer peening (right) on stiffened plate specimens

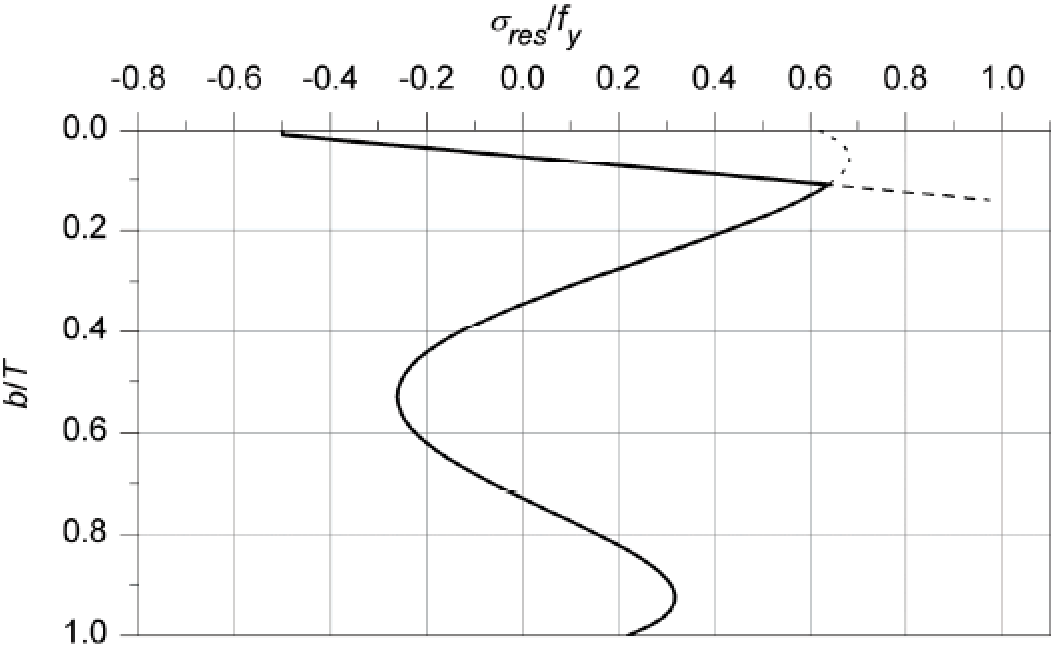


Figure 12 : residual stress distribution for needle peening crack site (t = 20 mm)

After treatment, a visual inspection should be carried out with a low power magnifying glass. It is recommended that fluorescent dye or toolmakers blue be sprayed on the areas to be treated, as the removal of these indicators by the peening operation may serve as a useful method of quality control. Regarding the other commonly discussed peening methods, the following comments are made:

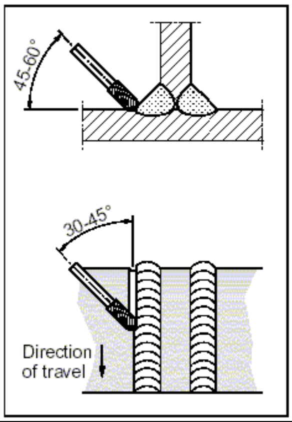
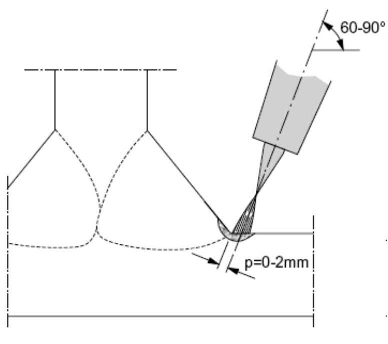
- With shot peening, the plastification of the surface layer is induced by small chilled cast-iron spheres or cuttings of high tensile steel wire [Gurney 1979]. Shots range in size from 0.4 to 1.0 mm and travel with a velocity of 40-60 m/s [Gurney 1979, Kirkhope et al. 1999].
- Ultrasonic hammer peening or ultrasonic impact treatment (UP or UIT) makes use of either a 16 mm hammer or multiple needles which vibrate at a frequency between 20

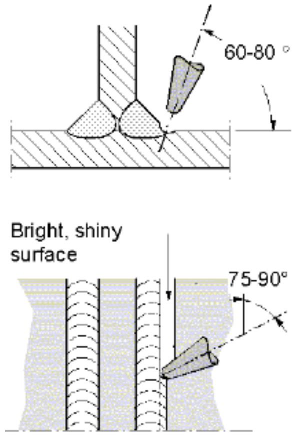
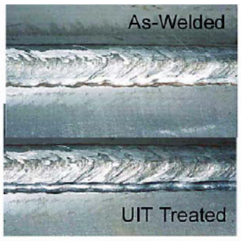
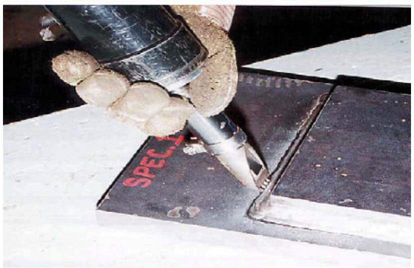
and 30 kHz. The tool is moved at a rate of 0.5 m/min. [Hou Lixing et al. 2000] and makes little audible noise [Kirkhope et al. 1999].

Peening methods are considered to be highly effective when properly applied. Furthermore, needle and hammer peening were seen to be the least expensive of the various available treatment methods in economic studies. Shot peening has the advantage of being well suited for treating large surfaces. For this reason it has seen wide application in the surface treatment of non-welded structures, in particular in the automotive and aerospace industries. Ultrasonic hammering is believed to give the most consistent results, i.e. the smaller scatter in improvement level, as the imprint of the treatment can be visually checked and it is a double treatment : the weld toe geometry improvement is caused by the mechanical cold working from tools pins at about 100Hz and the residual stress improvement is reinforced by transferring the ultrasonic wave vibrations during the pin impact [Cheng et al. 2003, Roy and Fisher 2005].

Hammer peening, and to a lesser extent needle peening, have the major disadvantage of involving high levels of noise and tool vibration, which means treatment may not be possible at all hours of the day, proper hearing protection must be worn by the operator and all those in close proximity, and there are likely limits to the amount of time an operator can spend peening over the course of a single day. It is believed that the vibration problem can be mitigated somewhat by wearing proper gloves. Newer peening tools may also contain built-in vibration isolation. With UIT/UP methods, the problems of noise and vibration associated with hammer and needle peening are largely mitigated. A major drawback of UIT/UP methods is that specialized equipment is required and the technique as well as the tools are patented.

Figure 13 : illustration of the improvement methods considered

Improvement method	Short description	Illustrations (from [IIW 2008] or [Cheng and al. 2003])
Grinding	Remove weld toe flaws and smooth it using a high speed pneumatic, hydraulic or electric grinder with burrs (hemispherical or spherical) and rotational speed from 15000 to 40000 rpm.	Pneumatic grinder and burrs  
TIG dressing	Remove weld toe flaws and smooth it by remelting the material at the weld toe using standard TIG welding machine. Argon is normally used as shielding gas.	 

Needle peening	Introduce compressive residual stresses in weld toe region by repeatedly hammering the weld toe region with a bundle of round-tipped rods. A standard needle gun of the type used for removing slag and scale is suitable.	
Hammer peening	Introduce compressive residual stresses in weld toe region by repeatedly hammering it with a blunt-nosed chisel. A pneumatic or hydraulic hammer is commonly used.	 
Ultrasonic hammering systems	Introduce compressive residual stresses in weld toe region by repeatedly hammering using an ultrasonic transducer that oscillates at a high frequency, with 20-30 kHz being typical. Two main patented systems : - Ultrasonic Impact Treatment (UIT) [Statnikov 1997]. - Ultrasonic Peening (UP) [Kudryavtsev et al. 2004].	UIT treatment   Ultrasonic peening 

4. Modelling of post-weld improvement effects

4.1. Linear elastic fracture mechanics

It is recalled here that the development of LEFM is generally acknowledged to have started with work by Griffith in the 1920s on glass specimens [Stephens et al. 2001]. More information can be found in previous courses. Griffith found that for glass plates, the applied stress and crack size at fracture could be related by the following expression:

$$\sigma \cdot \sqrt{a} = \text{constant} \tag{5}$$

wherein σ is the stress and a is a measure of the crack size (i.e. crack length). [Irwin 1957] subsequently introduced the concept of the stress intensity factor (SIF). Simply stated, for a given applied stress, σ, it can be shown that the stress distribution in close proximity to the crack tip is a function of the so-called stress intensity factor, K. In addition, it can be shown that provided the plastic zone at the crack tip is sufficiently small, two cracks with different lengths and loading conditions resulting in the same value of K should respond in a similar way. This makes K a useful parameter for the study of cracks in brittle and semi-brittle materials such as structural steel. For a crack in an infinitely large plate under a uniform nominal stress, it can be shown that:

$$K = \sigma \cdot \sqrt{\pi \cdot a} \tag{6}$$

A more general formula for the stress intensity factor is:

$$K = K_t \cdot Y \cdot \sigma \cdot \sqrt{\pi \cdot a} \tag{7}$$

wherein Y is a correction factor (or factors) to adjust for such things as the true shape of the crack, the presence of a free surface, the finite thickness of the plate, and K_t accounts for the non-uniformity of the stress distribution. [Paris & Erdogan 1963] showed that the rate of fatigue crack propagation, da/dN could be related to the applied stress intensity factor range under cyclic loading conditions, ΔK_{app} (= $K_{max} - K_{min}$), using the following expression:

$$\frac{da}{dN} = D \cdot \Delta K_{app}^{n} \tag{8}$$

wherein N is the number of cycles, and D and n are material constants. The material constant *n* for carbon steels is usually *n = 3*, i.e. identical to the slope *m* of the S-N curve for as-welded joints, see Figure 7 or in [Hirt et al. 2006]. This is logical since both represent the same behavior, the S-N curve can be found by integration of Equation (8). Effectively, the fatigue life, N_c, can be determined by integrating Equation (8) over a crack depth range, a_0 to a_c:

$$N_c = \int_{a_0}^{a_c} \frac{da}{D \cdot \Delta K_{app}^{n}} \tag{9}$$

In fact, equation (8) is known to only be valid for the intermediate or *stable propagation* phase of the fatigue life of a crack (see Figure 14). Modifications to equation (8) have been proposed to consider the other cases of crack propagation (i.e. slow propagation, limited by the introduction of a threshold stress intensity factor range, ΔK_{th}, and rapid crack propagation), as well as other phenomena such as the effects of crack closure and residual stresses. Details on such modifications can be found in a number of references, for example: [Broek 1991, Stephens et al. 2001].

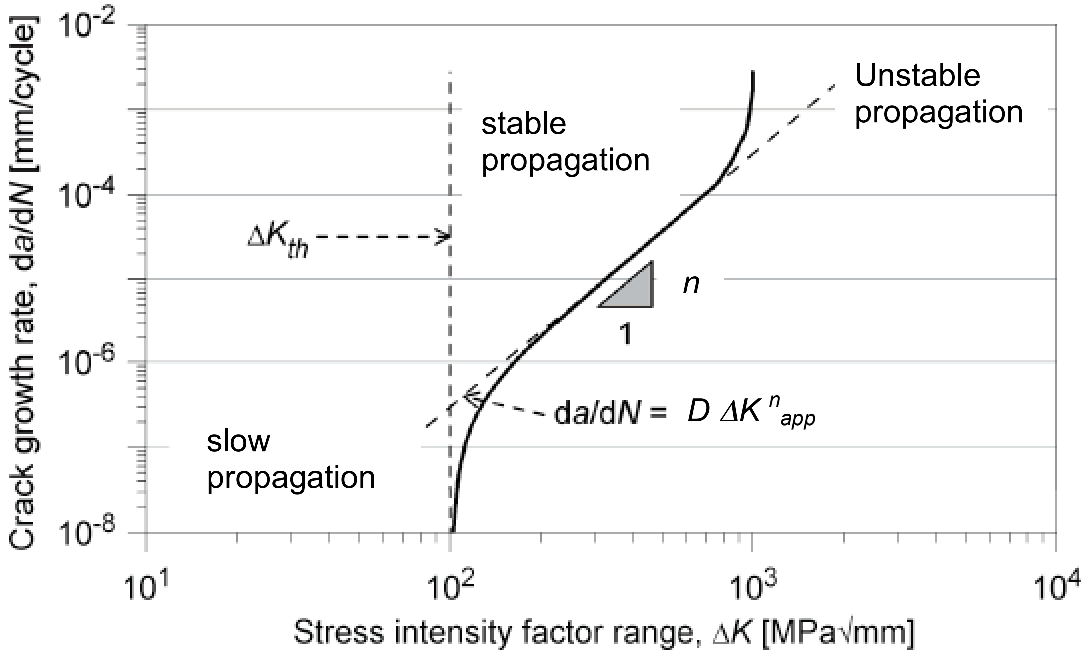


Figure 14 : Fatigue crack propagation

4.2. Crack closure

Crack closure under cycling loading was first discussed by Elber [Elber 1970] during studies on the behavior of aluminum, and he introduced the so-called Elber ratio, U, not much used anymore. It was assumed before Elber that a crack could only be closed under compressive stresses, but he showed it could also stay closed under tensile stresses. This « plasticity induced closure » results from the presence of plastic deformation (band of stretched material) left in the wake of the growing crack, but can also result from the residual stress field in the wake and ahead of the crack tip. To use this concept, lets start with the simple case where there are no residual stresses ad lets define the total stress intensity factor, K_{tot}, as follows:

$$K_{tot} = K_{app} + K_{pl} \qquad (10)$$

Wherein :

K_{pl} is the crack closure stress intensity factor, i.e. the SIF due to the theoretical stresses that must be present (according to [Elber 1970]) to cause the crack to be closed at stress levels less than the opening stress, σ_{op}

In order that $K_{tot} = 0$ at an applied stress level of $\sigma_{app} = \sigma_{op}$, the following must be true:

$$K_{op} = -K_{pl} \qquad (11)$$

K_{op} crack opening stress intensity factor, i.e. the SIF due to the theoretical stresses present as the crack tip opens upon loading (or closes upon unloading)

A number of researchers have proposed empirical equations for K_{pl}. The following equation, proposed in [Bremen 1989], is given here for its general validity for structural steels :

$$K_{pl} = -MIN\left(\frac{0.2}{(1-R)};0.28\right)\cdot K_{app,\max} \qquad (12)$$

To consider the effects of crack closure when computing crack propagation rate, the applied stress intensity factor range, ΔK_{app} in Equation (8) can be replaced with the effective SIF range, ΔK_{eff} to better describe the crack fatigue process. Since ΔK_{eff} is function of the crack opening stress intensity factor value, one can express it as follows :

$$\begin{aligned} \Delta K_{eff} &= K_{app,\max} - K_{op} \quad if \quad K_{op} > K_{app,\min} \\ &= K_{app,\max} - K_{app,\min} \quad if \quad K_{op} \le K_{app,\min} \end{aligned} \tag{13}$$

wherein:

$K_{app,max}$ is the maximum applied stress intensity factor (= $K_t \cdot Y \cdot \sigma_{\max} \cdot \sqrt{\pi \cdot a}$)
$K_{app,min}$ is the minimum applied stress intensity factor (= $K_t \cdot Y \cdot \sigma_{\min} \cdot \sqrt{\pi \cdot a}$)

Furthermore, including the slow propagation case through the threshold ΔK_{th}, this results in the following revised expression for the fatigue life, N_c:

$$N_c = \int_{a_0}^{a_c} \frac{da}{D \cdot \left(\Delta K_{eff}^n - \Delta K_{th}^n \right)} \tag{14}$$

As discussed in section 3.3 residual stress-based treatment methods such as needle peening are thought to work primarily by introducing compressive residual stresses near the surface of the treated detail, which have the effect of reducing crack growth rates in the early part of the *stable growth* phase of the total fatigue life. These methods work by reducing the effective SIF range, ΔK_{eff}, in a manner similar to that of the theoretical stresses due to crack closure (this is demonstrated in Figure 15 for a case wherein the minimum applied SIF, $\Delta K_{app,min}$, is smaller than the crack opening SIF, K_{op}). Thus, the influence of the residual stress distribution on the rate of crack propagation can be considered by redefining K_{op} as follows:

$$K_{op} = -\left(K_{res} + K_{pl} \right) \tag{15}$$

wherein K_{res} is the SIF due to the residual stress distribution, calculated as follows:

$$K_{res} = K_{t,res} \cdot Y \cdot \sigma_{res} \cdot \sqrt{\pi \cdot a} \tag{16}$$

In this expression, Y is the same as in the previous expressions for K (see Equation (7)) for a given plate thickness and crack geometry. The parameter K_t will not be the same however, since different stress distributions are implicated. Thus, $K_{t,app}$ and $K_{t,res}$ must be calculated separately. When considering residual stresses, Equation (12) for K_{pl} can be revised as follows:

$$K_{pl} = -MIN\left(\frac{0.2}{\left(1 - R_{eff}\right)} ; 0.28 \right) \cdot \left(K_{app,\max} + K_{res} \right) \tag{17}$$

wherein R_{eff} is the effective stress ratio, defined as follows:

$$R_{eff} = \frac{K_{app,\min} + K_{res}}{K_{app,\max} + K_{res}} \tag{18}$$

Once K_{pl} is calculated, K_{op} can be determined using Equation (15) and then ΔK_{eff} determined using Equation (13). Crack propagation calculations can then proceed using Equation (14).

4.3. Behavior of details improved by post-weld peening methods

The behavior of post-welded improved joint can be explained using either stress superposition, as it was done in Figure 5 (but for high tensile residual stresses) or using the concept of ΔK_{eff} presented in the previous section. Note that the influence of compressive residual stresses will be opposite to the influence presented in Figure 5, i.e. it will be dependent upon the R-ratio and increase fatigue lives even under tensile applied loads.

Using the concept of ΔK_{eff}, Figure 15 shows in a graphical way the influence of the compressive residual stresses due to post-weld treatment. In the upper part of the figure, the case as-welded is presented, i.e. where large tensile residual stresses are present and no crack closure occurs, the R-ratio has no influence.

In the lower part of the figure, the case with the compressive residual stresses due to the post-weld treatment, thus inducing crack closure, is shown. One sees that crack closure correspond to a decrease in the SIF range, thus resulting in a decrease in the crack propagation rate.

If the residual stress distribution due to post-weld treatment is known, studies have shown that the fatigue lives of single treated or untreated potential crack sites can be predicted reasonably well using an LEFM-based model such as the one described above. Post-weld treatment methods such as needle peening are proven to work primarily by introducing compressive residual stresses. They have the effect of reducing crack propagation rates in the early part of the stable propagation phase of the total fatigue life, as shown below.

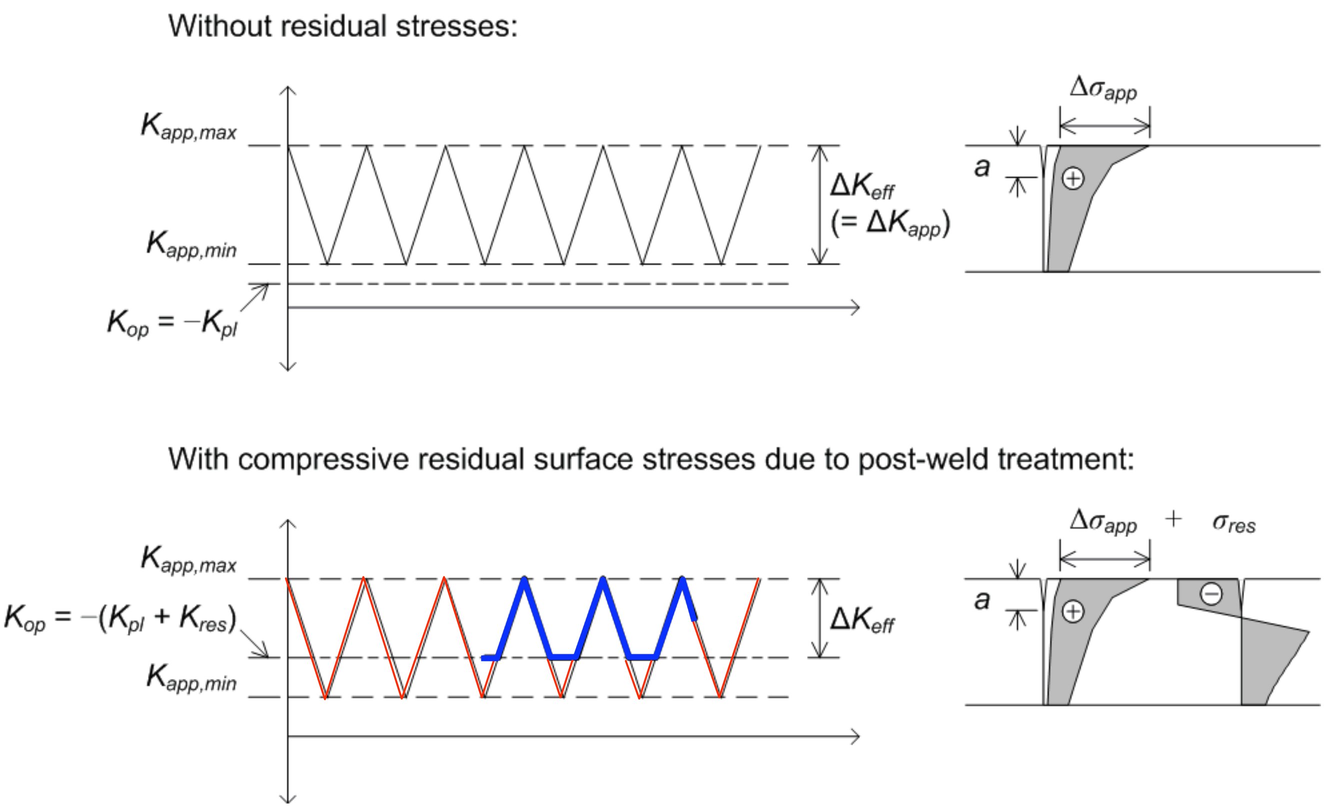


Figure 15: Effect of residual stresses due to post-weld treatment on ΔK_{eff} (for the case of $K_{op} > K_{app,min}$).

In Figure 16, the influence of the post-weld treatment on the SIF ranges and crack propagation are illustrated in an example [Walbridge 2005] of a detail under tension loading, treated by needle peening. The left part of the figure shows the depth over which the SIF range is reduced by the PWT, that is around 2 mm in this case. The right part of the figure shows how this translate into the propagation of the crack and the significant fatigue life increase due to the PWT.

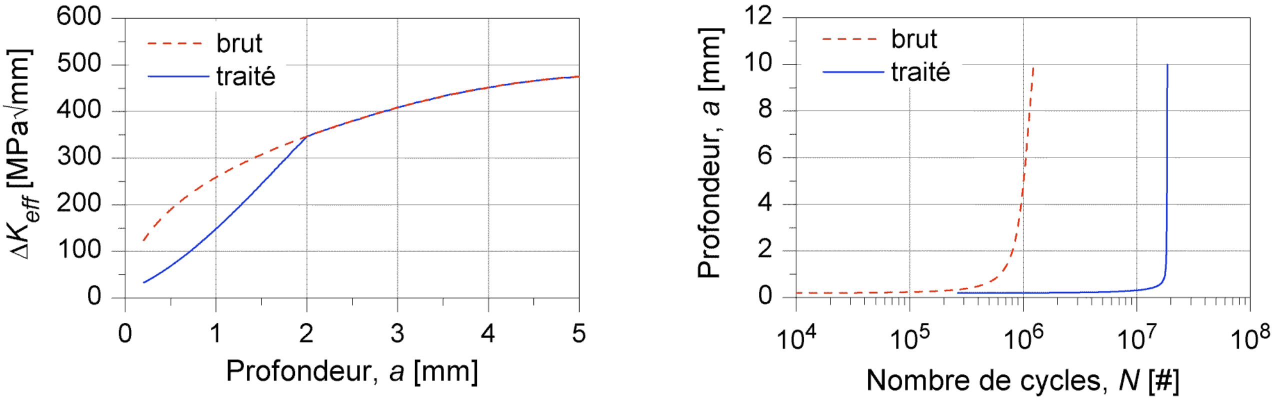


Figure 16 : SIF range plot (left) and crack propagation plot (right).

Other effects of post-weld treatment, such as the possible smoothing of the discontinuity at the weld toe (i.e. introduction of a weld toe or notch radius, $\rho > 0$), the potentially detrimental introduction of small notch-like dents, the potentially beneficial flattening and aligning of the surface grains, the increase in toughness of the surface layer etc., all have an influence on the fatigue life of welded details that can be assumed to either be negligible or small but beneficial. A significant basis of the current work is that these assumptions are true, if not always, then at least in all cases where proper care and quality control is exerted during the treatment process.

4.4. Concept of effective stress

As seen in the previous section, the fatigue strength benefit resulting from post-weld peening methods can be modeled using fracture mechanics. To understand the influence of the R-ratio, it is interesting to try to use the same concept, but simplified, on an S-N diagram by expressing the fatigue resistance curve of an improved joint with respect to a so-called “effective stress range”, $\Delta\sigma_{eff}$, as follows :

$$\log N = \log a - m \cdot \log \Delta\sigma_{eff} \qquad (19)$$

or $$N\left(\Delta\sigma_{e}\right)^{m} = a \qquad (20)$$

The definition of $\Delta\sigma_{eff}$ is given in the next paragraph, but let’s first look again at the S-N diagram and the detail class definition. The detail class is defined as the fatigue strength at 2 millions cycles. For the improved joint, the same fatigue class as the one used for the as-welded details is adopted but using $\Delta\sigma_{eff}$ instead. However, because of lack of knowledge on the detrimental influences of variable amplitude loadings, it is safer to consider fatigue curves with a unique slope, m = 3, and without cut-off limit under variable amplitude loading. The constant amplitude fatigue limit definition can be kept (fatigue strength at 5 million cycles). An example of such an S-N curve is given in Figure 17 for longitudinal attachments (category 56).

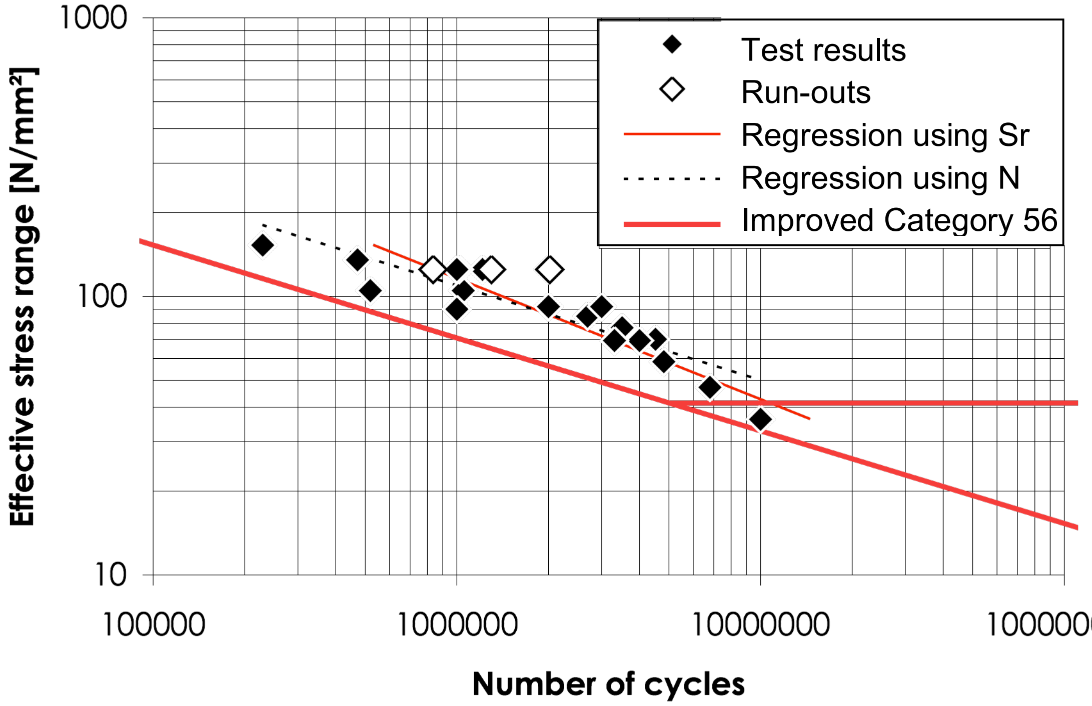


Figure 17 : S-N curve and tests results expressed in terms of effective stress range for hammer peened longitudinal attachments (l > 100 mm, as-welded category 56 according to EN1993-1-9:2005)

Effective stresses are defined as follows, with tension stress positive :

$$\sigma_{min,eff} = \sigma_{min} + \sigma_r \tag{21}$$

$$\sigma_{max,eff} = \sigma_{max} + \sigma_r \tag{22}$$

where σ_r = average level of the residual stress field (to be calibrated from analysis of test results).

The crack cannot propagate as long as $\sigma_{min,eff}$ is inferior to zero, as the crack is closed. The effective stress range $\Delta\sigma_{eff}$ can therefore be defined, with similarities with equation (13), as:

$$\begin{cases} \Delta\sigma_{eff} = \sigma_{max,eff}\,; & \sigma_{min,eff} \le 0 \\ \Delta\sigma_{eff} = \sigma_{max,eff} - \sigma_{min,eff}\,; & \sigma_{min,eff} > 0 \\ \Delta\sigma_{eff} = 0; & \sigma_{max,eff} < 0 \end{cases} \tag{23}$$

Note that in the first equation of the system, one can replace $\sigma_{max,eff}$ by an expression containing $\Delta\sigma$ and the stress ratio R only, therefore explaining the influence of R on the fatigue strength of improved joints. The third equation is here to eliminate the case where $\Delta\sigma_{eff} < 0$, which is theoretically impossible; it represents the case of an improved joint always in compression. Since it is known that excessive compressive peak stresses reduce the fatigue strength of improved joints, a modification in the R ratio definition is further introduced in order to limit the beneficial influence of the improvement in case of negative stress ratio. The new definition for the stress ratio is the following :

$$\begin{cases} R' = R; & R \ge 0 \\ R' = 0; & R < 0 \end{cases} \tag{24}$$

Introducing equations (21) and (22) into (23), and taking into account equation (24) leads to the final expression for the effective stress range :

$$\begin{cases} \Delta\sigma_{eff} = \dfrac{\Delta\sigma}{1-R'} + \sigma_r; & \sigma_{min,eff} \le 0 \\ \Delta\sigma_{eff} = \Delta\sigma; & \sigma_{min,eff} > 0 \end{cases} \tag{25}$$

The calibration of the average level of residual stress is done by reanalyzing the test data using the expressions in equations (21), (22) and (25). An example of such a reanalysis is given in Figure 17 for longitudinal attachments. For a properly chosen value of σ_r, the scatter in the data at different stress ratios is reduced and the slope of the regression S-N curve is close to m = 3. Such an analysis was made for different details and peening methods. The values found to best account for the compressive effects are given in Figure 18.

Figure 18 : calibrated levels of σ_r to be used with $\Delta\sigma_{eff}$ model developed for peening methods

Improvement method	σ_r [N/mm²]
Shot peening	-50
Multiple needle peening	-40
Hammer peening	-75

For variable amplitude loading, it has been shown that the improvement level is function of the applied spectrum, in particular of the maximum applied stresses [Dubois & Hirt 1995, Manteghi & Maddox 2004]. A method using an equivalent maximum stress $\sigma_{max,E}$ computed in a similar manner than the equivalent stress range $\Delta\sigma_E$ has been proposed [Dubois & Hirt 1995]. This method can be directly applied to our model by replacing in expression (25) $\Delta\sigma$ by $\Delta\sigma_E$ and $\sigma_{min,eff}$ by $\sigma_{max,E}$- $\Delta\sigma_E$+ σ_r. These expressions are however not yet used in any code and have only been validated in a limited number of cases.

4.5. Example of application

Most improved details are not included in design codes. Therefore, in order to use a higher fatigue strength than that of the as-welded detail, one has either to undertake laboratory tests or to use the international recommendations written by the International Institute for Welding (IIW). The IIW recommendations will be presented in the next section. In this section, to show a practical application of the subject of this course, the validation through testing of improved longitudinal attachments for a railway bridge is presented.

The case presented is the railway bridge at Zurich/Wipkingen, Switzerland. For that bridge, higher fatigue resistances than those given in the Swiss Code were required because high strength steel S460 had to be used in order to limit the bridge girder height. The EPFL, Lausanne, was commissioned to establish the fatigue classes of the improved longitudinal as well as other details.

Handouts of the summary of the study carried [Imhof & Nussbaumer 2001] are given to the students. The study is presented in class and discussed with the students.

5. Design rules using post-weld improvement methods

5.1. Introduction

In order to take into account for both the improvement in the geometry and the introduction of an initiation phase due to the post-weld improvement methods (grinding, dressing and peening methods), the simplest way would be to reuse the existing set of fatigue categories. Most studies on improved methods have kept the concept of the applied stress range, $\Delta\sigma$. The problem with this approach is that when doing the statistical analysis of the test results, one may find that the slope coefficients differ from the usual fatigue slope coefficient 3, which is not surprising (recall the S-N curves shown in Figure 7 and Figure 9). Furthermore, for peening methods, several S-N curves are needed for each detail class because the fatigue strength is in these cases R ratio dependent. Two approaches do exist :

- Use the effective stress range concept presented in section 4.4. With this concept, only one S-N curve in effective stress range, $\Delta\sigma_{eff}$, is needed since it is equivalent to a family of curves in $\Delta\sigma$. When performing this transformation, it can be seen from equation (25) that there is no more benefits for high stress range and high stress ratios ($R \geq 0.5$), which is consistent with test results [Huther & al. 1996]. It also predicts constantly varying slopes for each curve, which explains why it is nearly impossible to get a single value for the slope coefficient in regression analyses of test results.

- A reclassification, higher, in the existing set of fatigue categories. This reclassification goes with a change in the stress range definition, which becomes a function of σ_{max} and R, but is not equivalent to the effective stress range concept. This is the approach used by Haagensen and Maddox in their IIW recommendations [Haagensen and Maddox 2004][Haagensen and Maddox 2008].

Due to its international recognition, the IIW approach is used in the following sections to provide the currently usable design rules. An upper bound for the benefit due to the best improvement methods is achieved when the fatigue strength of improved details reaches the fatigue strength of built-up sections, butt welds, etc. that is, the controlling fatigue detail will shift to another, untreated, position. When using the reclassification approach, it typically means that the best category which can be reached is the fatigue strength of longitudinal fillet welds (cat. 125).

5.2. Grinding and TIG dressing

For **burr grinding** and **TIG dressing**, the proposition from the International Institute of Welding (IIW/IIS) [Haagensen & Maddox 2008] can be summarized as follow (see Figure 20):
- Benefit only if category of as-welded joint is equal to or lower than 90.
- If yield strength is equal to or higher than 350 MPa, increase in fatigue strength by a factor 1.5, with an highest category which can be claimed of cat. 125.
- If yield strength is lower than 350 MPa, increase in fatigue strength by a factor 1.3 with, in this case, an highest category which can be claimed of cat. 100 only.

Example : when a detail being in category 63 and in steel S 460 is toe ground, the new category is found by 63x1.5 = 94.5, which gives a category, or FAT class 90 (the closest lower category existing in the set of categories).

A logical limitation, no benefit, is due to the fact that the higher categories include non-welded details, details whose lives are not governed by weld toe failure or the welds that have already been improved, e.g. by grinding the weld flush with the surface. For both improvement methods, the level of improvement is not significantly influenced by the *R* ratio ($R=\sigma_{min}/\sigma_{max}$).

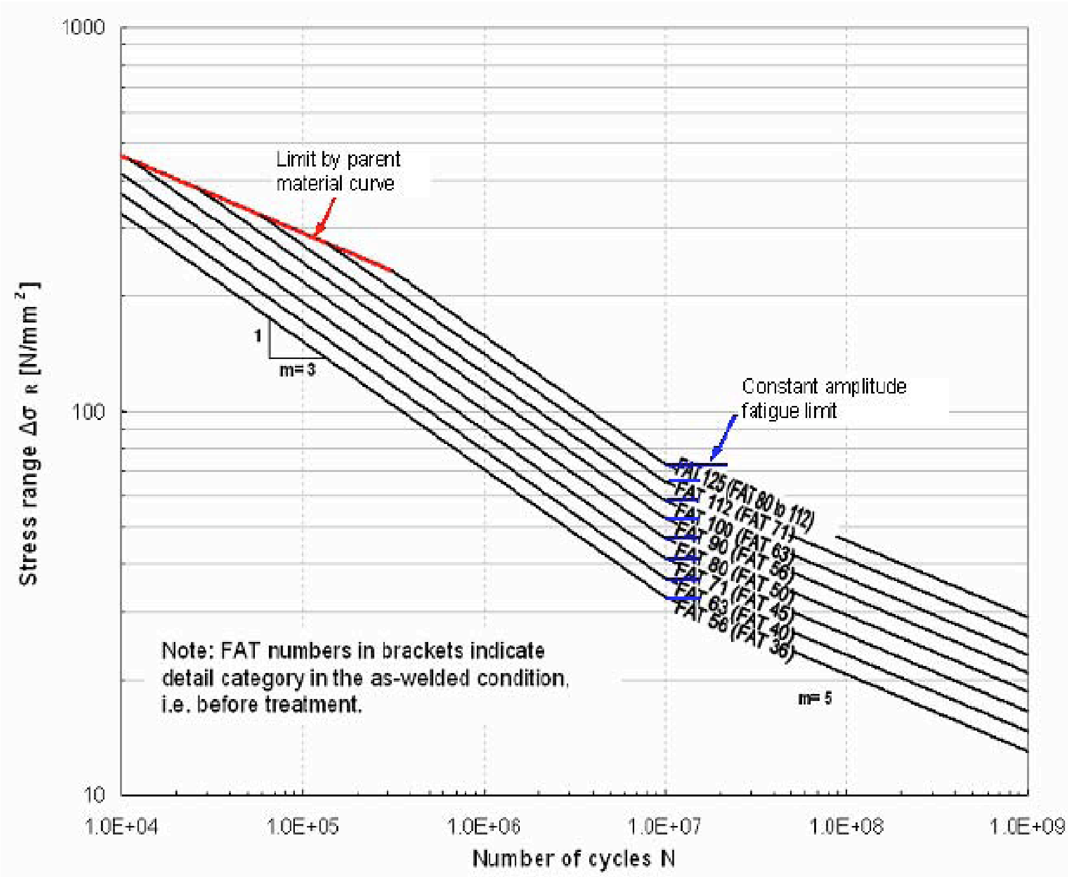


Figure 19: Design S-N curves for weld toe burr ground welds in steel structures, (extract from [Haagensen & Maddox 2008]).

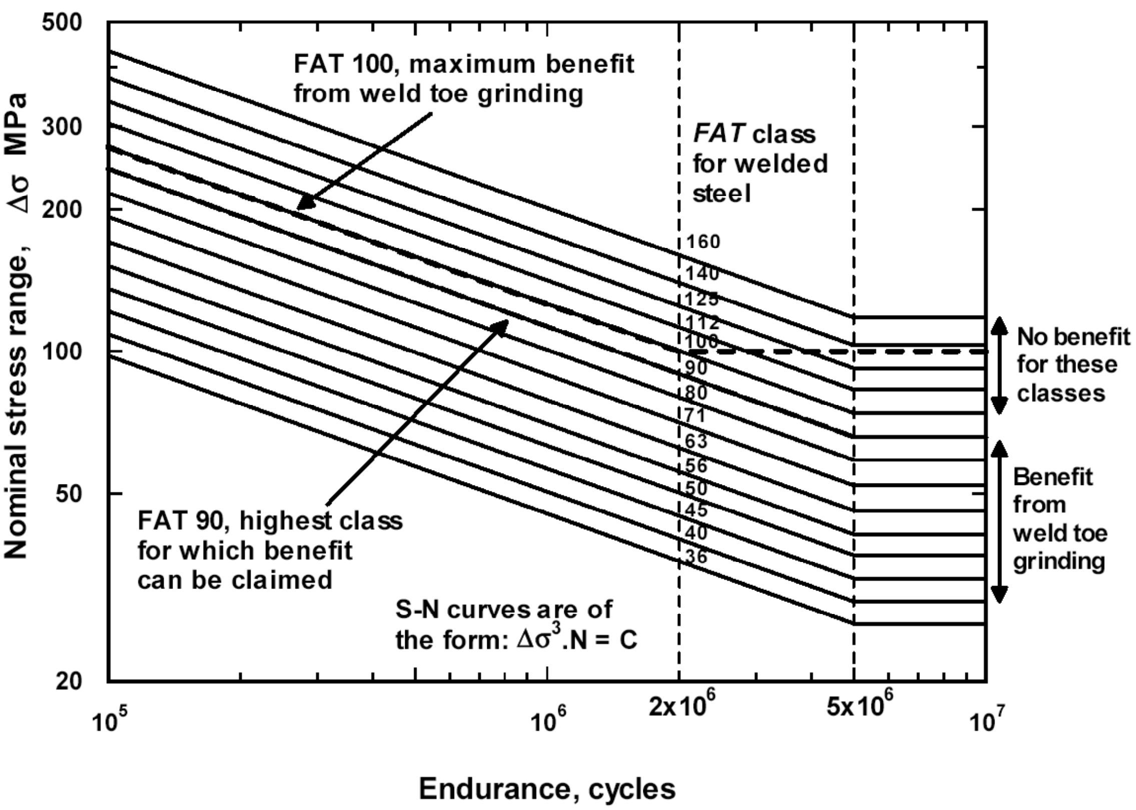


Figure 20: Design S-N curves for weld toe burr ground welds in steel structures, (extract from [Haagensen & Maddox 2004]).

Note the differences between version 2008, Figure 19 [Haagensen & Maddox 2008], and the 2004 version [Haagensen & Maddox 2008] :

- the limit set by the parent material is expicitely given in the S-N curves,
- the improved categories did not always stay the same,
- the constant amplitude fatigue limit is set at 10 millions cyles.

In the case of TIG dressing, it is interesting to compare this above proposition with the results reported by Dahle [Dahle 1998] concerning two inter-Nordic projects conducted on welded plates in high strength steels with longitudinal attachments (see Figure 21). In these projects, four steels with nominal yield strength 350, 590, 700 and 900 MPa were welded and TIG-dressed. The first two are micro-alloyed structural steels and the last two quenched and tempered low-alloyed steels. Tests on as-welded and TIG-dressed specimens were carried out under both constant and variable amplitude. Dahle found that the influence of the yield strength on the fatigue category (CAT), for design curves, can be given by the following relationship:

$$CAT_{increase} = (0.001056\, f_y + 0.65982)CAT \tag{26}$$

where f_y and CAT are in MPa.

This relationship as well as the IIW have been plotted in Figure 21. Dahle's increase seems lower, except for very high strength steels, but the reference value for the as-welded case (CAT 67) is higher than the one from the IIW recommendations (CAT 56). Therefore, when computing the category for a 350 MPa steel detail, the resulting categories are almost identical (CAT_{IIW} 73 vs CAT_{Dahle} 70). This comparison confirms the fact that high strength steels do beneficiate more from post weld improvement methods, in this case from TIG dressing.

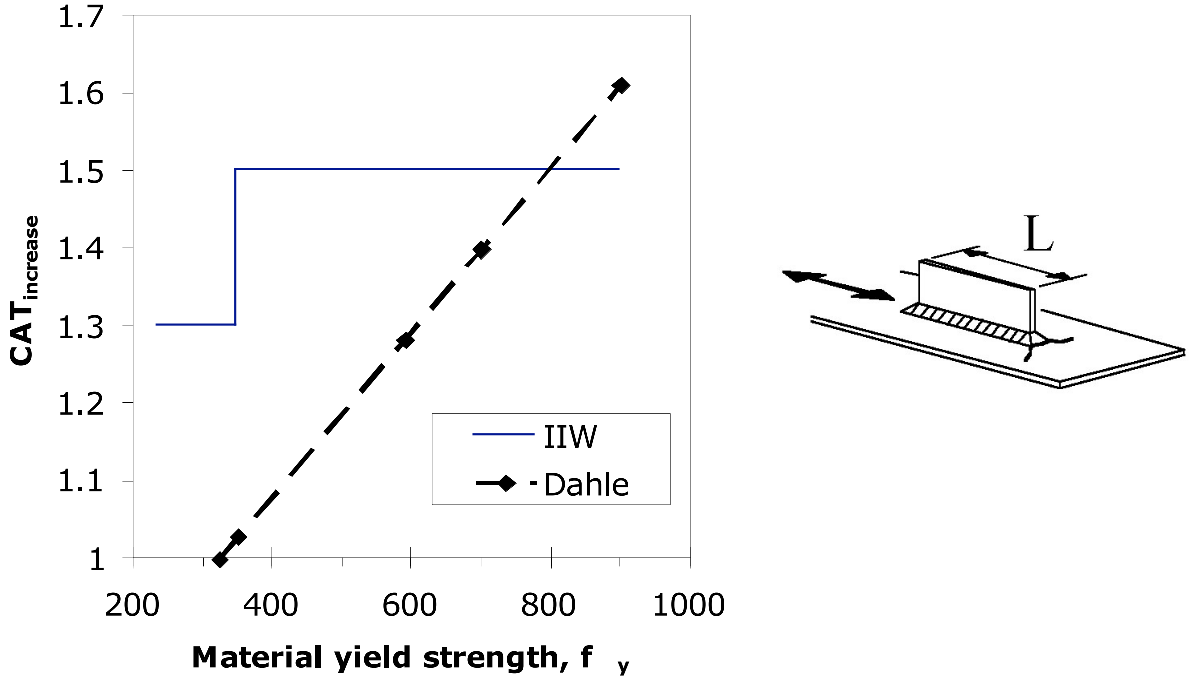


Figure 21 : Increase in fatigue category ($CAT_{increase}$) of longitudinal attachment due to TIG as a function of material yield strength.

5.3. Needle and hammer peening

For these methods, the proposition from the International Institute of Welding (IIW/IIS) [Haagensen & Maddox 2004, Haagensen & Maddox 2008] is presented. A reclassification in a higher category of the existing set of fatigue categories is made. As already said in the introduction, this reclassification goes with a change in the stress range definition, which becomes a function of σ_{max} and R, but is not equivalent to the effective stress range concept. In the IIW recommendations, the following change in the stress range definition is made :

$$\begin{cases} \Delta\sigma' = \sigma_{max}; & R \geq 0 \\ \Delta\sigma' = \sigma_{max} - \sigma_{min} = \Delta\sigma; & R < 0 \end{cases} \tag{27}$$

This change reflects the observed behavior of having lower improvements for higher stress ranges. More precisely, when R > 0, that is $\sigma_{min} > 0$, it implies that the modification in the stress range definition results in values higher than $\Delta\sigma$, thus contrebalancing the higher fatigue resistance curves used for improved details. Due to the sensitivity of hammer peened welded joints to applied mean stress (or stress ratio R), the higher S-N curves can only be used if the maximum nominal compressive stress in the load spectrum is lower than $0.25f_y$. Moreover, the stress ratio R must stay below 0.5 because under high stress ratio the compressive stresses introduced by the post weld improvement are eliminated by the applied loading.

For **hammer peening**, the proposition from the International Institute of Welding (IIW/IIS) [Haagensen & Maddox 2008] can be summarized as follows (see Figure 22):

- Benefit only if category of as-welded joint is equal to or lower than 90.
- If yield strength is lower than 350 MPa, increase in fatigue strength by a factor 1.3, with an highest category which can be claimed of cat. 112.
- If yield strength is equal to or higher than 350 MPa, increase in fatigue strength by a factor 1.6, with an highest category which can be claimed of cat. 125.
- For structural elements with thicknesses above 20 mm, the benefit for yield strengths above 350 MPa is reduced to a factor 1.5 on strength and to a highest claimable category of 100 (t > 20 mm).

The latest condition on the thickness is set because fatigue tests on large-scale structures (that is with higher tensile welding residual stresses) indicate, logically, lower benefit from hammer peening than for small-scale specimens.

For **needle peening**, the proposition from the International Institute of Welding (IIW/IIS) [Haagensen & Maddox 2008] is identical to the one for hammer peening given above.

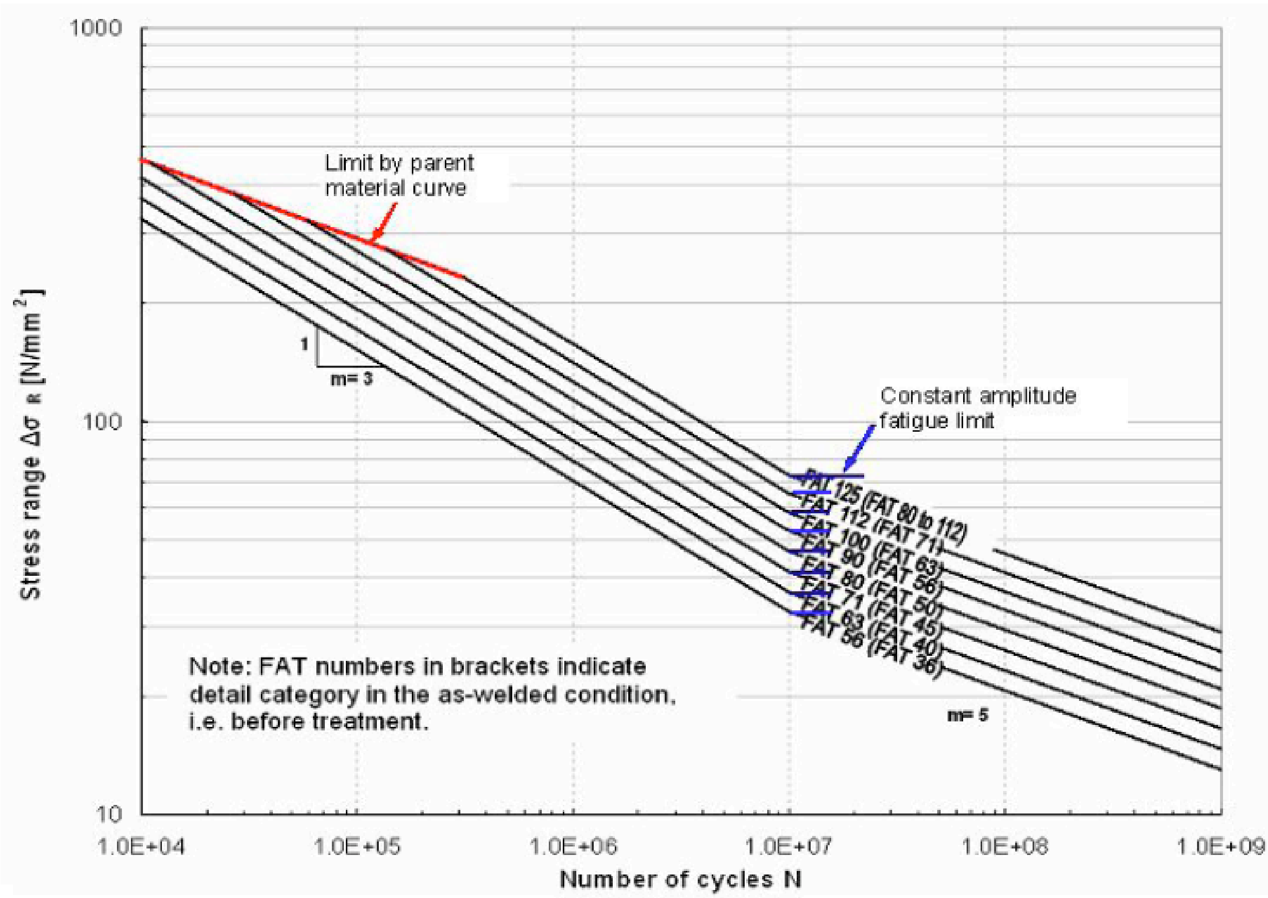


Figure 22. Design S-N curves for weld toe hammer or needle peened welds in steel structures (extract from [Haagensen & Maddox 2008]).

Finally, for **ultrasonic hammering systems**, recommendations to AASHTO where made by Roy and Fisher [Roy and Fisher 2005] and future recommendations for sign structures are in preparation in the USA [Connor 2008]. From literature [Cheng 2003, Statnikov 1997, Kudryavtsev et al. 2004, Roy and Fisher 2005], improvements on fatigue strengths are as high or higher than for hammer peening. However, validation tests before industrial application are currently needed to claim any benefit from those systems.

6. Final remarks

We learned in this lesson that improvement in fatigue strength can be achieved:

- By improving the stress flow in welded details.
- By modern welding processes and good workmanship which contribute to reduce the size of the defects to a level where the remaining defects are small notches from which the crack has to initiate.
- By increasing the crack initiation period through the reduction of surface defect adversity and size.
- By introducing compressive residual stresses in the weld toes regions after welding. The fatigue behavior is than best described by using the concept of effective stress intensity factor range or by modifying the applied stress range definition.
- Increase in fatigue strength and fatigue life can be best achieved using post-weld improvement methods, particularly for high strength steels.
- Improvement is limited by cracks starting from other locations, such as the root in a coverplate weld or internal defects (blowholes in longitudinal fillet welds).
- Fatigue strength increase is more significant for low fatigue resistance categories (typically cat. 36 to cat. 71). An upper bound for the benefit due to the best

improvement methods is achieved when the fatigue strength of improved details reaches the fatigue strength of built-up sections, i.e. the fatigue strength of longitudinal fillet welds, which is category 125.

7. Bibliography

AASHTO (2007), *LRFD bridge construction specifications*, American Association of State Highway and Transportation Officials, Washington DC, USA.

Barsom, J.M., and Rolfe, S.T. (2000), *Fracture and fatigue control in structures*, 3rd edition, Butterworth-Heiemann Publ.

Bremen, U. (1989), *Amélioration du comportement à la fatigue d'assemblages soudés : étude et modélisation de l'effet de contraintes résiduelles*, Thesis EPFL N° 787, Swiss Federal Institue of Technology, Lausanne.

Broek, D. (1991), *Elementary Engineering Fracture Mechanics*, 3rd edition, Kluwer Academic Publishers, Holland.

Cheng, X., Fisher, J.W., Prask, H.J., Gnäupel-Herold, T., Yen, B.T., and Roy, S. (2003), *Residual stress modification by post-weld treatment and its beneficial effect on fatigue strength of welded structures*, International Journal of Fatigue, Vol. 25, pp. 1259–1269.

Coffîn L. F. (1954), *A Study of the Effects of Cyclic Thermal Stresses on a Ductile Metal*, Trans. of the American Society of Mechanica Engineers, pp. 931-950.

Connor, R., Private conversation, May 2008.

Dahle, T. (1998), *Design fatigue strength of TIG-dressed welded joints in high-strength steels subjected to spectrum loading*, Int. journal of fatigue, Vol. 20, N° 9, pp. 677-681.

Dubois, V. and Hirt, M.A. (1995), *Efficacité des traitements d'amélioration sur des assemblages soudés soumis à des sollicitations d'amplitude variable*, Construction Métallique, Saint-Rémy-lès-Chevreuse, France, n° 3.

ECCS (2001), *Good design practice: a guideline to fatigue design*, publication n° 105, ECCS, Brussels.

Elber, W. (1970), *Fatigue Crack Closure under Cyclic Tension*, Engineering Fracture Mechanics, Vol. 2, pp. 37-45.

EN 1011-2 : 2001, *Welding – Recommendations for welding of metallic materials – Part 2: Arc welding of ferritic steels*, CEN, Brussels, 2001.

EN 1993-1-9 : 2005, *Eurocode 3 : Design of steel structures, Part 1.9: Fatigue*, CEN, Brussels.

EN 10025 : 2004 (in 6 parts), *Hot-rolled structural steels products, technical delivery condition*s, CEN, Brussels.

Fisher, J. W., Nussbaumer, A.C., Keating, P.B. and Yen B.T. (1993), *Resistance of Welded Details under Variable Amplitude Long-Life Fatigue Testing*, National Cooperative Highway Research Program (NCHRP) Report 354, Highway Research Board, Washington, D.C.

Gurney, T.R. (1979), *Fatigue of welded structures*, 2nd Ed., Cambridge University Press, Cambridge.

Haagensen, P.J. (1997), *Fatigue of tubular joints and fatigue improvement methods*, in Progress in structural engineering and materials, Vol.1 , N° 1, sept. 1997

Haagensen, P.J., and Maddox, S.J. (2004), *IIW Recommendations on Post Weld Improvement of Steel and Aluminum Structures*, IIW commission XIII Working Group 2, Doc. IIW XIII-1815-00, revised 5 July 2004.

Haagensen, P.J., and Maddox, S.J. (2008), *IIW Recommendations on Post Weld Improvement of Steel and Aluminum Structures*, IIW commission XIII Working Group 2, Draft Doc. IIW XIII-2200-07, revised March 2008.

Hirt, M. A., Bez, R., and Nussbaumer, A. (2006), *Construction Métallique : Notions fondamentales et méthodes de dimensionnement*, nouvelle édition revue et adaptée aux nouvelles normes de structures. Traité de Génie Civil, Volume 10, PPUR, Lausanne, Switzerland.

Huther, I., Lieurade, H.P., Souissi, R, Nussbaumer, A., Chabrolin, B., and Janosch, J.-J. (1996), *Analysis of results on improved welded joints*, Welding in the world, 37(5), pp. 242-266.

Imhof, D., Nussbaumer, A. (2001), *On the Practical Use of Weld Improvement Methods*, Progress in Structural Engineering and Materials, Wiley Interscience, Vol. 3, N° 1, pp. 95-105.

Irwin, G.R. (1957), *Analysis of Stresses and Strains near the End of a Crack Traversing a Plate*, Journal of Applied Mechanics, Vol. 24, pp. 361-364.

Kirkhope, K.J., Bell, R., Caron, L., Basu, R.I., & Ma, K.-T. (1999), *Weld detail fatigue life improvement techniques – Part 1: review*. Marine Structures, Vol. 12, pp. 447-474.

Kudryavtsev, Y., Kleiman, J., Lobanov, L., Knysh V. and Prokopenko, G. (2004), *Fatigue Life Improvement of Welded Elements by Ultrasonic Peening*, International Institute of Welding, IIW Document XIII-2010-04, 20 p.

Maddox, S.J. (1991), *Fatigue strength of welded structures*, Abington Publishing, UK (3rd edition, CRC Press, 2005).

Mang, F., Bucak, Ö., and Stauf, H. (1991), *Fatigue Behavior of Welded Hollow Section Joints and their Connections Made of High-Strength Steels*, Research report, Testing Center for Steel, Timber and Stone, University of Karlsruhe.

Manson S. S. (1954), *Behavior of Materials under Conditions of Thermal Stresses*, National Advisory Commission on Aeronautics : Report 1170, Cleveland, Lewis Flight Propulsion Lab.

Manteghi, S. and Maddox, S.J. (2004), *Methods for fatigue life improvement of welded joints in medium and high strength steels*, International Institute of Welding, Doc. XIII-2006-04.

Miki, C., Homa, K., and Tominaga, T. (2002), *High strength and high performance steels and their use in bridge structures*, Journal of constructional steel research, 58, pp. 3-20.

Nussbaumer, A. (1996), *Etablissement de courbes de fatigue pour les assemblages parachevés*, Construction Métallique, Saint-Rémy-lès-Chevreuse, France, n° 1, pp. .

Otha, A., Suzuki, N., and Maeda, Y. (1996), *Effective means for improving the fatigue strengths of welded structures*, Welding in the World, Vol. 37, no 2, march-april, pp. 84-89.

Paris, P. & Erdogan, F. (1963), *A Critical Analysis of Crack Propagation Laws*, Transactions of the ASME, Series D, Vol. 85, No. 4, pp. 528-534.

Roy, S., and Fisher, J.W. (2005), *Enhancing Fatigue Strength by Ultrasonic Impact Treatment*, International Journal of Steel Structures, vol. 5, pp. 241-252.

SED n° 8 (2004), *Use and application of high performance steels (HPS) for steel structures*, Structural Engineering Document n° 8, IABSE, Zurich.

Stacey, A., Barthelemy, J.-Y., Leggatt, R.H., & Ainsworth, R.A. (2000), *Incorporation of Residual Stresses into the SINTAP Defect Assessment Procedure*. Engineering Fracture Mechanics, Vol. 67, pp. 573-611.

Statnikov, E.S. (1997), *Applications of operational ultrasonic impact treatment (UIT) technologies in production of welded joints*, International Institute of Welding, IIW Doc. XIII-1667-97.

Statnikov, E. (2005), *Improvement in Quality and Reliability of Structures by Means of Esonix UIT*, Presented in Commission XIII, 58th Assembly of the International Institute of Welding, Prague, Czech Republic.

Stephens, R. I. et al. (2001), *Metal fatigue in Engineering*, 2nd Edition, John Wiley & Sons, New York.

Walbridge S. (2005), *A probabilistic study of fatigue in post-weld treated tubular bridge structures*. EPFL Thesis No. 3330, Lausanne (download : icom.epfl.ch/publications).

Annex: list of books on fracture mechanics and fatigue of structures

	Title	Authors	Details	Edition	ISBN
	**Advanced Fracture Mechanics**	Melvin F. Kanninen, Carl H. Popelar	Hardcover, 576pp; Oxford University Press	June, 1985	195035321
	**Elementary Engineering Fracture Mechanics**	David Broek	540 pages • Kluwer Academic Publishers	December, 1982	9024726565
	**Fatigue and Fracture (Asm Handbook)**	Steven R. Lampman	• Hardcover: 1057 pages • ASM International	January 1, 1997	871703858
	**Fatigue Assessment of Welded Joints by Local Approaches**	D. Radaj, C. M. Sonsino and W. Fricke	• Hardcover: 660 pages • Woodhead Publ. Limited	October, 2006	1 85573 948 8
	**Fatigue of Structures and Materials**	Jaap Schijve	• Paperback: 536 pages • Kluwer Academic Publishers	August 1, 2001	792370147
	Fatigue Strength of Welded Structures	S. J. Maddox	Hardcover, CRC Press	3rd edition (October 1, 2005)	849317746
	**Fracture and Fatigue Control in Structures**	John M. Barsom, Stanley T. Rolfe	Hardcover, 548pp; Butterworth-Heinemann	3rd edition January 2000	075067315X
	**Fracture Mechanics: Fundamentals and Applications, Second Edition**	T.L. Anderson	• Hardcover: 88 pages • CRC Press;	2nd edition (December 16, 1994)	849342600
	Fretting Fatigue	R.B. Waterhouse; T.C. Lindley	ESIS Publication 18	1994	0852989407
	**Metal Fatigue in Engineering**	R. I. Stephens, A. Fatemi, R. R. Stephens, H. O. Fuchs	• Hardcover: 472 pages • Wiley-Interscience;	2 edition (December, 2000)	471510599
	**Principles of Fracture Mechanics**	R. J. Sanford	Hardcover: 404 pages Prentice Hall;	1st edition (March 29, 2002)	130929921
	**Problems of Fracture Mechanics and Fatigue: A Solution Guide**	E. E. Gdoutos, C. A. Rodopoulos, J. R. Yates	• Hardcover: 570 pages • Kluwer Academic Publishers	December 1, 2003	1402017596
	**Stress Intensity Factors and Weight Functions (Advances in Fracture Mechanics Vol 1)**	T. Fett, D. Munz	• Hardcover: 385 pages • Computational Mechanics, Inc.	January 1, 1997	1853124974
	Stress Intensity Factors Handbook	Y. Murakami	Hardcover, 3100 pages, Elsevier Science & Technology Books	September 2001	80440436
	**The Practical Use of Fracture Mechanics**	David Broek	Paperback 522 pages • Kluwer Academic Publishers	July 1989	792302230
	**The Stress Analysis of Cracks Handbook**	Hiroshi Tada, P. C. Paris, George Rankin Irwin	• Hardcover: 696 pages • American Society of Mechanical Engineers;	3rd edition (February 1, 2000)	791801535
	**Time-Dependent Fracture Mechanics (Mechanical Engineering Series (Berlin, Germany))**	Dominique P. Miannay	Hardcover: 420 pages Springer Verlag	August, 2001	387952128