PROPERTIES AND DESIGN OF WELDED JOINTS OF HIGH-STRENGTH STEELS

RICHARD M. STROETMANN[1] and THORALF KÄSTNER[1]

[1]*Institute of Steel and Timber Construction, Technische Universität Dresden, 01062 Dresden, Germany.*

E-mail: richard.stroetmann@tu-dresden.de, thoralf.kaestner@tu-dresden.de.

In the AiF-FOSTA research project P1020 (Stroetmann et. al. 2019) a new design model for welded joints was developed. In this context, a flat tensile test specimen was designed, to study various influences on the strength and ductility of the welds. These include those from the base material and filler metal, the cooling rate and the number of weld layers. The following article describes the design model and its input parameters. After a characterization of the investigated steels and welding consumables, the tensile test specimen to determine the mechanical properties of the welds is explained. Subsequently, parameter studies on the most important influencing variables on the properties of weld seams are carried out. On the basis of statistical evaluations, weld strengths are specified as a function of the filler metal and the cooling time $t_{8/5}$.

Keywords: high-strength steel, welding, cooling time $t_{8/5}$, tensile tests, strength of welds

1 New Design Model for Welded Joints

The use of high-strength steels provides economic and ecological advantages in many supporting structures in steel and plant construction, but also in mechanical engineering due to the resource-saving use of materials. In the case of welded constructions, these advantages are partially offset by unfavorable design rules for the joints and a more difficult execution. Within the framework of the research project P1020 (Stroetmann et. al. 2019), basic principles for the improvement of the technical rules for the design and execution of welded joints on high-strength steels were established.

As the strength of the steels increases, it becomes more and more difficult to achieve that the mechanical properties of the welded joints correspond to those of the base material. However, this is not necessary in the majority of welded joints in practical constructions. Examples are the fillet welds of I- and box sections and all joints whose stresses are significantly below the strength of the high-strength steels. Depending on steel grade and chemical composition, peak temperature and cooling time during welding, the properties of the base material change and a more or less distinctive softening can lead to failure outside the weld, but within the heat-affected zone.

With the simplified and directional design method for fillet welds and partial penetrated butt welds according to EN 1993-1-8, the influences of base and filler metal, manufacturing parameters, joint form and type of stress on the strength of the welds are subsumed in a single parameter, the correlation coefficient β_w. The reference value is the tensile strength of the base material f_u (Eq. 1 and 2). The German National Annex DIN EN 1993-1-12/NA prescribes for high-strength steels that only filler metals with a strength equal to or greater than that of the base metal may be used. In addition, the correlation coefficient β_w calibrated mainly on the basis of the fillet welds of overlap joints was increased from 1.0 to 1.20 deviating from EN 1993-1-12. In Part 1-

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12, it is required that for steel grades above S460 to S700, the length of fillet welds in the longitudinal direction of overlapping joints shall not exceed 50a, unless the uneven stress distribution is taken into account in the design.

$$\sigma_v = \sqrt{\sigma_\perp^2 + 3\left(\tau_\perp^2 + \tau_\parallel^2\right)} \leq \frac{f_u}{\beta_w \gamma_{M2}} \tag{1}$$

$$\sigma_\perp \leq \frac{0{,}9 \cdot f_u}{\gamma_{M2}} \tag{2}$$

In order to improve the design rules for welded joints, the design format Eq. 3 was proposed as part of project P1020 and input values were determined for it. This design model is based on a separation of the weld strength and the design requirements for the deformation capacity.

$$\sigma_v = \sqrt{\sigma_\perp^2 + 3\left(\tau_\perp^2 + \tau_\parallel^2\right)} \leq \alpha_w \cdot \frac{f_{wu}}{\gamma_{M2}} \tag{3}$$

using

f_{wu} Tensile strength of the weld,
α_w Factor for consideration of the joint type and ductility of the weld,
σ_v von Mises stress from the acting stress components.

The mechanical properties of the welds are highly influenced by the chemical composition of the filler metals and the welding process parameters. Due to the type and dimension of construction, different requirements are placed on the deformation capacity of a welded joint in order to activate the strength over the entire joint surface. For example, overlap joints with longitudinal fillet welds show concentrations of stresses at the ends of the welds. The plastic deformation capacity of the welds lead to rearrangements within the joints, so that the strength in the integral can be better exploited via the connection surface.

The verification format Eq. 3 requires the determination of the ultimate strength f_{wu} of the weld. A small flat tensile test specimen was developed for this purpose, which is described in Chapter 3. On the basis of load tests and parameter studies with the aid of FEM structural analysis, various joint types were investigated in order to calibrate the a_w-factors. A further article will report on this at a later stage.

2 Selection of Base and Filler Metals

The thermomechanical rolled steels S500ML and S700MC as well as the quenched and tempered fine grain steels S690QL and S960QL with a sheet thickness of 20 mm each were selected for the experimental investigations. Steels with different alloys and hardening mechanisms should be specifically investigated. The chemical compositions according to the delivery certificate and the resulting carbon equivalents are listed in Table 1.

The selection of weld filler metals should cover a wide range of strength classes and mismatching scenarios with an emphasis on under matching. Solid wire electrodes were used for metal active gas welding (process 135) according to the standards EN ISO 14341 and EN ISO 16834. The product standards for welding consumables have upper limits and more or less large bandwidths of the alloying elements. In addition, the minimum values of yield strength and elongation at break as well as tensile strengths within specified strip widths are defined. Under these conditions, it is at the discretion of the manufacturers to determine the alloys. The welding consumables used and their chemical composition are shown in Table 2.

Table 1. Steel grades, chemical composition and carbon equivalents in %

Steel	C	Si	Mn	P	S	Cr	Ni	Mo	V	Ti
S500ML	0,078	0,350	1,480	0,010	0,000	0,040	0,270	0,005		
S700MC	0,044	0,328	1,940	0,008	0,001	0,166	0,014	0,119	0,004	0,014
S690QL	0,140	0,300	1,150	0,009	0,001	0,300	0,100	0,170	0,010	0,008
S960QL	0,168	0,273	0,880	0,008	0,001	0,491	0,514	0,517	0,043	0,002

Steel	Cu	Al	Nb	B	N	Sn	Fe	CET	CEV	PCM
S500ML	0,141	0,340			0,002	0,002	rest	0,361	0,242	0,178
S700MC	0,014	0,037	0,042	0,001	0,005		rest	0,427	0,259	0,177
S690QL	0,010	0,036	0,001	0,002	0,002		rest	0,435	0,290	0,247
S960QL	0,026	0,031	0,013	0,000	0,004		rest	0,561	0,346	0,295

Table 2. Chemical composition of filler metals according to delivery certificate in %

Designation	Standard	C	Si	Mn	P	S	Cr	Ni
G 35 A M23 Z2Si1	EN ISO 14341-A	0.090	0.300	1.150	0.010	0.007	0.030	0.010
G 42 4 M21 3Si1	EN ISO 14341-A	0.070	0.840	1.440	0.011	0.013	0.030	0.010
G 62 5 M21 Mn3Ni1Mo	EN ISO 16834-A	0.090	0.630	1.490	0.007	0.010	0.030	1.090
G 79 5 M21	EN ISO 16834-A	0.080	0.730	1.660	0.008	0.009	0.290	1.650
G 89 6 M21	EN ISO 16834-A	0.100	0.780	1.830	0.005	0.010	0.360	2.280

Designation	Standard	Mo	V	Ti	Cu	Al	B	Zr
G 35 A M23 Z2Si1	EN ISO 14341-A	<0,01	<0,01	<0,01	0.020	<0,01	0.000	<0,01
G 42 4 M21 3Si1	EN ISO 14341-A	<0,01	<0,01	<0,01	0.010	<0,01	0.000	<0,01
G 62 5 M21 Mn3Ni1Mo	EN ISO 16834-A	0.430	<0,01	0.060	0.080	<0,01	0.000	<0,01
G 79 5 M21	EN ISO 16834-A	0.570	<0,01	0.090	0.060	<0,01	0.000	<0,01
G 89 6 M21	EN ISO 16834-A	0.630	<0,01	0.080	0.040	<0,01	0.000	<0,01

3 Experimental Investigations to Determine the Weld Properties

3.1 *Development and execution of a flat tensile test*

In the case of welded joints, the method of calibrating calculation models based on the results of tests on typical joint types has so far been used. This allows the joint to be considered in its entirety. In research projects carried out, it was regularly found that the calibration of the resistance models "should" distinguish between the different joint types.

In order to avoid that for each relevant combination of steel grade, filler metal, process technology and joint type separate, comparatively laborious tests have to be performed, it is advisable to separate the properties of the weld and the complete joint (see Eq. 3). The tensile strength f_{wu} and the ductility are characteristic properties for the load-bearing behavior of welds. For the experimental determination of these mechanical properties, a small flat tensile test was developed within the framework of project P1020. The following design principles were taken into account:

- The specimen shall be designed as a flat tensile test specimen in accordance with EN ISO 6892-1 and EN ISO 4136. This enables the execution of the tests with simple test and measurement equipment as well as the use of the test procedure in practice for welding process qualification and quality assurance.
- The size and geometry of the weld must be clearly defined so that the test results are reproducible and comparable.
- The test specimen shall be suitable for testing different combinations of materials and welding processes.
- The failure of the test specimen shall take place in the area of the weld metal in order to enable a quantitative determination of the mechanical properties and their transfer to the joint level.

Based on these principles, a flat tensile test specimen was developed with DV-weld shown in Figure 1. The load is applied perpendicular to the longitudinal axis of the weld. The cross section S_0 to be tested is defined by the thickness of the flat tensile specimen, a central hole in the area of the weld root and the shape of the specimen. This makes the test results comparable and reproducible. The targeted cross-section reduction by the hole also leads to a failure in the weld metal for overmatching joints. The use of a large weld-opening angle of the DV-weld in conjunction with a short initial measuring length L_0 makes it possible to limit the influence of the base metal on the measured deformations. The weld area before and after the test is shown in Figure 2.

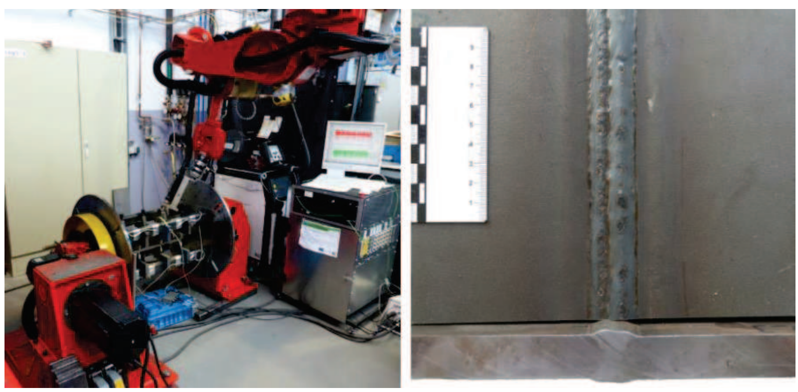


Figure 1. Welding test stand (left) and plate with butt-weld (right).

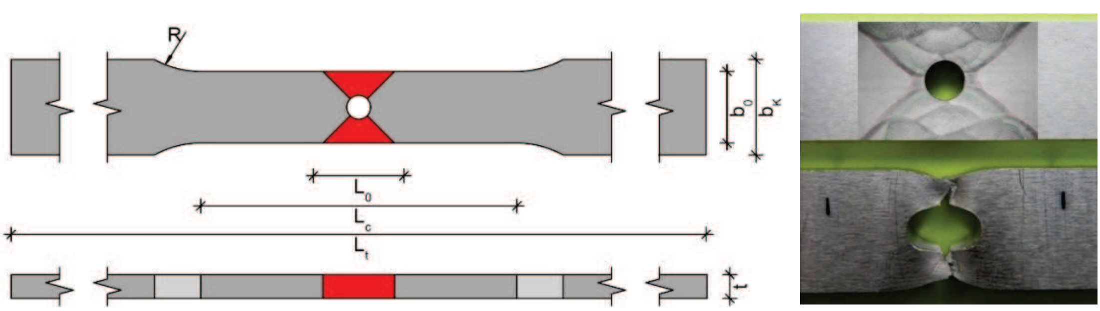


Figure 2. Test specimen and range of initial gauge length (L_0) before and after test procedure

This type of test is a comparative test for determining the mechanical properties of welds. Using the design model presented in Chapter 1, the results are transferred to the component level. To determine the stress, the machine force F is divided by the net cross-sectional area S_0 in the unloaded state (Eq. 4). The yield and tensile strength are determined in accordance with the specifications of EN ISO 6892-1. These test-specific characteristic values are marked with the index w. The strain is determined by dividing the change in length at the time of evaluation by the initial gauge length L_0 (Eq. 5). This strain is not a local value, but an integral quantity for the measuring range.

$$\sigma_w = F/S_0 \tag{4}$$

$$\varepsilon_w = \Delta L/L_0 \tag{5}$$

Table 3 shows the dimensions of the flat tensile specimens used in the research project. The use of specimens in two scales was necessary because the specimen width b_0 of geometry A was not continuously available for the welds with reduced number of layers. A scaling to geometry B and a corresponding reduction of the initial measuring length were carried out in order to achieve comparability of the results.

Table 3. Geometry of the specimen and initial gauge length in mm

Dimension	b_0	t	d	L_0
Geometry A	15,0	5,0	5,0	25,0
Geometry B	13,5	4,5	4,5	20,0

3.2 *Test program and specimen preparation*

In the series of small part tests, the influences of the steel grade and filler metal, the cooling time $t_{8/5}$, the number of weld layers and the weld opening angle were to be investigated. For selected material combinations, test series were performed to evaluate these influences on the mechanical properties of the welded joints (Table 4).

Table 4. Material combinations for the determination of mechanical properties

	Material combination			
Designation	S500ML	S700MC	S690QL	S960QL
Filler metal 1	G35	G42	G42	G42
Filler metal 2	G42	G62	G62	G62
Filler metal 3	G62	G79	G79	G89

Cutting and weld preparation of the plates to be welded was carried out by flame cutting and subsequent edge milling to eliminate the structural changes caused by local heat input. The welding of the samples was carried out, among other things, in a fully mechanized test stand, consisting of a six-axis welding robot and a synchronized tilt and turn table, in which the plates to be welded were stored selectively. During the production process, the welding parameters were recorded and the cooling time t8/5 was measured for each welding bead with thermocouples in the melt. To produce the flat tensile specimens, segments perpendicular to the seam direction were first cut out of the welded plates and then milled onto the specimen geometry. The positioning of the hole in the area of the weld root took place in the middle of the sample width b0.

3.3 *Influence of the base metal on the weld strength*

In order to investigate the influence of the base materials on the properties of welds, the steels grades presented in Section 2 were combined with various welding consumables. Figure 3 shows the stress-strain curves of 12 flat tensile specimens welded with a G62 and a cooling time $t_{8/5}$ of 12 seconds. It can be seen that the curves are very close to each other. There is no systematic influence of the base material for the yield and tensile strength as well as for the uniform elongation and elongation at break. The percentage deviations shown are negligible. Based on the mean value of the tensile strength of 803 N/mm², a standard deviation of 15 N/mm² was obtained for this test series.

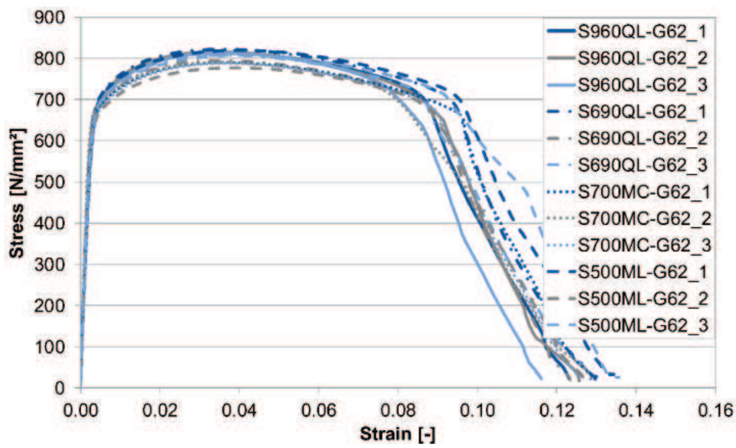


Figure 3. Stress-strain curves of G62 welds on four steel grades with a $t_{8/5}$-time of 12 seconds

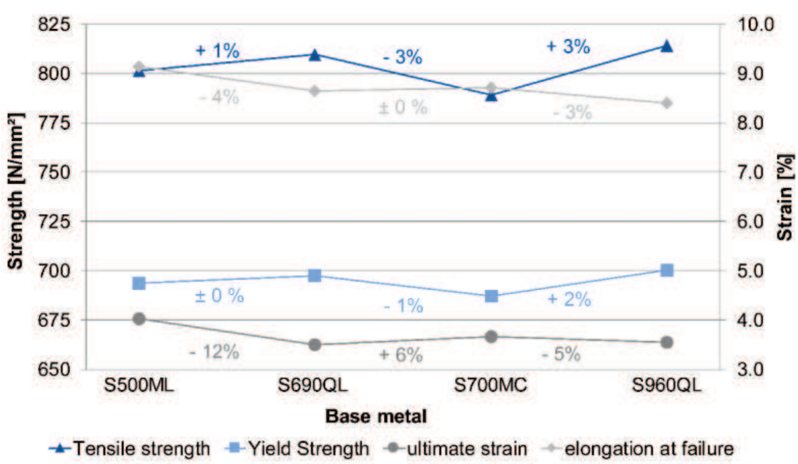


Figure 4. Mechanical properties (mean values) of the filler metal G62 in combination with four steel grades and a $t_{8/5}$-time of 12 seconds

In the arc welding process, the filler metal is melted and the base material is melted on. The strength-enhancing effects from quenching and tempering or thermomechanical rolling are lost at temperatures in the phase transformation range at the latest. The influence of the molten base material on the chemical composition of the weld depends on the geometry, number of layers and penetration depth. The alloying concepts of thermomechanically rolled steels and quenched and tempered steels differ considerably from each other. There is no direct dependency between the strength class and the strength-enhancing alloying elements (see Table 1).

3.4 *Influence of cooling time $t_{8/5}$*

One focus of the parameter studies carried out was to examine the influence of the cooling time $t_{8/5}$. Tests were carried out with the material combinations S500ML-G35, S690QL-G42, S690QL-G79, S700MC-G42 and S960QL-G42 with cooling times $t_{8/5}$ of 5, 12 and 20 seconds. Test specimens of geometry A according to Table 3 were used. Figure 5 shows the stress-strain curves and Figure 6 the strength parameters for the material combination S690Q-G79 at three cooling times $t_{8/5}$. Their influence on the strength and ductility of the welds is clearly visible. With regard to the tensile strength of the base material of 867 N/mm², the three cooling times $t_{8/5}$ resulted in clear overmatching, matching and slight undermatching. The difference between the mean tensile strengths f_{wu} is 142 N/mm² for the investigated $t_{8/5}$ times. For the yield strength, the difference of 213 N/mm² is 50 % higher.

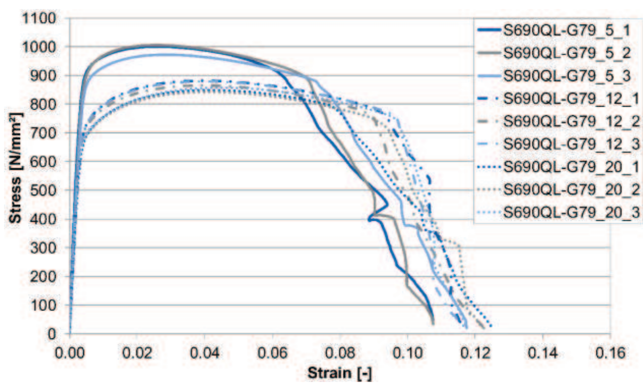
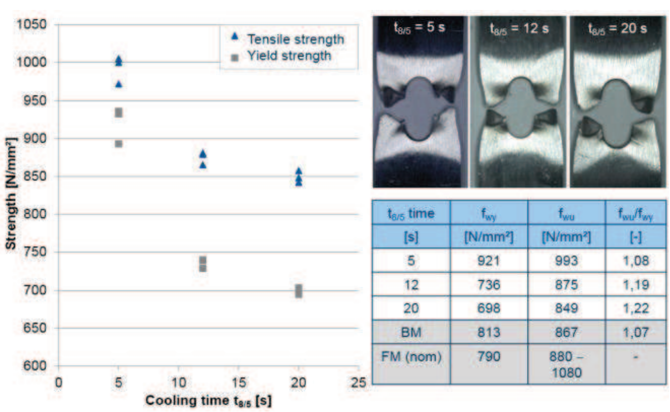


Figure 5. Stress-strain curves for material combination S690QL–G79 for three cooling times



$t_{8/5}$ time	f_{wy}	f_{wu}	f_{wu}/f_{wy}
[s]	[N/mm²]	[N/mm²]	[-]
5	921	993	1,08
12	736	875	1,19
20	698	849	1,22
BM	813	867	1,07
FM (nom)	790	880 – 1080	-

Figure 6. Strength values of welds S690QL–G79 for three $t_{8/5}$-times

4 Statistical Evaluation of the Weld Strength

The evaluation of numerous test results in (Stroetmann et. al. 2019) has shown that the filler metal and the cooling time $t_{8/5}$ significantly influence the weld tensile strength f_{wu}. From the investigations on the influence of the base metal described in Section 3.3, only minor differences without a clear tendency result for the four steel grades. Also in the tests on single-layer longitudinal fillet welds of overlap joints, the differences in strength were in the range of statistical scattering. In addition to the production of the butt welds in the test rig described in Section 3.2, welded joints were produced by the steel construction companies involved in the P1020 project. The strength values determined in the flat tensile test showed good agreement with the values of the automatically produced welds. The test results were included in the statistical evaluations according to EN 1990 Annex D.

The characteristic values of the weld tensile strengths $f_{wu,k}$ are summarized in Table 5. This evaluation considers on the one hand the different strengths for the cooling times $t_{8/5}$, on the other hand the different coefficients of variation. The characteristic weld tensile strength is up to 17 % higher with a $t_{8/5}$ time of 5 seconds and up to 5 % higher with a $t_{8/5}$ time of 12 seconds than with neglect of the influence. A $t_{8/5}$ time of 20 seconds results in up to 3.6 % lower strengths. The neglect of the $t_{8/5}$ time thus provides conservative values over wide ranges, but to a lesser extent also leads to overestimations of the strengths in the investigated time window.

Table 5. Tensile strengths $f_{wu,k}$ of welds with and without consideration of the cooling time $t_{8/5}$

SZ	G35	G42	G62	G79	G89
$t_{8/5}$ [s]	$f_{wu,k}$ [N/mm²]				
5	595	685	-	918	-
12	540	613	740	819	958
20	513	564	-	785	-
[-]	522	585	700	783	899

5 Summary and Outlook

In this article, a new design model for welded joints was presented. The main difference to existing models is that the strength of the weld is not determined by reference to the base metal and/or the filler metal and subsequent adjustment, but directly by means of flat tensile tests. Thus, it is also possible to consider the essential influence of the process parameters on the strength. The joint type and ductility of the weld are considered with the factor α_w. This allows a stronger differentiation between the joint types and their ductility requirements. The verification format is kept simple and does not lead to any additional effort in the calculation of welded joints.

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