Investigations on longitudinal fillet welded lap joints of HSS

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ABSTRACT: The developments of steel structures aim at light and slender constructions. Therefore, high strength steels with good welding characteristics and a high ductility in addition to higher strength have been developed by the steel industry. The application of high strength steels can bring significant savings in terms of material consumption, weight, transportation and fabrication costs. By increasing the strength of steel loads which have to be transferred by the welded connections increase in the same way. In the building industry fillet and partial penetration welds are commonly used. Existing design rules according to Eurocode 3 are introduced and discussed as they lead to very thick fillet welds for high strength steel. This paper presents the results of a research project, analysing the strength and ductility of fillet welded connections of high strength steel S460 and S690, with the aim to optimise the actual normative rules. Additionally strength tests on longitudinal fillet welded connections with steel grade S690 have been conducted together with numerical simulations to study the behaviour and possible influencing parameters on the load bearing capacity in detail, especially the influence of the strength of filler metals on the behaviour of welded connections.

1 DESIGN METHOD OF FILLET WELDS ACCORDING TO EUROCODE 3

In Europe, there are two methods to calculate the strength of fillet welded connections according to EN 1993-1-8 (2005) and EN 1993-1-12 (2005): the directional method and the mean stress method. Thereby, the mean stress method is a simplification of the directional method. By using the directional method the carried forces divided by the area of the throat section of the weld are split up into stress components $\sigma_\perp$, $\tau_\perp$ and τ_{II}. The normal stress component σ_{II} parallel to the weld axis is traditionally neglected. The stresses are calculated using design loads assuming a uniform stress distribution. The stress components, illustrated in Figure 1, result in an equivalent stress $\sigma_{w,Ed}$ which has to be smaller than the design resistance:

$$\sigma_{w,Ed} = \sqrt{\sigma_\perp^2 + 3\cdot\tau_\perp^2 + 3\cdot\tau_{II}^2} \le \frac{f_u}{\beta_w \cdot \gamma_{M2}} \quad \text{and} \quad \sigma_\perp \le \frac{0.9\cdot f_u}{\gamma_{M2}} \qquad (1)$$

The design resistance is expressed by a function of the tensile strength of the base metal f_u in combination with the correlation factor β_w. The strength of the filler metal is not considered. Instead of that EN 1993-1-8 (2005) prescribes matching or over-matching filler metal. But according to EN 1993-1-12 (2005) f_u has to be replaced by the strength of the filler metal when using under-matched electrodes for steels grades higher than S460 up to S700.

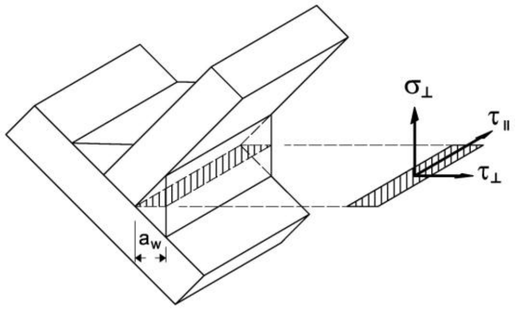

Figure 1. Stress components longitudinal and perpendicular to the weld throat

Table 1. Values for the design weld resistance according to EN 1993 in case of fillet welds, t ≤ 40mm

Steel grade		S235[1)]	S355[1)]	S460[2)]	S690[3)]
f_y	[MPa]	235	355	460	690
f_u	[MPa]	360	510	540	770
β_w	[MPa]	0.8	0.9	1.0	1.0
$\frac{f_u}{\beta_w \cdot \gamma_{M2}}$	[MPa]	360	453	432	616

EN 10025 (2005) 1) Part 2, 2) Part 3 and 4, 3) Part 6

The correlation factor β_w, given in EN 1993-1-8 (2005) and EN 1993-1-12 (2005), increases from 0.8 for mild steel to 1.0 for high strength steel. The partial safety factor γ_{M2} describing the resistance of welds is γ_{M2} = 1.25. In Table 1 the design weld resistance for fillet welds depending on the structural steel grades according to EN 10025 (2005) is summarised. The table shows that the design resistance of the higher strength steel grade S460 is currently somewhat lower compared to steel grade S355. According to Background Documentation D.03 (1990) and Gresnigt (2002) the reason for the low design resistance of steel grade S460 in comparison to S355 is seen in the limited number and the large scatter of available test results. Additionally, one can see an increased design resistance of steel grade S690 compared to S460.

2 INVESTIGATIONS OF RESEARCH PROGRAMME P652

2.1 *Scope and test programme*

The absence of well defined strength functions for welds of steel grade S460 and S690 according to EN 10025 (2005) as well as the restrictions of EN 1993-1-8 (2005) and EN 1993-1-12 (2005) which lead to very thick fillet welds led to the initiation of a German national research project realised by four partners in Stuttgart, Weimar, Darmstadt and Jena (Kuhlmann et al. (2008a)). The aim of this project was the investigation of strength and ductility of welded high strength steel connections by means of experimental and numerical analyses.

For the determination of the strength function three joint types were tested: longitudinal fillet welded lap joints, fillet welded cruciform joints and butt joints with partial penetration welds. The test specimens were designed in a way to force failure in the weld. Within a lot of tests the strength and ductility of joints with fillet welds and partial penetration welds of high strength steel S460M and S690Q have been investigated. Most experimental tests were performed at room temperature on longitudinal fillet welded lap joints, see Figure 2. This configuration is well known from other research work (Background Documentation D.03 (1990), Gresnigt (2002) or Feder & Werner (1977)) to be the most severe configuration and thus governs the strength function for fillet welds. A limited number of specimens were tested at low temperature (-40°C). Most test specimens were fabricated in a semi-mechanised way using MAG welding. Welding parameters, cooling rate etc. were chosen following the recommendations for welding of metallic materials according to EN 1011-2 (2001).

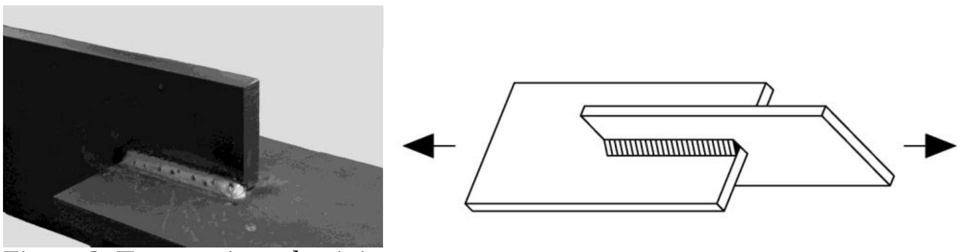
Figure 2. Test specimen lap joint

2.2 *Test results for lap joints and recommendations*

For lap joints where the welds are orientated parallel to the load direction, Figure 3 illustrates a comparison of the test results for steel grades S355J2, S460M and S690Q in terms of the ultimate shear stress τ_{II}. Herein the ultimate shear stress is determined based on the maximum force measured during the test divided by the fracture area measured after the test. For all steel grades matching conditions were chosen, which means that the nominal yield strength of the filler metal is the same as for the base metal. Indirectly the yield strength of the filler metal determines a compatible ultimate strength which causes the load bearing capacity of the weld. By comparing the mean values of the ultimate stresses it seems that the connections made of steel grade S460M have a clearly higher strength than S355J2, whereas for the steel grade S690Q only a slightly higher strength compared to S460M may be evaluated. The test specimens only included semi-mechanised MAG-welding and thereby produce a "real life" scatter, which made it difficult to develop more precise strength functions. But the scatter is very important for the statistical evaluation and the safety of the results.

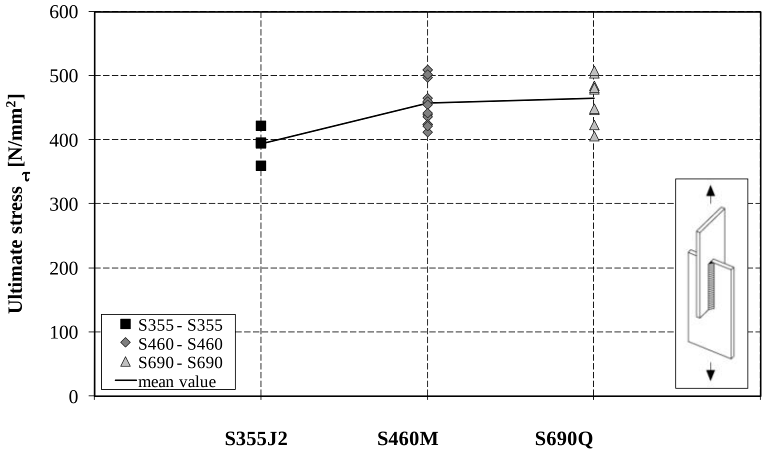

Figure 3. Comparison of ultimate stresses of lap joints of S355J2, S460M and S690Q, matching condition

A statistical evaluation was done in accordance with EN 1990 Annex D: Statistical determination of resistance models. This method is an evaluation procedure for deriving and calibrating resistance models or design models for a resistance function. The aim of the statistical evaluation was to improve the existing resistance model according to Equation (1) by updating the correlation factor β_w for high strength steels of grade S460 and S690. Details regarding the statistical evaluation and the improved strength functions are given in Kuhlmann et al. (2008a). For matching conditions, the values of β_w were evaluated taking into account the required minimum partial safety factor for the resistance of welds according to EN 1993-1-8 (2005) of $\gamma_{M2} = 1.25$. In Figure 4 the experimentally determined ultimate loads r_e for longitudinal fillet welded lap joints with steel grade S460M are compared with the theoretical predicted loads r_t. These were obtained by using the strength function of Equation (1). For the specified test data the evaluation led to $\beta_w = 0.79$ for steel grade S460M. Compared with the existing design specifications in EN 1993-1-8 (2005) for longitudinal fillet welded connections with the base metal S460M the test results show a much higher load bearing capacity.

Based on the given results an improvement of the resistance function has already been realised within the German National Annex DIN EN 1993-1-8/NA by fixing the correlation factor to $\beta_w = 0.85$ instead of 1.0 for steel grade S460, resulting in a higher resistance of about 15 %. For the steel grade S690 the tests which were carried out with longitudinal fillet welded lap joints could not confirm the existing values of β_w given in EN 1993-1-12 (2005) that were based on an evaluation in Collin & Johansson (2005). Further investigations have to be realised. First results are presented in the following.

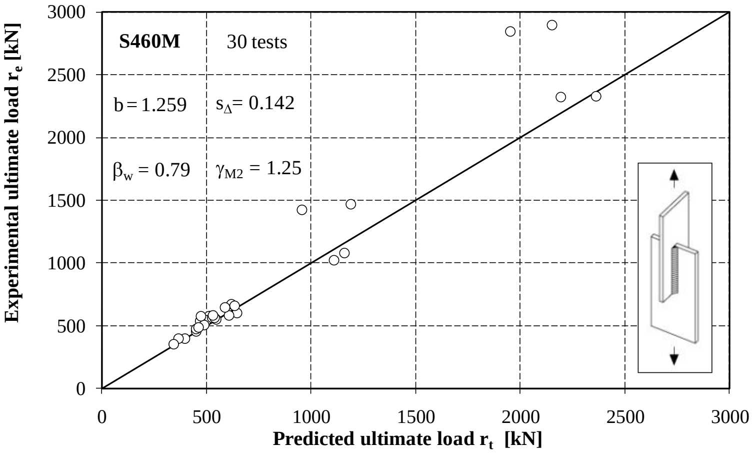

Figure 4. Plot of test results r_e over theoretical predicted results r_t for longitudinal fillet welded lap joints and steel grade S460M

3 ADDITIONAL INVESTIGATIONS ON FILLET WELDS OF STEEL GRADE S690Q

3.1 *Scope and test programme*

Additional experiments have been planned and carried out to study the behaviour of longitudinal fillet welded lap joints of steel grade S690Q more detailed. The aim of these additional tests was to investigate possible factors influencing the strength in four series: influence of fully mechanised manufacturing process and the type of test specimen, variation of the cooling rate, filler metal with matching and mismatching conditions and single- and multi-layer welds.

The additional test serial was set up by simply using a full-mechanised welding process. Furthermore, the kind of specimen form was chosen in a way that excluded any influence of start and end regions of the weld. In Figure 5 the test specimen is illustrated after mechanical work. For additional test specimens the variation of welding speed, ampere and voltage results in test specimens with different cooling rates $t_{8/5}$ = 7.5, 10 and 15 seconds for test specimens with filler metal G69. Besides, investigations on the influence of the strength of the filler metal have been carried out using matching and over-matching filler metal G69 with nominal yield strength of 690 N/mm² and G89 with 890 N/mm². With test specimens using a filler metal G89 the influence of the weld thickness has been investigated by variation of single and multi-layer welds with a weld thickness of a = 4 mm and a = 9 mm. The material properties are listed in Table 2. The measurement at the ends of the weld has been carried out with displacement transducers in addition to standard strain gauges. During the tests, fracture always occurred in the weld itself (see Figure 5), not in the heat affected zone or in the base metal. More information can be found in Kuhlmann et al. (2008b).

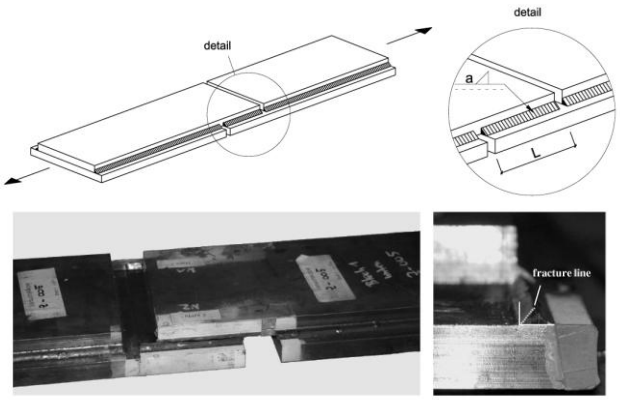

Figure 5. Test specimen after mechanical work and typical fracture

Table 2. Material properties of the used base and filler metal

Name		$R_{p0,2}$ [N/mm²]	R_m [N/mm²]	A [%]
S690Q[1)]	longitudinal	713	760	22,2
	transversal	767	797	19,5
G69[2)]	--	724	836	15,4
G89[2)]	--	931	981	18,5

[1)] EN 10025 (2005), [2)] EN 12534 (1999)

3.2 *Test results*

Figure 6 shows a comparison of all test results in terms of the ultimate stress $\tau_{II.}$ It should be noticed that due to the careful preparation the two nominally identical test specimens delivered almost the same values. So scatter has really vanished throughout the whole test series. By comparing the ultimate stresses the connection made of steel grade S690Q with filler metal G89 has a higher strength compared to S690Q with G69. Comparing the mean values of the test results, an increase of the load bearing capacity of about 9% is apparent.
In Figure 7 the comparison of the deformation capacity for different filler metals is shown. The increase in strength is related to a loss of ductility as it can be seen from the load-displacement curve, where Δu indicates the relative displacement between the weld ends at the base metal.

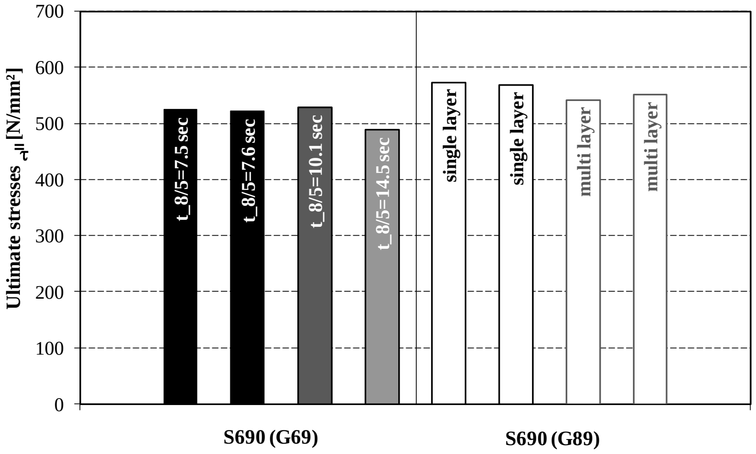

Figure 6. Comparison of all test results

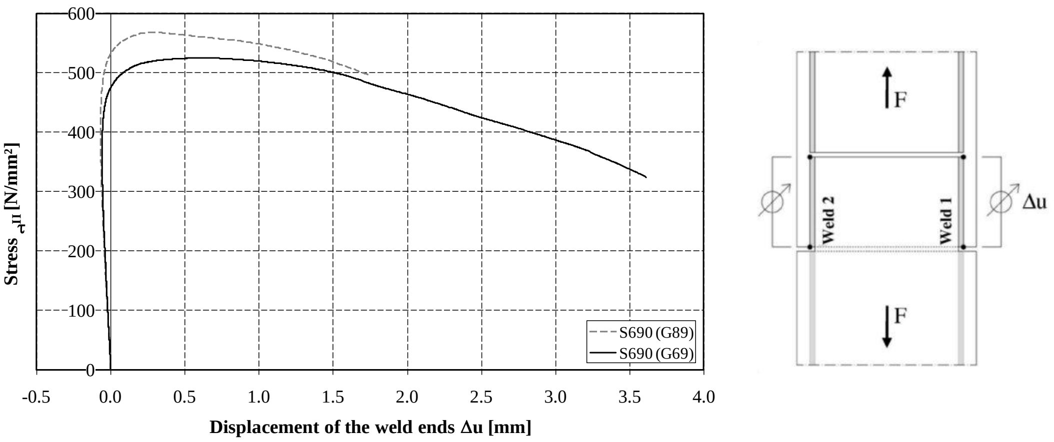

Figure 7. Influence of the strength of the filler metal to the deformation capacity

3.3 *Hardness tests*

To investigate the differences between the load bearing capacities of joints with the base metal S690 and the filler metals G69 and G89 hardness measurements on macro specimens have been carried out in accordance to EN 1043-1 (1995). The compared hardness values for a line placed near the surface are shown in Figure 8. The regions of the base metal (BM), the heat affected zone (HAZ) and the weld metal (WM) are marked. Comparing the values of the hardness in the region of the weld it seems that the strength of the weld made of filler metal G89 is 10 - 15 % higher than for the filler metal G69.

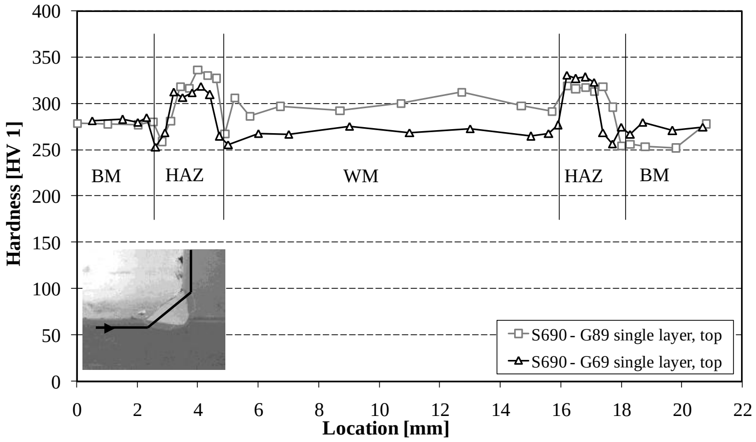

Figure 8. Comparison of hardness of different filler metal G69 and G89

4 NUMERICAL SIMULATIONS

Beside the experimental work, numerical investigations have been performed to determine the ultimate load and the deformation behaviour. The Finite Element (FE) simulations were realised using the commercial software package ANSYS® 11.0 and verified by the load-displacement and -strain measurements obtained in the experimental tests. The FE simulations consider geometrical nonlinearity and an elastic-plastic material model including rate independent von-Mises plasticity with a multi-linear isotropic hardening model. Two different material properties (weld metal and base metal) are covered whereas the properties were derived from standard tension tests and in dependence of Table 2 from inspection certificates. Figure 9 shows the meshed cross-section. The cross-section of the weld was modelled with the aid of a macro specimen. Figure 10 illustrates the whole model, half of the test specimen by using symmetrical properties. The mechanical strains and equivalent stresses show the fracture behaviour of the test specimen.
The results of an ultimate load simulation performed by the authors are presented in Figure 11. The diagram compares the load-displacement curve obtained by tests with the FE simulation of a standard test specimen of steel grade S690Q with matching filler metal. When using a multi-linear material model the ultimate load is predicted with an accuracy of about 4 %. The stress and strain redistribution was analysed and showed a good agreement between simulation and test.

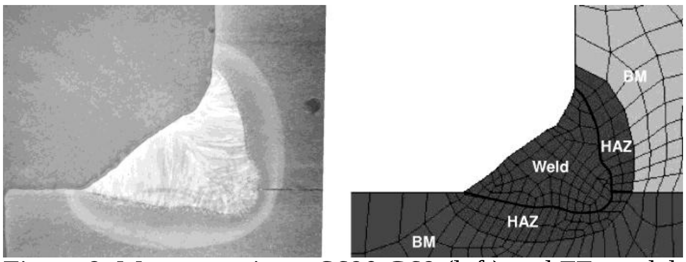

Figure 9. Macro specimen S690 G69 (left) and FE-model (right)

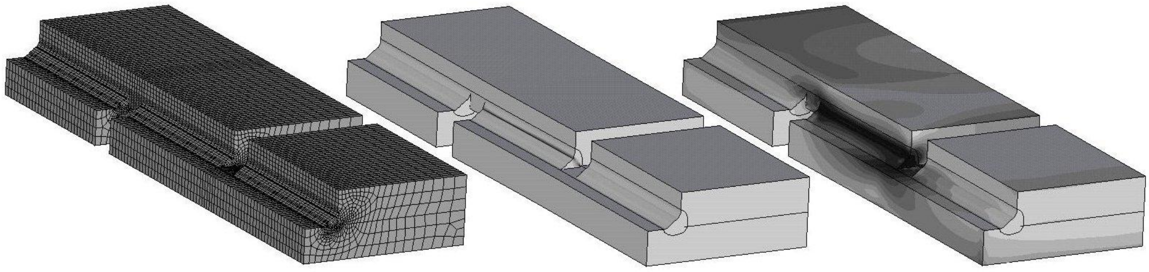
Figure 10. FE-Model – First principal total mechanical strain - Equivalent stresses

With the verified model additional calculations have been carried out to investigate the influence of different material combinations of base and filler metal. Figure 12 illustrates the numerical results of two different material combinations. It can be seen that by increasing the strength of the filler metal from G69 to G89 the load bearing capacity increases almost in the same way. The numerical calculations exhibit a difference of 14 % in the load bearing capacity between the two tests. This difference reflects the results of the tests and the hardness measurements.

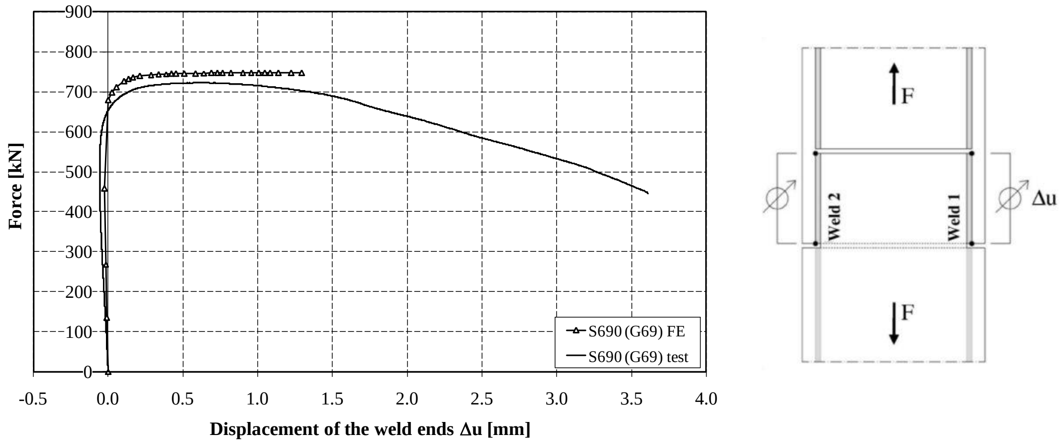

Figure 11. Load–displacement diagram, FE simulation vs. test result

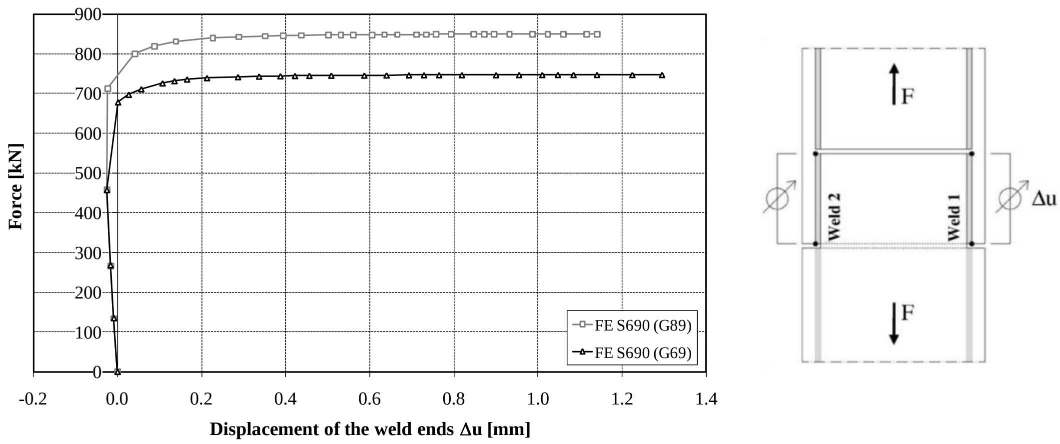

Figure 12. FE results, load-displacement behaviour for different base and filler metal combinations

5 SUMMARY, OUTLOOK AND ACKNOWLEDGEMENT

This paper presents parts of the results of a research project dealing with the strength and ductility of welded high strength steel connections. It is shown that the existing design rules given in Eurocode 3 (steel structures) present a rather conservative approach especially for S460M. The described experimental investigations indicate the need to update the existing design rules in terms of improved resistance functions. Based on the given results an improvement of the resistance function has already been realised within the German National Annex of Eurocode 3 Part 1-8 DIN EN 1993-1-8/NA by fixing the correlation factor to $\beta_w = 0.85$ instead of 1.0 for steel grade S460. However, further improvements for steel grades S690 and the possibility to take into account the strength of the filler metal are still necessary. Thus, the results may lead to an improvement of the design and safety of welded high strength steel connections in the construction industry. This project has been realised by four German research partners: Universitaet Stuttgart, Bauhaus-Universitaet Weimar, Technische Universitaet Darmstadt and the Guenter-Koehler-Institute, IFW Jena. Detailed information about the research project may be found under: http://www.uni-stuttgart.de/ke/AiF_14195.html or Kuhlmann et al. (2008a).

The results of additional tests show that by means of a fully mechanised manufacturing process and a test specimen without a start and end region of the weld a low scatter in test results can be achieved. The experimental results of the longitudinal fillet welded connections of base metal S690Q with a filler metal G89 have shown an increase in strength of 9 % compared to the results of the same base metal in combination with filler metal G69. Comparing the results of the hardness measurements with the test results it is obvious that the differences in the load bearing capacity are well reflected by the hardness values. This difference is also detected in the numerical simulations.
By comparing the results of the research project Kuhlmann et al. (2008a), based on a semi-mechanised welding process, with the additional test results, based on a full-mechanised welding process and an improved test specimen form without any influence of a weld start and end region, no difference between the mean values of the load bearing capacities could be observed. Contrary to the existing normative regulations, the evaluations of the test results show that the determined ultimate stresses τ_{II}, due to the failure in the weld, exhibit a good correlation with the tensile strength of the filler metal. Thus, the load bearing capacity of the connection is essentially determined by the strength of the filler metal. Further investigations are planned to determine the behaviour of fillet welded lap joints with steel grade S690 in detail.
Special thanks are given to the German Federation of Industrial Research Associations „Otto von Guericke“ e.V. (AiF) and the German Research Association for Steel Application (FOSTA) for the financial support and to all the industry partners for the supply of material and the welding work done. We thank the project partners for the good team work. Furhtermore we want to thank voestalpine in Linz/Austria for preparing the additional test specimens.

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