Structural Engineering Document

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Use and Application of High Performance Steels (HPS) for Steel Structures

Extract, chapter 5.4

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5.4 Improving the fatigue resistance

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5.4.1 Introduction

High strength steels are intended for structures subjected to high stress levels to create lighter and more slender structures. But, 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 the fatigue resistance does not increase in the same manner as the steel tensile strength. For the details located in the critical sections, i.e. that cannot fulfill the 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 objective of this section is to provide practical information on these solutions, with an emphasis on post-weld improvement methods.

To explain why the fatigue resistance does not increase in the same manner as the tensile strength, one can take advantage of the analytical modeling of fatigue failure. Fatigue failure can be separated in the following two different phases:

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 of 0.5 to 1 mm are often considered.

2 Crack propagation: the presence of the crack creates a stress concentration 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 continues to propagate until a critical size corresponding to the instability of the cracked element is reached.

Crack initiation fatigue life is highly dependant upon material characteristics, as shown by the parameters in the Manson-Coffin relationship [5.20]. 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, is independent of mechanical properties. Thus, total fatigue life and the relative importance of the initiation versus the propagation fatigue life depends on the presence of defects which, according to their size and shape, reduce or suppress the initiation period.

In machined steel parts, 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). This is reflected in most structural codes, for example Eurocode 3 [5.21]. 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, as mentioned in section 5.1 and [5.22]. 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 some studies, for example [5.23], [5.24], show a better fatigue resistance for welded high strength steels elements.

Finally, fatigue life is also influenced by the fracture toughness of the material (see also section 5.2). In this respect, thermo-mechanical steels (TM steels, often called “low alloy steels”, according to EN 10113, Part 3 [5.25]), are very interesting. TM steels have excellent toughness properties, with values higher than 50 J at -20°C (or even lower temperatures). This results in longer allowable crack sizes in components. This means a longer crack growth period (extended lifetime), less frequent inspection intervals and cracks that are easier to detect. Furthermore, because of lower carbon content, preheating before welding can be reduced or even omitted in the case of TM steels. All these aspects have a significant economic impact and make TM steels very competitive [5.26].

5.4.2 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 [5.27]. In order to get better fatigue strength 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.
- 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.

5.4.3 Welding Procedures and Workmanship

As said in the introduction, the requirements (steel fabricator, supervisor, welder) for welding high strength steels are set higher, which should help getting structures with better fatigue strength. This is however not sufficient and it also requires state of the art production processes (see section 5.1). 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 [5.28] 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 [5.27].

For improving the fatigue strength, new developments such as low temperature transformation welding material may also be considered (see section 4.5).

5.4.4 Post-Weld Improvement Methods

The methods consisting in treating the **weld toe regions** of a joint after welding have been studied by various industries, in particular the offshore industry [5.29]. Large databases of test results can be found in the literature, for example [5.30]. These post-weld improvement methods influence, within certain limits, beneficially the fatigue strength of the improved joint. 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 we will only deal with four of them, which are among the most popular ones, that is :

1 Grinding;

2 Tungsten Inert Gas (TIG) dressing of the weld toe;

3 Needle peening;

4 Hammer peening.

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

- Reduction of local stress concentrations;
- Creation of a crack initiation phase;
- Alteration of the residual stress field of the superficial layer.

Consequently, the improvement methods can be divided into two distinct groups :

1 Methods which smoothen the weld bead-base plate transition (parameter 1) and eliminate the surface defects (parameter 2), that is methods A and B;

2 Methods which change tensile residual stresses into compressive stresses around locations of potential fatigue cracks (parameter 3), that is methods C and D. Note that in some cases these methods can also smoothen the weld-plate transition but this is not their primary intended goal.

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 Fig. 5.4.1. As can be seen, the fatigue class of the improved detail is raised by both the translation and the rotation. 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.

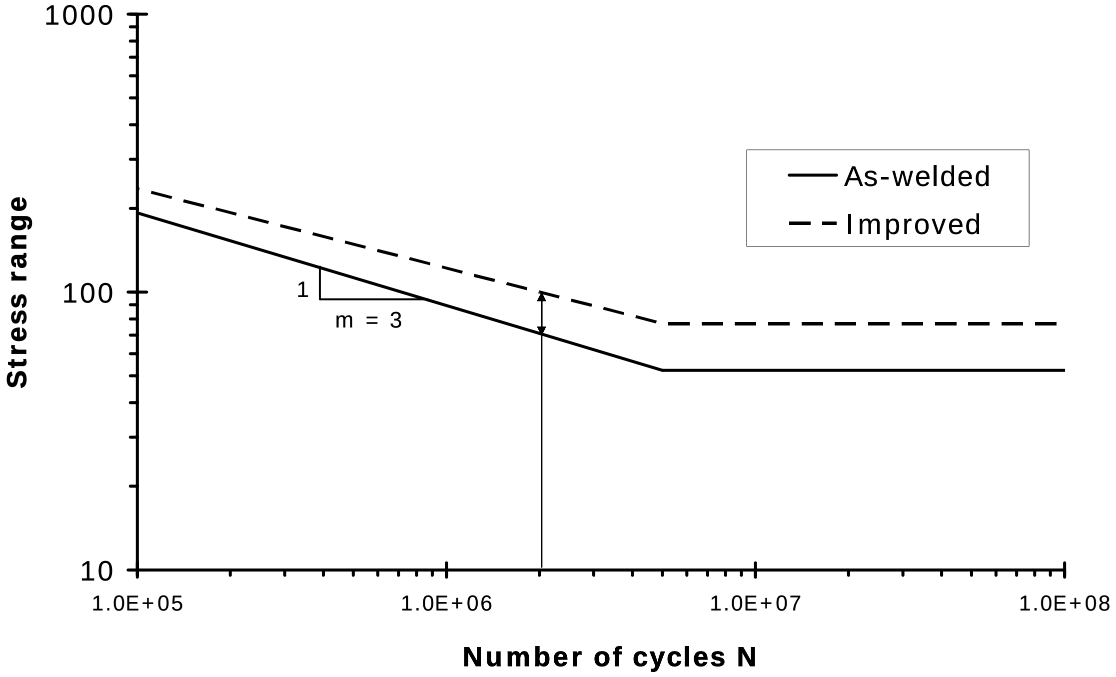

Fig. 5.4.1: Influence of the use of an improvement method on the S-N curve of a welded joint

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 [5.29]. 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.

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 [5.31]. These cover steels with yield strength up to 900 MPa, including austenitic steels, and will serve as a basis in the next paragraphs. The reader is referred to these recommendations for equipment, procedures, inspection and quality control criteria.

5.4.4.1 Grinding and TIG Dressing

In order to take into account for both the improvement in the geometry and the introduction of an initiation phase due to the improvement method, the simplest is to use the existing set of existing fatigue categories. Unfortunately, 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 (see Fig. 5.4.1). Currently, it is difficult to justify a different slope coefficient for each improved joint fatigue curve. Therefore, the fatigue curves for improved joints are simple translations from the as-welded code curves, that is without change in the slope coefficient.

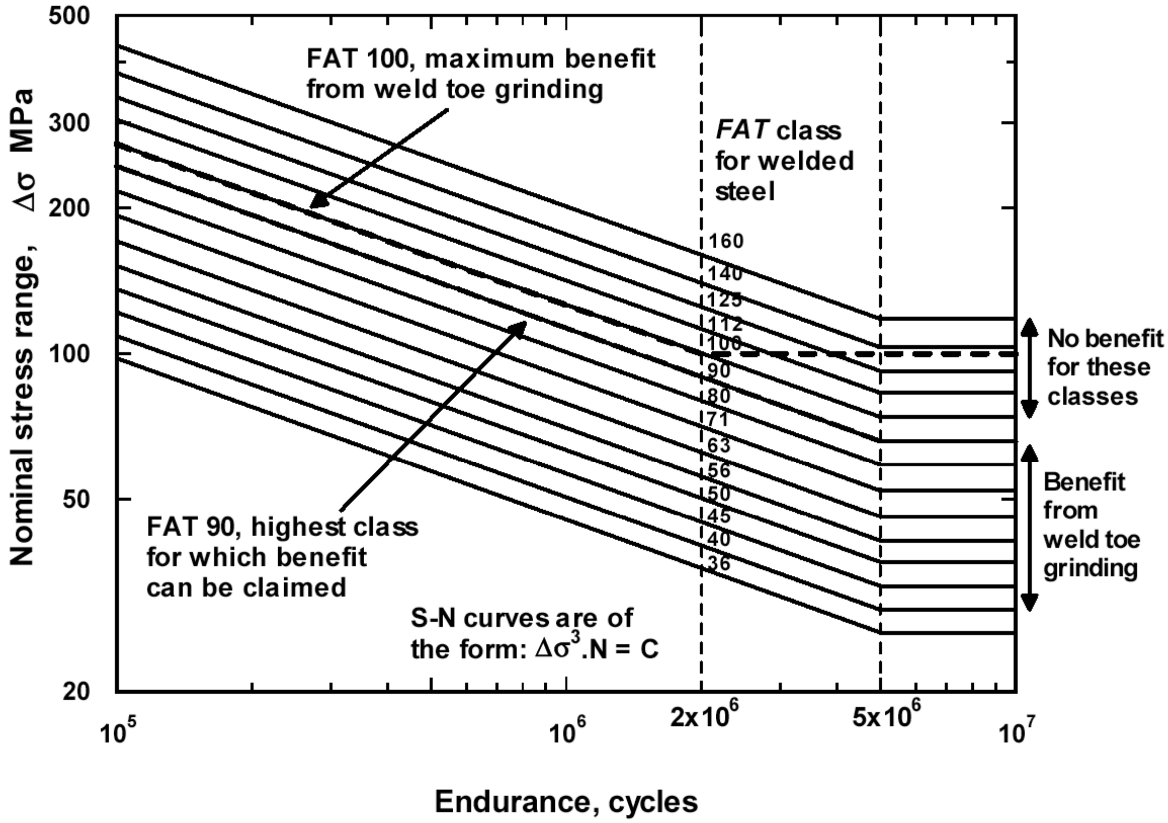

Fig. 5.4.2: Design S-N curves for weld toe burr ground welds in steel structures, (extract from [5.31])

For **burr grinding**, the proposition from the International Institute of Welding (IIW/IIS) [5.31] can be summarized as follow (see Fig. 5.4.2):

- 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 up to a maximum of category 100.
- If yield strength is equal to or higher than 350 MPa, increase in fatigue strength by a factor 1.5 up to a maximum of category 100.

The first limitation 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.

In the case of **TIG dressing**, the proposition is very similar, and can be summarized as follows:

- 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 up to a maximum of category 112.
- If yield strength is equal to or higher than 350 MPa, increase in fatigue strength by a factor 1.5 up to a maximum of category 112.

For both improvement methods, the level of improvement is not significantly influenced by the R ratio ($R = \sigma_{min}/\sigma_{max}$).

In the case of TIG dressing, it is interesting to compare this above proposition with the results reported by Dahle [5.32] concerning two inter-Nordic projects conducted on welded plates in high strength steels with longitudinal attachments (see Fig. 5.4.3). 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:

$$CAT_{increase} = \left(0.001056\, f_y + 0.65982\right) CAT \tag{1}$$

where f_y and CAT are in MPa.

This relationship as well as the IIW have been plotted in Fig. 5.4.3. 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 in 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).

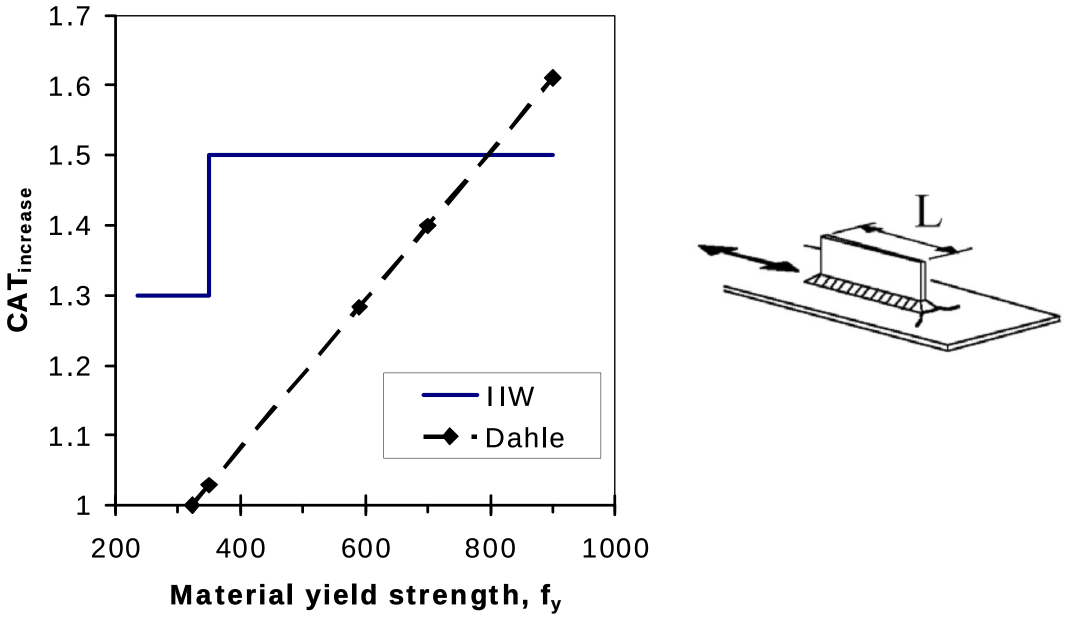

Fig. 5.4.3: Increase in fatigue category ($CAT_{increase}$) of longitudinal attachment due to TIG as a function of material yield strength

This comparison confirms the fact that high strength steels do beneficiate more from post weld improvement methods, in this case from TIG dressing.

5.4.4.2 Needle and Hammer Peening

Most studies on improved methods have kept the concept of the applied stress range, $\Delta\sigma$. The problem with this approach is that several S-N curves are needed for each detail class because the fatigue strength is R ratio dependent. Therefore, the definition of the stress range has to be modified. In the IIW recommendations, the following change in the stress range definition is made :

$$\begin{cases} \Delta\sigma' = \sigma_{max}; & R \geq 0 \\ \Delta\sigma' = \sigma_{max} - \sigma_{min} = \Delta\sigma; & R < 0 \end{cases} \tag{2}$$

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 0.25 fy. 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) [5.31] can be summarized as follows (see Fig. 5.4.4):

- 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 up to a maximum of category 125.
- If yield strength is equal to or higher than 350 MPa, increase in fatigue strength by a factor 1.6 up to a maximum of category 125.
- For structural elements with thicknesses above t = 20 mm, the benefit is reduced to a factor 1.5 on strength and to a maximum of category 100.

The latest condition was set because fatigue tests on large-scale structures indicate lower benefit from hammer peening than for small-scale specimens.

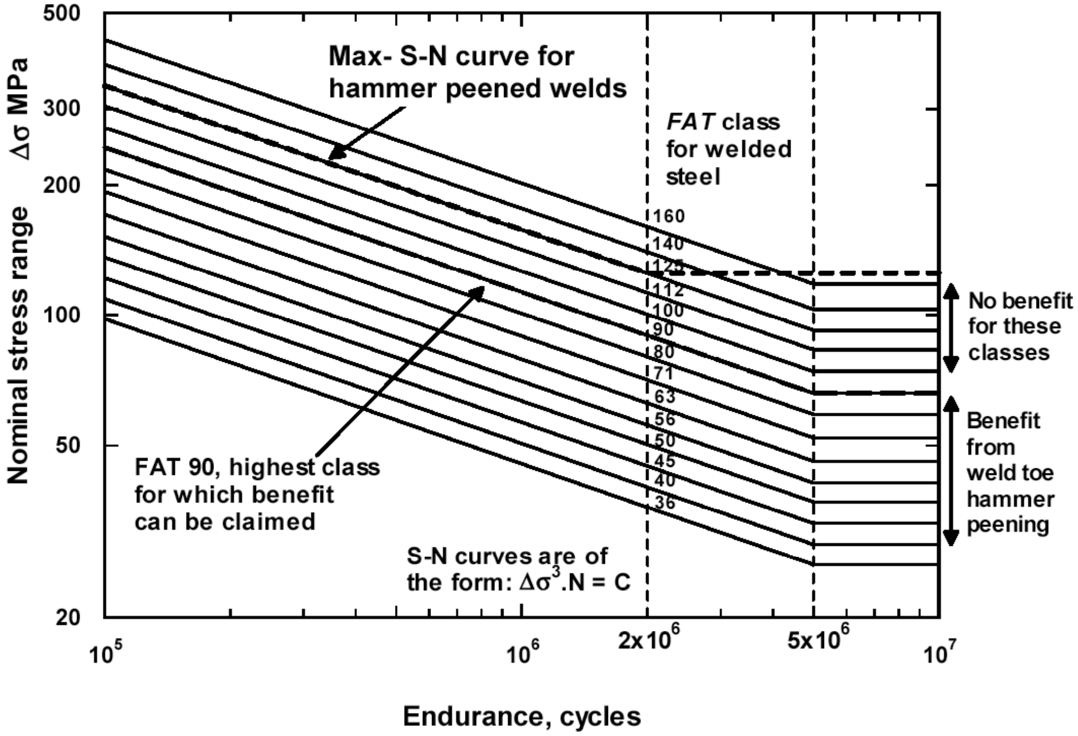

Fig. 5.4.4: Design S-N curves for weld toe hammer peened welds in steel structures (extract from [5.31]).

For **needle peening**, the proposition from the International Institute of Welding (IIW/IIS) [5.31] is identical to the one for hammer peening and can be summarized as follow:

- 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 up to a maximum of category 125.
- If yield strength is equal to or higher than 350 MPa, increase in fatigue strength by a factor 1.6 up to a maximum of category 125.
- For structural elements with thicknesses above t = 20 mm, the benefit is reduced to a factor 1.5 on strength and to a maximum of category 100.

5.4.5 Conclusions

Conclusions are 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. For high strength steels, this can be best achieved using post-weld improvement methods.
- 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)
- The fatigue strength increase is more significant for low fatigue categories. An upper bound 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.

5.5 Examples and Applications

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5.5.1 Fast Bridge 48 Military Bridge, Sweden [Höglund]

5.5.1.1 General description

Fast Bridge 48 is a 48 m single-span bridge system for loads up to Military Class 70 (MLC70, approximately 64 metric tonnes) according to North Atlantic Treaty Organization (NATO) standards. The bridge is made of extra high strength steels (HPS steels S960 and S1100) and can be deployed in less than 90 minutes and retrieved in the same time from either side of a river or dry gap.

The bridge is the result of about eight years of research and development in cooperation mainly between the Swedish Defence Material Administration (FMV) and Karlskronavarvet AB. The design is patented.