DESIGN OF WELDS IN HIGH STRENGTH STEEL

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ABSTRACT

Welds in high strength steel have been studied experimentally and results from two test series are reported. One series concerned butt welds with undermatching electrodes with the purpose of investigating the strength and ductility. The conclusion is that moderately undermatching can be used maintaining a sufficient ductility. The other test series concerned fillet weld with the purpose of developing a design formula covering undermatching as well as overmatching electrodes. Such a formula is proposed using results from the new tests as well as tests reported in literature.

1 INTRODUCTION

Welding of high strength steel (HSS) has been studied extensively by steel makers and they have recommendation for welding of their steel. The weldability has been one of the major concerns in the development of modern HSS. Because HSS may be produced in many different ways it is essential to follow the recommendations of the steel maker in order to get a reliable weld. However, also design codes have to be followed and there are some questions to be resolved. EC3-1-8 [1] requires for instance matching electrodes for all welds. As the scope presently is limited to grades up to S460 this it not big problem but in connection with an extension to higher grades this requirement should be reconsidered. One reason is that lower strength electrodes may be preferable for the production process. Another reason is that for very high strengths there are no matching electrodes. For fillet welds it is obviously no need for matching electrodes but there is a need for design rules for welds with non-matching electrodes. One example of such rules can be found in the Swedish code [2]. For butt welds it is normally a loss of strength associated with the use of undermatching electrodes. For a fully stressed transverse butt weld matching electrodes are preferred but for other butt welds undermatching electrodes are preferable.

2 BUTT WELDS IN HHS

2.1 General

Butt welds in e. g. a bridge flange are in most cases located at positions where they are fully utilized. The welds should preferably have at least the same strength as the smallest flange plate in order to use the material in an efficient way. Other welds e. g. a longitudinal butt weld in a deep web will be lightly stressed and the weld will perform satisfactorily with lower strength. The ductility of the welds should also be sufficient, a requirement that depends on the design method. Here it is assumed that the structure is designed with elastic analysis, which gives quite low required ductility.

Welding a QT-steel may create a narrow annealed zone in the HAZ. This causes a local reduction of the strength, which is counteracted by a tri-axial state of stress in the softened zone. If this is a problem it should be worse with undermatching electrodes than with overmatching. In order to investigate the strength and ductility of welds with undermatching electrodes a study was carried out by SSAB Swedish Steel and the Swedish Institute of Steel Construction [3], which is referred below.

2.2 Test specimens

The study included testing of welds with 12 different electrodes in 30 mm thick plates of S500QT (WELDOX 500) and S690QT (WELDOX 700). The welds were made using manual metal arc welding, submerged arc welding and flux core welding. For each combination of steel and electrode two specimens were fabricated and tested with weld geometry according to Figure 1. The specimens had a nominal cross section 30x60 mm. The welding parameters are given in Table 1 and 2.

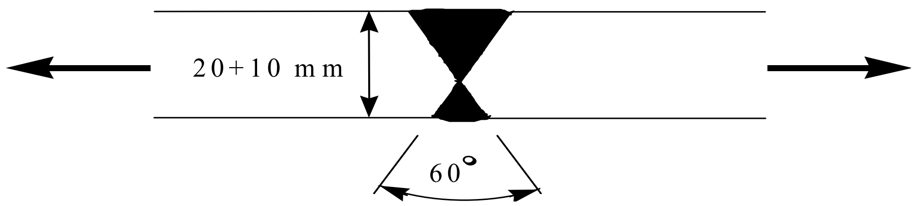

Figure 1: Asymmetrical butt weld used for test specimens. The initial gap between the plates was 3 mm. The three rot passes were made using a softer electrode (OK48.00)

2.3 Test results and conclusions

The test results are reported in Table 1 and 2. The stresses at failure were evaluated with measured dimensions and are given as average values of two tests. In order to obtain an accurate strength of the electrode material three tensile specimens were made from each type and the values reported are mean values. The scattering is for each combination within the range +/- 25 MPa from the mean value. An example of rupture area as well as the necking is illustrated in Figure 2.

One important conclusion from the test results is that large plastic deformations in the base material can be achieved also with undermatching electrodes, which can be seen from the high values of A5 and area reduction. No detrimental effects of the softened zone in the HAZ can be observed. The strength of the welds is at the same level as the base material for S500. For S690 the strength is slightly lower than that of the base material and with one exception it is higher than the strength of the electrode material.

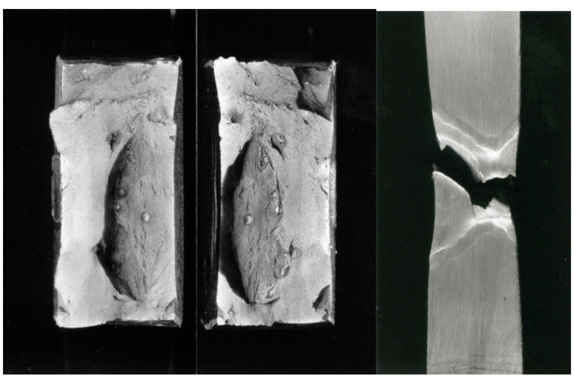

Figure 2: Rupture surface and necking of for S690 welded with manual metal arc and electrode OK 78.16.

Table 1: Welding parameters and test results for welds in S500, as well as the tested strength of the electrodes and the base metal.

Electrode	OK 73.68	OK 74.78	OK 12.24	Fluxcord 41	OK 13.09	OK 13.13
Heat input kJ/mm	2,2	2,1	1,8-2,2	1,8-2.2	1,8	1,9
Number of passes	20	21	16	18	14	14
Preheating ^oC	no	no	No	no	no	175
Base material f_y MPa	575	575	575	575	575	575
Base material f_u MPa	702	702	702	702	702	702
Electrode f_{eu} MPa	560	624	657	719	643	670
f_{eu}/f_u	0,80	0,89	0,94	1,02	0,92	0,95
Test strength f_{wu} MPa	706	707	707	727	724	713
Fracture location	weld	weld	Weld	weld/HAZ	weld	HAZ
A5 %	23	24	20	21	23	21
Area reduction %	34	39	31	30	34	28

Table 2: Welding parameters and test results for welds in S690, as well as the tested strength of the electrodes and the base metal.

Electrode	OK 75.75	OK 78.16	OK 12.40	OK 13.43	OK 13.29	PZ 6148
Heat input kJ/mm	1,9	1,5	2,0	2,0	2,0	2,0
Number of passes	21	26	16	16	15	16
Preheating ^oC	125	125	125	125	125	125
Base material f_y MPa	816	816	816	816	816	816
Base material f_u MPa	862	862	862	862	862	862
Electrode f_{eu} MPa	788	790	690	870	784	798
f_{eu}/f_u	0,91	0,92	0,80	1,00	0,91	0,93
Test strength f_{wu} MPa	822	819	781	847	827	868
Fracture location	weld	weld/HAZ	Weld	weld/HAZ	weld	HAZ
A5 %	21	-	23	24	24	23
Area reduction %	34	25	40	33	30	29

It seems reasonable to accept undermatching butt welds in situations there the stress level is low or moderate. A limitation can be formulated as a design rule thatthe strength of the weld f_{wu} is taken as the lower of f_u and f_{eu}. An evaluation of the test results according to [13] based on this assumption gives a mean value for test over prediction of 1,086 and a coefficient of variation of 0,064. The plot of results in Figure 3 indicates that there is a systematic difference between S500 and S690. As the number of tests is low they are anyway taken as one population. With the same statistical data for other variables as was used in 3.4 the required partial safety factor becomes 1,12. Although it is a small number of tests, 24, this indicates that the normal partial safety factor for fracture γ_{M2} = 1,25 can be used for undermatching electrodes in structures designed with elastic analysis. The restriction to elastic analysis is believed to be necessary as the measured A5 values refers to short length and local necking contributes significantly to the deformations. The plastic deformation capacity may be insufficient for plastic analysis.

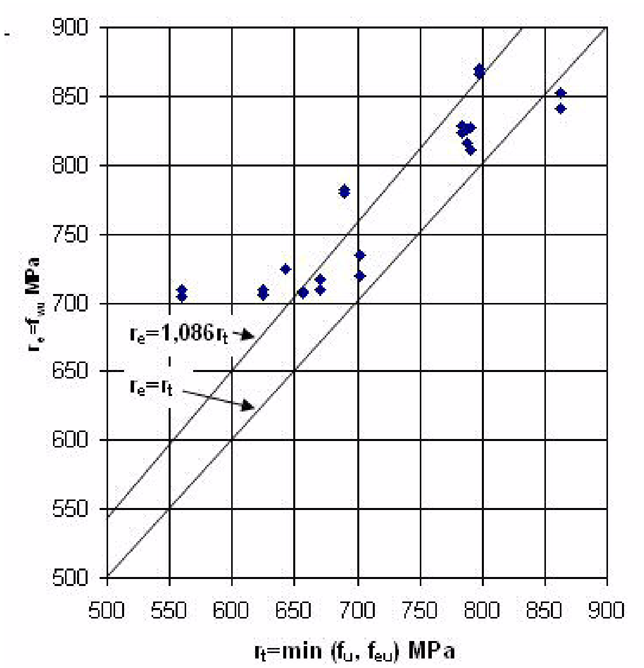

Figure 3: Tested values compared to proposed design values

3 FILLET WELDS IN HSS

3.1 General

The design rules in Eurocode 3 are valid for steel up to and including S460. A working group is preparing a Part 1-12 of Eurocode 3 that will give additional rules for extending the scope to cover grades up to S690. This study is part of the justification of this extension. More specific, the questions that will be dealt with here are:

- Define the basic strength for the weld material such that it is valid for both under- and overmatching electrodes.
- Define a suitable resistance function for fillet welds.
- Calibrate the design method to the safety requirements of the Eurocodes.

3.2 Test Specimens

Two sets of specimens according to Figure 4 were tested at LTU at the end 2003. The specimens denoted W were made by SSAB Oxelösund and the ones denoted D were made by Brisab, Piteå. Both series were welded with MMA and comprised longitudinal (L) and transverse (T) welds and nominal weld sizes are listed in Table 4. The displacements between the overlapping plates were measured in two points at a distance of 25 mm and accordingly the readings include some deformations in the base material. However, most of the plastic deformations are in the weld.

The base material properties were measured with standard coupon tests and the electrode material properties with specimens from molten electrode material Three specimens were tested for each type of electrode. The results from the material tests are given as average values in Table 3.

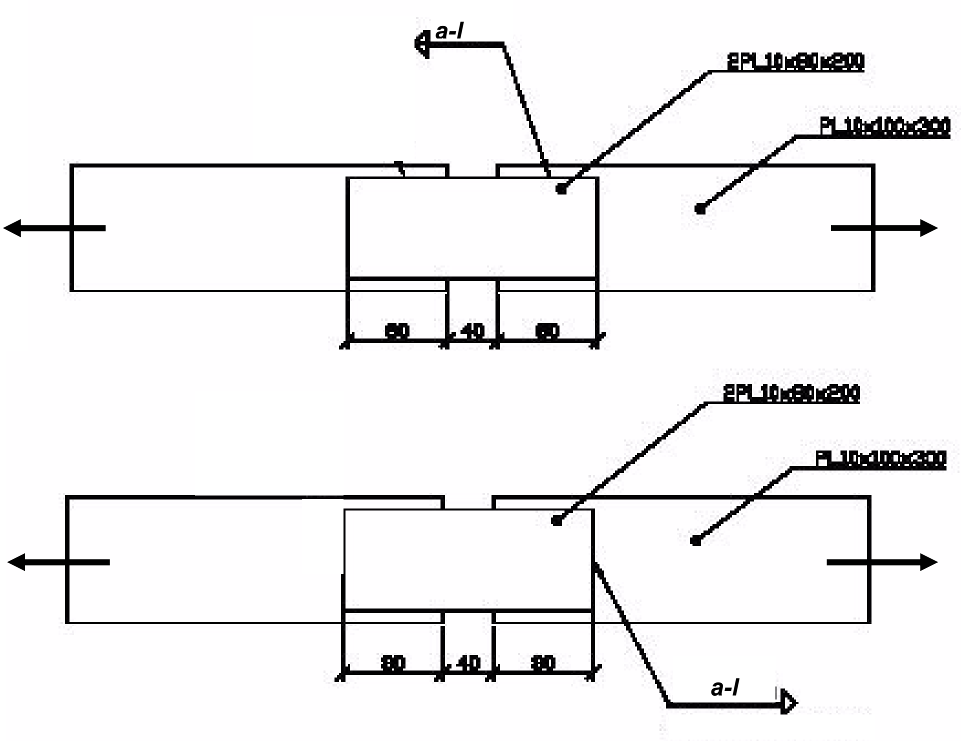

Figure 4: Test specimens for longitudinal welds (top) and transverse welds (bottom)

Table 3: Measured mechanical properties for base material and electrode material

		$Rp_{0,2}$ MPa	**R_m MP**	**A5 %**
Test series W	**Base material Weldox 700 E**	789	833	15
	Electrode OK75.75	619	758	24
Test series D	**Base material Domex 650 MC**	779	827	18
	Electrode OK48.00	462	548	27

3.3 Test results

The specimens were tested with the testing machine run in displacement control. After failure the fracture area was measured and this area was used for evaluating stresses at failure, see Table 4. The column F_u/A_w represents the longitudinal shear stress for the longitudinal welds and a fictitious axial stress for the transverse welds. This fictitious axial stress is transformed to transverse tensile stress and shear stress by division with $\sqrt{2}$. The Table 4 also gives the relative displacements between the plates at failure as the average of the readings from the two sidesof the end that failed .

3.4 Evaluation of design formula

Two questions will be dealt with in this section, first the weld material strength and secondly the effective stress in the weld. For the evaluation tests from literature will be used in addition to the results in Table 4. Those test result are reproduced in [4]. Niemi [6] used a steel grade S640 and matching electrodes and report 26 tests. They are of interest as the steel grade

Table 4: Test results for fillet welds series W and D.

Specimen	Nominal		Measured			
	a mm	l mm	A_w mm^2	F_u kN	F_u/A_w MPa	Displacement at failure mm
WL1	3	50	890	472	531	1,4
WL2	3	50	925	465	503	1,3
WL3	3	50	862	461	535	1,5
WL4	3	50	877	433	494	1,2
WL5	3	50	886	453	511	N. A.
WT1	4	60	617	575	932	0,33
WT2	4	50	469	401	855	0,82
WT3	4	50	450	445	988	0,69
WT4	4	50	429	431	1005	0,64
WT5	4	50	489	466	953	0,72
DL1	3	50	701	333	476	1,3
DL2	3	50	730	343	469	1,3
DL3	3	50	732	338	462	1,4
DL4	3	50	749	318	425	1,3
DL5	3	50	785	337	429	1,6
DL6	6	60	1162	573	493	3,2
DL7	6	60	1219	581	477	3,4
DL8	6	60	1086	525	483	3,1
DL9	6	60	1236	571	462	3,8
DL10	6	60	1264	584	462	3,2
DT1	4	60	548	470	857	0,61
DT2	4	60	579	447	772	0,56
DT3	4	60	500	407	814	0,55
DT4	4	60	535	422	789	0,51
DT5	4	60	542	431	796	0,52
DT6	6	60	719	593	825	0,50
DT7	6	60	705	571	811	0,98

was quite high. Kato and Morita [7] reports 20 tests with a steel roughly S355 with matching or slightly undermatching electrodes. The interesting contribution is that the size of the welds varied from 4 to 29 mm and no size effect was observed. Ligtenberg [8] summarise a large international investigation on fillet welds within IIW. The materials used were S235 and overmatching electrodes and S355 with more or less matching electrodes. The report includes tests series were the electrode strength had not been measured. Those tests have not been considered in the evaluation. A total of 255 tests from [8] with measured electrode strength are included. Finally Grondin, Driver and Kennedy [9] reports 65 tests on transverse weld in S355 with matching electrodes and different weld methods. The weld sizes were 6 and 12 mm and the welding methods were MMA and FCAW.

A first observation is that where there is a substantial difference between the strength of the base material and the electrode material the weld strength seems to be closer to the strength of the stronger material, whichever is stronger. This may be an effect of confinement, which however will not be studied in this investigation. As hypothesis for the weld strength a more conservative expression is taken:

$$f_w = \frac{f_u + f_{eu}}{2} \tag{1}$$

This expression wasalready suggested as a conclusion of the IIW international test series [8] and it has actually been used in an early version of the Swedish design code [2]. What is new here is that it is used also for undermatching electrodes. This formula works for both under- and overmatching electrodes and it is more rational than the method in [1] there a corrected ultimate strength of the base material is used. This correction assumes overmatching electrodes for low strength steel but the code only requires matching electrodes.

The stress component method for fillet welds in [1] tends to underestimate the strength of transverse welds compared to longitudinal. This is clear from the results in Table 4 as well as from many other tests. One way of correcting this is given in an Appendix to the LRFD [5] there the angle between the force and weld is taken as a parameter. Another way is to change the coefficients in the formula for the effective stress. The latter is proposed here and the expression for effective stress is changed into:

$$\sigma_{eff} = \sqrt{\sigma_\perp^2 + 2\tau_\perp^2 + 3\tau_{//}^2} \tag{2}$$

From the hypothesises (1) and (2) the following resistance functions can be derived :

$$\mathrm{F}_{\mathrm{R}//} = \frac{\mathrm{f_w A_w}}{\sqrt{3}} \approx 0{,}58\mathrm{f_w A_w} \tag{3}$$

$$\mathrm{F}_{R\perp} = \frac{\mathrm{f_w A_w}}{\sqrt{1{,}5}} \approx 0{,}82\mathrm{f_w A_w} \tag{4}$$

Formula (4) gives a 15% increase in the resistance compared to [1] if f_w is taken as same.

The resistance functions shall now be calbritated accordning to Annex Z of EC3-1-1 [10]. This is consistent with the present Annex D of EC0 but it gives more details of the procedure. Statistical data for the basic variables are taken from [11] and are as follows :

	Mean	Coeff. of variation
f_u/f_{unom}	1,14	0,07
f_{eu}/f_{eunom}	1,14	0,07
A_w/A_{wnom}	1	0,10

A first check of test over prediction is shown in Table 6 in which the different test series are shown separated. The tests collated by Ligtenberg stick out with a quite high average and also a high scatter. Presumably this is caused by the way the throat thickness was measured. It was measured before testing to the surface of the weld and any root penetration will not be included. This could lead to a too small weld area and accordingly too high stresses at failure. Also the test of Niemi on transverse weld fall out of the pattern for unknown reasons. The results will anyway be taken as one population but longitudinal and transverse weld will be treated separately as there is a systematic difference. Figure 5 shows all test results in a plot according to Annex Z.

Table 6: Test result over prediction for the separate test series

Study	**Longitudinal welds 210 tests**		**Transverse welds 183 tests**	
	mean	Stand. Deviation	mean	Stand. deviation
Weldox	1,12	0,03	1,46	0,08
Domex	1,17	0,05	1,44	0,05
Niemi	1,17	0,07	1,00	0,07
Kato, Morita	1,19	0,09	1,17	0,07
Ligtenberg St 52	1,44	0,18	1,58	0,25
Ligtenberg St 37	1,46	0,18	1,64	0,20
Grondin m fl	-	-	1,31	0,29
average	**1,28**	**0,11**	**1,36**	**0,16**

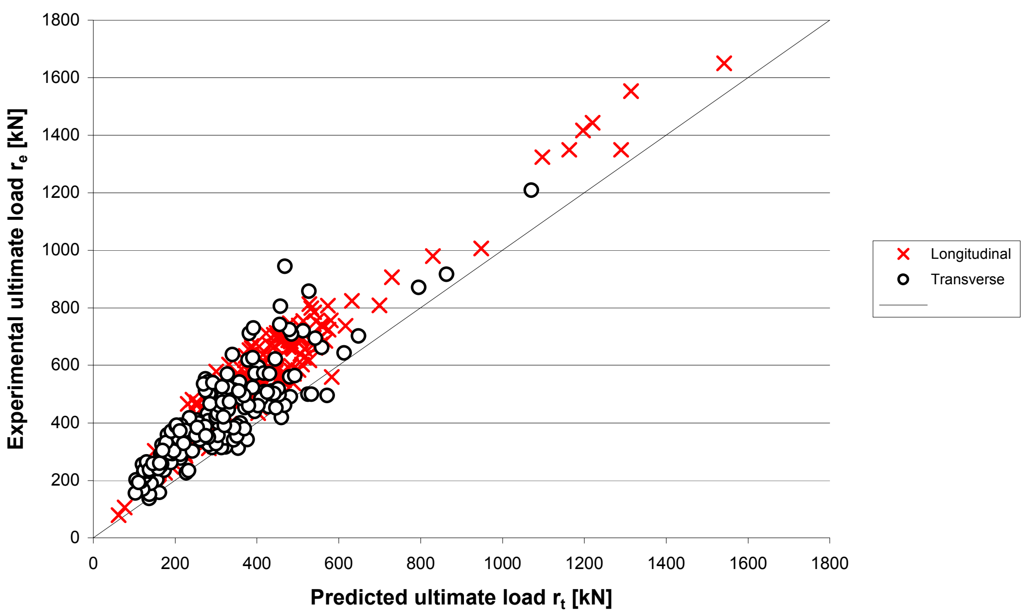

Figure 5: Plot of test result over prediction for all tests

The details of the calibration are omitted and the reader is referred to [4] for the details. The result turns out to be

$\gamma_{M2} = 1{,}16$ for longitudinal welds

$\gamma_{M2} = 1{,}26$ for transverse welds.

This is close enough to justify the use of the normal value $\gamma_{M2} = 1{,}25$.

4 CONCLUSIONS

The study of undermatching butt welds shows that such welds can safely be used in structures designed by elastic analysis provided that the design strength is taken as the lower of the ultimate strength of base material and the electrode material divided by γ_{M2} = 1,25. The experimental data includes tests with electrode strength down to 80% of the base material strength.

The study of fillet welds ends up with a proposal that the design strength of the weld material should be taken as the average of the strength of the base material and the electrode material. This can be used for over- as well as undermatching electrodes. Transverse fillet welds have an over-strength compared to present design rules. A new expression for the effective stress in fillet welds is proposed that corrects the strength of transverse welds.

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KEYWORDS

Butt welds, fillet welds, undermatching electrodes, design strength, high strength steeel.