On the practical use of weld improvement methods

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Summary

Many laboratory studies have shown the beneficial effects of weld improvement methods on the fatigue strength of welded details. However, no structural codes systematically include weld improvement methods in detail classification. The purpose of this paper is to discuss the possibilities of using these methods in practice on either new or existing structures. This paper provides the reader with practical rules for designing and computing the fatigue strength of improved welded joints.
A computation method based on the concept of effective stress range is introduced to model the effects of peening improvement methods on fatigue strength. For the most popular improvement methods, the fatigue strength of improved details can be deduced from the extensive existing database of full-scale test results. However, for non-classified details, or when fabrication and improvement processes require validation, testing of the improved details is the only method available to guarantee the fatigue strength of a particular detail. In this paper a recent application of validation through testing in the case of longitudinal attachments is described.

KEY WORDS: fatigue; welded structures; improvement methods; grinding; peening; large-scale testing; fabrication

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1. Introduction

It is well known that methods involving treatment of the weld toe regions of a joint after welding may influence beneficially, within certain limits, the fatigue strength of a welded joint. A short review of these methods and their effects was published in a previous issue of this journal[1]. The weld improvement methods to be considered in this paper are:

1. weld toe burr grinding
2. weld toe remelting (Tungsten inert-gas (TIG) dressing)
3. peening methods (shot peening, needle peening, pneumatic or ultrasonic hammer peening)

The beneficial influence of methods 1 and 2 can be explained by the change in bead-plate transition geometry (reduction of local stress concentration) and elimination of surface defects. The beneficial influence of the third group of methods can also be explained partially by the change in bead-plate transition geometry, however the benefits of this method are primarily a result of the compressive residual stress field in the superficial layer induced by peening methods. Thus, these methods cannot be grouped together in design recommendations as will be seen in sections 3 and 4 herein.

It must be pointed out that improvement methods must not be used to compensate for bad design or workmanship. It should also be mentioned here that not every detail can be improved. Important rules and restrictions for the use of weld improvement methods will be presented. Present knowledge and lack of experimental data on full-scale details does not allow for a valid evaluation of the influence of all variables and fabrication processes and therefore, in this paper, conservative lower bounds for the levels of improvement have been given. For example, even though higher improvement levels can be expected for high-strength steels, the levels given herein are applicable to all structural steels. If a detail has not been classified, a fabrication process has not been validated, or a higher fatigue strength for an improved detail is expected, validation through testing is the only method available to determine fatigue strength. An example of such a validation for the case of longitudinal attachments on a beam in a railway bridge structure is presented in section 5.

The rules given herein for the design of weld-improved details use the fatigue chapter in Eurocode 3[2, 3] for non-improved details. Eurocode 3 nominal stress *S–N* curves were described in a previous paper[1]. Table 1 cross-references fatigue detail classes among design codes. The next section summarizes the restrictions associated with the use of improvement methods.

2. Restrictions to the beneficial influence of improvement methods

2.1 General points

The beneficial influence of weld improvement methods is strongly dependent on the fabrication process, the quality assurance techniques and the fatigue loads applied at the welded joint. Guidelines on the fabrication process and quality assurance techniques for various improvement methods have been published by several authors[4–6], but at this time no specifications have been introduced into design codes. Among several studies, three[5,7,8] have compiled all the existing fatigue test results on improved welds and have attempted to draw conclusions on the influence and efficiency of the improvement methods used. Improvement methods are most efficient for details with high local stress concentrations and for details in the low-stress range/high number of cycles region of the *S–N* diagram ($>2\times10^6$ cycles). For details in the high-stress range/low number of cycles region ($<100\,000$ cycles), these methods lose their efficiency and can even become unfavourable. They also lose their efficiency in the case of variable amplitude spectrums with high peak stresses[6,9]. It has been shown that the fatigue strength of improved welds is often influenced by the stress ratio R. This is an important parameter that will be used later on in this paper; it is defined as:

$$R = \frac{\sigma_{min}}{\sigma_{max}} \quad (1)$$

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

The fact that the improved part of the joint, that is the weld toe, is not the only possible initiation site must not be overlooked; fatigue cracking can also develop from a lack of penetration, an internal defect, etc. Thus, another restriction on the efficiency of these improvement methods arises, the effects of which must be mitigated absolutely by good workmanship of welded joints.

2.2 Requirements for improved welds in addition to Eurocode 3

The use of improvement methods should be limited by several restrictions in addition to the requirements of Eurocode 3. These are as follows:

- these methods must not be considered for short fatigue lives; $N > 100\,000$ cycles;
- the nominal maximum stress range of a cycle or spectrum must not exceed the nominal yield stress of the steel; $\Delta\sigma_{max} < f_y$;
- the nominal applied stress spectrum (with constant or variable amplitude) must not contain peak stresses in tension or compression exceeding the nominal yield stress of the steel; $|\sigma_{max}| < f_y$;
- the minimum plate thickness for which improvement methods can be implemented effectively is 10 mm;
- Owing to the uncertainty with regard to the initiation site of the fatigue crack and a lack of experimental results, the following welded details must be excluded from any beneficial influence that could result from the improvement of the weld toe (see Fig. 1 and Eurocode 3 tables[3] for more information):

  - all longitudinal welds, both continuous and intermittent (parallel to main stress direction); transverse butt welds made from one side or made onto permanent backing;
  - connectors and studs;
  - cruciform or T-joints with partial penetration butt or fillet welds, and more generally speaking, all load-carrying fillet or partial penetration welds. To avoid confusion, note that transverse attachments attached by fillet welds are *not* part of this class;
  - lap joints.

- welded details for which the code already requires special manufacturing such as grinding (for example transverse butt welds with profile dressed flush) cannot benefit from subsequent TIG dressing.

Improvement methods can be implemented on new as well as existing structures (existing structures not being covered in Eurocode 3). Several studies indicate that these improvement methods can cancel previous fatigue damage at the weld toe. However, this damage must be small; the fatigue crack must not have developed yet or must typically be less than 2 mm deep at the time of application of an improvement

Table 1 Cross-references for *S–N* curves (nearest curve at 2×10^6 cycles) between codes

AISC [20]	ECCS–EC3 [3]	BS 5400 [19]
A	160	B
B	140, 125	C
B′	112, 100	T
C	90	D
D	80, 71	E, F
E	63, 56	F2, G
E′	50 and below	W

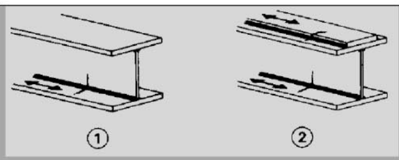
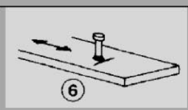
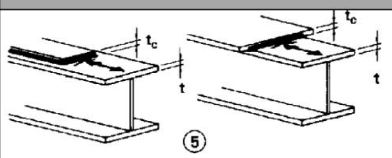
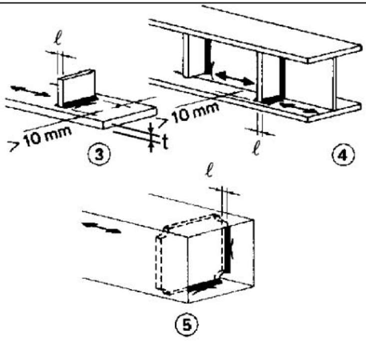
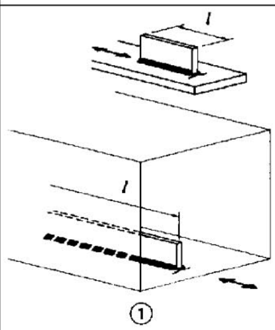
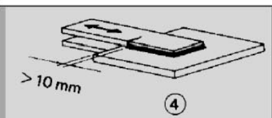
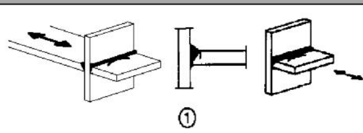
Class	Detail	Description
125 112		longitudinal weld
50		transverse weld on backing bar
80		connectors
56		coverplates
80		transverse attachments
56		longitudinal attachments
50		lap joints
71		full-penetration butt-welded cruciform joints

Fig. 1 Typical fatigue details according to Eurocode 3[2,3]; shading indicates that the detail can not be improved

method such as TIG dressing or hammer peening[10–12]. Again, note that when repairing or improving the weld toe of a detail on an existing structure, the other crack initiation points in the detail are not improved (weld root, internal defects, etc.).

Table 2 Fatigue classes corresponding to as-welded, ground and TIG-dressed welded details

	Class of detail		
Description[1]	**As-welded $\Delta\sigma_C$**	**Improved by grinding $\Delta\sigma'_C$**	**Improved by TIG dressing $\Delta\sigma'_C$**
Transverse full-penetration butt weld			
With overfill $\leqslant$ 0.1 b[3]	90	100[2]	100[2]
With overfill $\leqslant$ 0.2 b[3]	80	90[2]	90[2]
Ends of longitudinal attachment			
l $\leqslant$ 50 mm	80	100	100
50 < l $\leqslant$ 100 mm	71	90	90
l > 100 mm	56	71	71
With round shaped ends, $R > 150$ mm	N/A	80	N/A
Transverse attachment	80	100	112
Cruciform full-penetration weld	71	80	90

[1] See Fig. 1 for more information
[2] Weld toe improvement; best improvement flush to ground for class 112 joint according to Eurocode 3 [2, 3]
[3] b is the maximum width of the weld

3. Fatigue resistance curves for burr grinding and TIG dressing

In order to take into account both the improvement in the geometry and the introduction of an initiation phase due to the improvement method, one could simply develop a new set of curves, using the classical procedure for the evaluation of fatigue test results. Unfortunately, there is a lot of scatter in the slope coefficients found in this way, and it is difficult to justify a different slope coefficient for each improved joint fatigue curve. In order to clarify the situation, another procedure has been proposed[13]; the idea behind this procedure is to double-check each test result used in the evaluation of the slope coefficient. Indeed, for short fatigue lives, the fatigue strength of the joint can reach that of the base metal. Consequently the results relative to base metal and joint fatigue failures must be separated before being used statistically. Processing the data with this procedure results in fatigue curves that are simple translations from the as-welded code curves, that is without change in the slope coefficient. The level of improvement should therefore not change with the number of cycles, and that is in fact what has been found in statistical analyses on ground and TIG-dressed welds[5].

The latest proposition from the International Institute of Welding (IIW/IIS) for ground and TIG-dressed welds is to multiply the original detail class by a factor of 1.3 to account for the beneficial influence of the improvement[6]. The validity of this rule should be limited to class 90 or below. As shown earlier[18], the influence of the R ratio can be neglected. Instead of a single multiplication factor, we have chosen to reclassify individually the details improved by grinding and TIG dressing. This reclassification is given in Table 2. The reclassification values given in the table are conservative and are in good agreement with those found in the literature[5,7,14]. Moreover, for low-stress range levels, they are even more conservative since they do not fully account for the beneficial influence of the creation of an initiation phase, owing to the elimination of surface defects.

4. Fatigue resistance curves for shot, needle and hammer peening

4.1 Concept of effective stress

In contrast to the previously described improvement methods, the fatigue strength benefit resulting from these improvement methods can be modelled only by using fracture mechanics. Most of these models use the concept of effective stress, and show that the main parameter responsible for the benefit is the introduction of compressive residual stresses which slow down the propagation of the fatigue crack[15,16]. The idea here is to use the same concept with the S–N curves, and to express the fatigue resistance of an improved joint with respect to the effective stress range:

$$\log N = \log a - m \log \Delta\sigma_{\mathrm{eff}} \quad (2)$$

or

$$N(\Delta\sigma_{\mathrm{eff}})^m = a \quad (3)$$

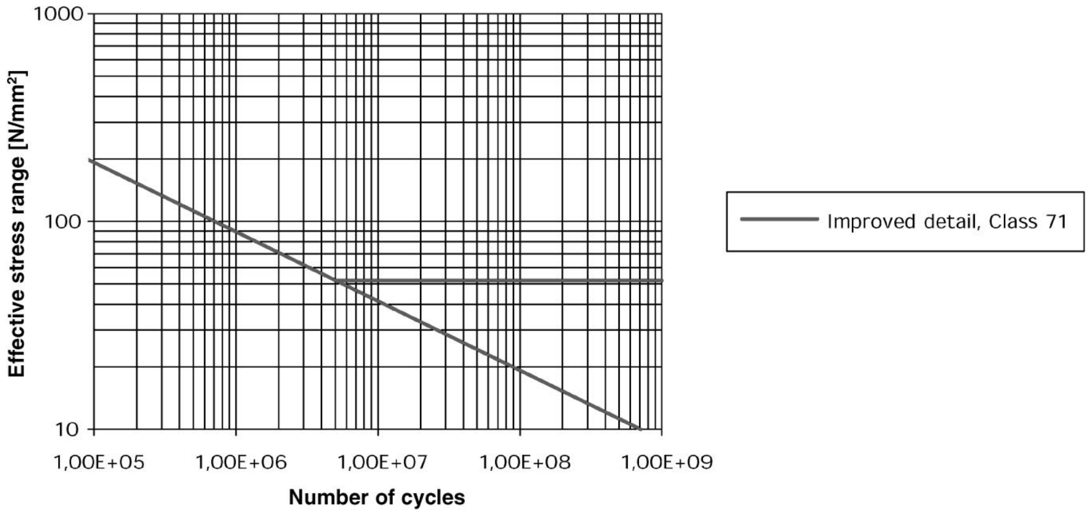


Fig. 2 Example of a *S–N* curve expressed as $\Delta\sigma_{eff}$ for an improved (group 3) joint class 71

The definition of $\Delta\sigma_{eff}$ is given in the next paragraph. The detail class is kept the same when using $\Delta\sigma_{eff}$, but owing to the uncertainty, the fatigue curve is modified conservatively with a unique slope, $m = 3$. The fatigue limit under variable amplitude loading is omitted. The constant amplitude fatigue limit is kept at 5×10^6 cycles (Fig. 2).

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

$$\sigma_{min,eff} = \sigma_{min} + \sigma_r \quad (4.1)$$

$$\sigma_{max,eff} = \sigma_{max} + \sigma_r \quad (4.2)$$

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

The crack cannot propagate as long as $\sigma_{min,eff}$ is less than zero. The effective stress range $\Delta\sigma_{eff}$ can therefore be defined as:

$$\Delta\sigma_{eff} = \sigma_{max,eff}; \qquad \sigma_{min,eff} \leqslant 0 \quad (5.1)$$

$$\Delta\sigma_{eff} = \sigma_{max,eff} - \sigma_{min,eff}; \quad \sigma_{min,eff} > 0 \quad (5.2)$$

$$\Delta\sigma_{eff} = 0; \qquad \sigma_{max,eff} < 0 \quad (5.3)$$

Note that in eq. (5.1), 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. Eq. (5.3) is included 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 excessive compressive peak stresses reduce the fatigue strength of improved joints, we introduce a modification in the R ratio definition in order to limit the beneficial influence of the improvement in the case of a negative stress ratio. The new definition for the stress ratio is as follows:

$$R' = R; \quad R \geqslant 0 \quad (6.1)$$

$$R' = 0; \quad R < 0 \quad (6.2)$$

Introducing eqs (4) into (5), and taking into account eqs (6) leads to the final expression for the effective stress range:

$$\Delta\sigma_{eff} = \frac{\Delta\sigma}{1 - R'} + \sigma_r; \quad \sigma_{min,eff} \leqslant 0 \quad (7.1)$$

$$\Delta\sigma_{eff} = \Delta\sigma; \qquad \sigma_{min,eff} > 0 \quad (7.2)$$

For variable amplitude loading, it has been shown that the improvement level is a function of the applied spectrum, in particular of the maximum applied stresses[9,15]. A method using an equivalent maximum stress $\sigma_{max,E}$ computed in a similar manner to the equivalent stress range $\Delta\sigma_E$ has been proposed[9]. This method can be directly applied to our model by replacing in eq. (7) $\Delta\sigma$ by $\Delta\sigma_E$, and $\sigma_{min,eff}$ by $\sigma_{max,E} - \Delta\sigma_E + \sigma_r$. Results using these expressions have been encouraging[15,17] and, for the time being, should be used in design.

Other recommendations, such as the IIW recommendations on improved methods[6] have retained the concept of the applied stress range $\Delta\sigma$. The problem with this approach is that it cannot model properly the R ratio dependency and the change in slope associated with it. In the IIW recommendations, all joints improved by hammer peening are reclassified as class 125 joints. With this reclassification a new definition for the stress range is given that differentiates only between negative and positive R ratios.

4.2 Application of the concept

With the help of an existing database[7], one can plot, on an effective stress *S–N* diagram, the test results for each detail type and improvement method. The calibration of the residual stress level is then made by setting different values for this level in eq. (7). A best fit with the proposed design curve is obtained by trial

Table 3 Numerical values for fatigue resistance curves of joints improved by peening methods

Type of detail	Class of improved detail $\Delta\sigma_{C,eff}$	log *a* for any *N* (slope $m = 3$)	Stress range at constant amplitude fatigue limit ($N = 5 \times 10^6$) $\Delta\sigma_{D,eff}$
Transverse full-penetraion butt weld			
With overfill $\leqslant$ 0.1 b	90	12.151	66
With overfill $\leqslant$ 0.2 b	80	12.001	59
Ends of longitudinal attachment			
$l \leqslant 50$ mm	80	12.001	59
$50 < l \leqslant 100$ mm	71	11.851	52
$l > 100$ mm	56	11.551	41
Transverse attachment	80	12.001	59
Cruciform full-penetration weld	71	11.851	52

Table 4 Calibrated levels of σ_r to be used with $\Delta\sigma_{eff}$ model developed for peening methods

Improvement method	σ_r (N mm^{-2})
Shot peening	−50
Multiple needle peening	−40
Hammer peening	−75

and error. This involves checking that the mean positions of the data points corresponding to the different *R* ratios are similar, and minimizing the standard deviation of the whole test database for the particular detail and improvement under consideration. The proposed design curves and the levels of residual stresses obtained are given in Tables 3 and 4.

Fig. 3 shows the comparison between the test results and the design curve for shot-peened longitudinal attachments. The slope coefficient of the regression, with *N* taken as the dependent variable, is 3.5, which is close to 3. Some of the observed scatter can result from differences in the operating procedure of the improvement. This point must be emphasized, and explains the need for operating procedure guidelines in fatigue design codes on improved welds.

5. Validation through testing: the case of longitudinal attachments of a railway bridge

5.1 INTRODUCTION

The fatigue performance of a welded joint can be considerably enhanced by the use of weld improvement techniques. Table 5 shows the fatigue design classes for standard and improved longitudinal attachments (length $l > 300$ mm)[2,6,18–21]. The standard attachment consists of a rectangular gusset welded on a plate and not ground (see Fig. 1, longitudinal attachments). On the improved details the ends of the gusset plates are shaped so as to create transition corners, thus reducing stress concentrations and eliminating weld toe defects. The transition corners should be as smooth as possible, and their radius *r* should be at least 150 mm.

Eurocode 3[2,3], the British Standard 5400[19] and the American AISC Code[20] have different fatigue strength curves and classes for such longitudinal attachments, either along the side of the plate (‖) or perpendicular (⊥). In the AISC Code the class varies with the radius of the transition corner.

Kulak[24] has shown the beneficial effect of circular shaping. As can be seen in Table 5, improved details are not included in most codes, therefore in order to use a higher class than that of the unimproved detail, one has to undertake laboratory tests. In the case of the new railway bridge at Zurich–Wipkingen, Switzerland, higher fatigue resistances than those given in the Swiss Code[22] were required. The Institute of Steel Structures (ICOM) of the Swiss Federal Institute of Technology in Lausanne was commissioned to establish the fatigue classes of the improved longitudinal as well as other details.

5.2 TEST PROGRAM

The laboratory tests were executed in two phases: tests on specimens and tests on beams. The specimens (Fig. 4) were 1300 mm in length and 160 mm in width. The longitudinal attachment had a width of 16 mm.

The beams (Fig. 5) were much larger (9000 mm in length and 695 mm in height) in order to take into account the influence of the residual stresses and the scale of the real structure. The longitudinal attachment used on the beams had a width of 20 mm. All tests

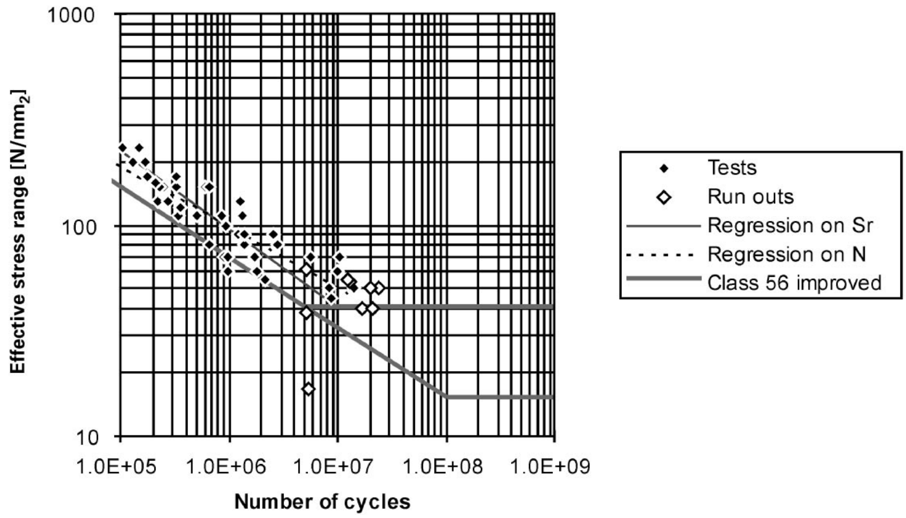


Fig. 3 Comparison between test results and $\Delta\sigma_{eff}$ design curve for shot-peened longitudinal attachment joints

were conducted with a stress ratio $R = \sigma_{min}/\sigma_{max} = 0.1$. A total of 17 specimens were tested at different stress ranges. Two beams were tested on a four-point bending bench at two different stress ranges.

In addition to the expected cracking at the end of the transverse (detail 1) and longitudinal attachments (hereafter refered to as the longitudinal detail 2), a third detail was also found to provoke fatigue failures. This third detail was seen to correspond with the transition between two types of weld (specimens) or two types of welding processes (beams). All specimens improved by grinding and needle peening cracked at the internal detail and not at the longitudinal one. Fig. 6 shows the results obtained for the longitudinal detail only.

After statistical treatment of the results according to the IIS/IIW procedure[18] fatigue resistance values of 83 N mm^{-2} for the ground details and > 90 N mm^{-2} for the ground and needle-peened details were found. The exact value of the latter could not be determined because, for the needle-peened specimens, no crack appeared at the longitudinal detail. From the specimen results for the internal detail ($\Delta\sigma_c = 95$ N mm^{-2}) and the fatigue resistance of the weld in the direction of the stress it is possible to deduce that $\Delta\sigma_c$ should lie between 95 and 112 N mm^{-2}. The improved longitudinal details for the beams that cracked are all above the class 90 fatigue curve. The ICOM Test Report[21] gives more precise information concerning the interpretation of the results. In order to obtain the strengths described herein, a precise fabrication process must be followed.

5.3 Fabrication process

In this section a fabrication procedure for improving weld details by grinding and needle peening is described. This procedure is based on experience gained during the specimen and beam tests described in section 5.2.

5.3.1 Preparation of pieces for assembly

To realize a continuous transition between the stiffener and the plate (welding of the transition corner), the stiffener is equiped with an appendix (Fig. 7). The corner is then built up by welding prior to grinding. The height of the appendix should be at least 10 mm.

5.3.2 Tack welding

Fixing at the end of the appendix and in the fillet weld zone of the attachment is allowed, but in no case shall fixing be permitted in the transition corner zone.

5.3.3 Welding (Fig. 8)

The end zone has a completely penetrated butt weld at the rounded end of the appendix and in the extension zone of the transition corner (width of end zone $> r$). The median zone has fillet welds for the rest of the attachment.

5.3.4 Quality control

Quality control of welding is performed with ultrasonic or other suitable methods, to detect planar defects inside the material, and to control the degree of penetration.

5.3.5 Removal of the appendix and grinding of the transition corner

Removal is achieved by grinding or another suitable technique, completed by grinding with a disc. The axis of the disc must be perpendicular to the stiffener. After this treatment there should be no striation perpendicular to the load direction. To obtain the maximum benefit from this type of treatment it is important to extend the grinding to a sufficient depth to remove all small undercuts and inclusions. The degree of improvement achieved increases with the

Table 5 Fatigue design classes for standard and improved longitudinal attachments according to different codes and recommendations

	$\Delta\sigma_c$ (N mm^{-2})		
	Standard	Grinding($r > 150$ mm)	Grinding and peening
IIS/IIW [6,18], ∥	40	90	
IIS/IIW [6,18], ⊥	50	90	
Eurocode 3 [2] ∥	45[1]	90	
Eurocode 3 [2] ⊥	50[1]		90–112
BS 5400: Part 10 [19] ∥	G (56)		
BS 5400: Part 10 [19] ⊥	F2 (63)		D–T (90–112)
AISC [20] ∥	E		
AISC [20] ⊥	E	C[2]	C–B′
IIS/IIW [6]			90–125[3]
ICOM [21]		83	90–112

[1] Eurocode 3 permits an increase to the next fatigue class if the fatigue limit is taken at 10^7 cycles instead of 5×10^6
[2] Fully penetrated groove weld, ultrasound testing (UT) checked, subsequently ground smooth
[3] Under different conditions

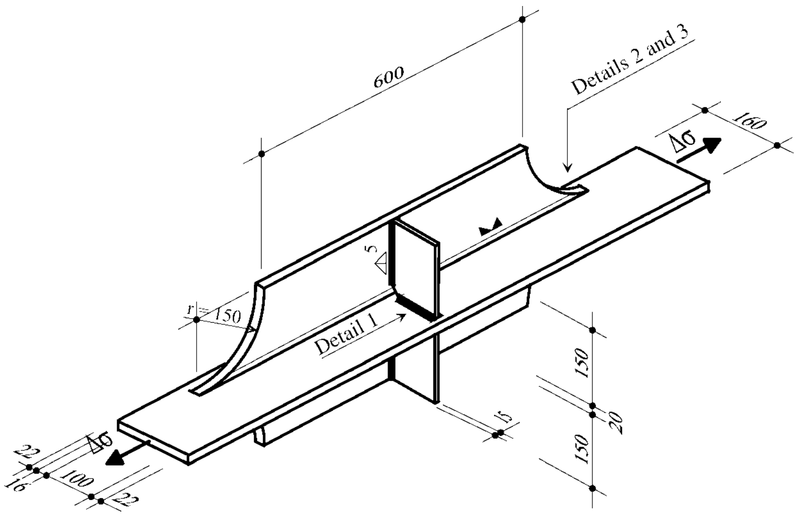


Fig. 4 Geometry of the test specimen

care taken by the operator to produce a smooth transition.

5.3.6 Visual testing

Visual testing implies careful inspection of the welded surface and surrounding zones in order to detect all visible flaws, discontinuities, corrosion marks, surface porosity, weld splatter, etc.[23]. Proper visual testing also requires comparison with a reference specimen and control of round-off geometry.

5.3.7 Needle peening

The improved fatigue properties of peened welds are obtained by extensive cold working of the toe region. The zones to be peened have to be clearly indicated on the workshop drawings. The peening speed should be at around 10 cm min^{-1} (multi-pass). The position of the hammer should be perpendicular to the peening surface. Needle peening has to be executed very carefully by an experienced worker, and special attention should be given to the plate edges and the weld toe. Control of the peening quality includes visual testing and comparison with the reference specimen (peening area, state and regularity of the surface).

5.4 RESTRICTIONS AND RECOMMENDATIONS

Owing to the lack of cracked test results, a slope of 3 has been assumed for the fatigue curves. This does not necessarily mean that an improved detail will always have the same slope as the unimproved one.

Fig. 5 Four-point bending tests on beams

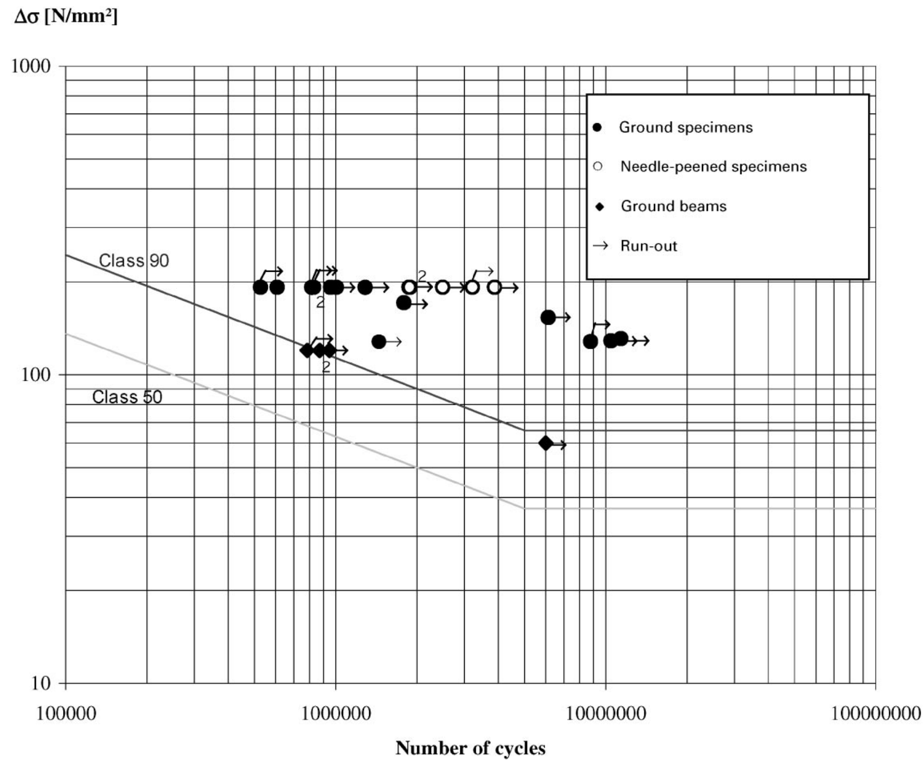


Fig. 6 Test results for the longitudinal attachment detail (ground and needle-peened)

The results obtained showed that a fatigue improvement of at least three classes is possible by the creation of a transition corner and the application of grinding and needle peening. However, one should be aware that by modifying the fatigue resistance of one detail, another detail may become critical. Special attention has to be paid to the transition between two different welding processes or weld types (butt/fillet welds). Weld transitions, including start–stop positions, have to be avoided in high stress concentration zones. They should be executed with great caution (progressive preparation of the edges, clearly defined welding sequence).

We also must remember that the fatigue resistances obtained are valid only if the stress ratio R is smaller than 0.1. For needle peening the ratio between the

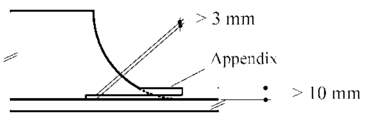


Fig. 7 Close-up view of the appendix

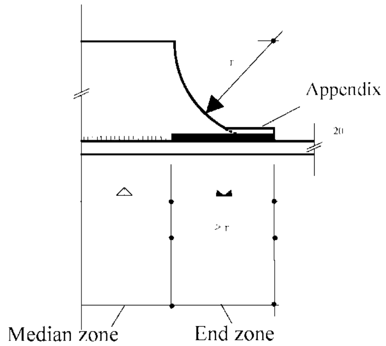


Fig. 8 Weld types in different zones

minimal and maximal stress has a big influence on the effectiveness of the treatment. No improvement is obtained for values above 0.5. Because of the risk of relaxation, attention should be paid to ensuring values below 0.5, and to large compression cycles. The lower the value of R, the more effective the treatment will be; that is why we recommend that peening be executed after erection of the steel structure, and not in the workshop.

To guarantee the desired fatigue resistance, a fabrication procedure has to be established in collaboration with the steel manufacturer. A reference-specimen should be given to the workshop supervisor in order to facilitate control of the state of the surface and the area to be peened.

6. Concluding remarks

This paper has shown how to use weld improvement methods in practice and has pointed out the following in particular:

- to use improved details, one can use design curves such as those given in this paper or conduct validation through testing;
- the fabrication, sequence of assembly and improvement procedure must be well defined;
- in contrast to as-welded details, the fatigue strength curves for details improved with peening methods have different slopes, and depend significantly on the stress cycle ratio R.

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