ce/papers Proceedings in civil engineering

Ernst & Sohn A Wiley Brand

ORIGINAL ARTICLE

eurosteel AMSTERDAM 2023 Ernst & Sohn A Wiley Brand

# Study on load-carrying capacity of MAG butt-welded mixed connections with different steel strengths

Mareike von Arnim[1] | Stefan Eichler[2] | Oliver Brätz[3] | Jörg Hildebrand[2] | Ulrike Kuhlmann[1] | Jean Pierre Bergmann[2] | Wilko Flügge[3]

**Correspondence**

Mareike von Arnim, M. Sc.
University of Stuttgart
Institute of Structural Design
Pfaffenwaldring 7
70569 Stuttgart, Germany
Email: mareike.von-arnim@ke.uni-stuttgart.de

[1] University of Stuttgart, Institute of Structural Design, Stuttgart, Germany
[2] Technische Universität Ilmenau, Department of Mechanical Engineering, Product Engineering, Ilmenau, Germany
[3] Fraunhofer IGP, Rostock, Germany

**Abstract**

Mixed connections of normal-strength steel and high-strength steel can enable an optimum resource-saving use of materials by adapting the material strength to the forces acting on them. But the design and calculation of butt-welded mixed connections is not clearly regulated in the currently valid standards EN 1993-1-8 and EN 1993-1-12. In the research project *Effective design concepts for mixed connections in steel structures* an extensive experimental program with 180 mixed connections has been conducted to investigate the load-carrying capacity and behaviour of these connections. The weld joint specimens were made with normal-strength steel S355J2+N and different high-strength steels S690QL, S700MC or S960QL. Varying parameters were also the filler metals, plate thicknesses, weld bevels and the heat input during welding. The influence of these parameters on the load-carrying capacity and the deformation behaviour of mixed connections was investigated. Moreover, high-resolution microhardness mappings (UCI) on the welded specimens were carried out to examine the formation of the soft zone in the heat-affected zone of the high-strength steels.

**Keywords**

mixed connection, butt weld, high-strength steel, tensile test, heat-affected zone, soft zone, GMAW welding

## 1 Introduction

The use of high-strength steel has many beneficial aspects, such as the reduction of material requirements and consequently a decrease of the overall construction weight. In order to use high-strength steels efficiently, the need of butt-welded mixed connections of normal-strength and high-strength steel may be necessary. In bridge construction or wind turbines, the load-carrying capacity can be adapted to the moment curve without having to adjust the plate thicknesses. Moreover, this avoids time-consuming and cost-intensive joint preparations for butt welds on plates of different thicknesses. This results in an improved environmental balance and cost savings due to lower plate thicknesses with reduced weld metal volume.

Current research results show that welding high-strength steels can lead to a formation of a soft zone with locally reduced strength in the heat-affected zone (HAZ) of the base material [1]-[3]. This may result in a premature failure in the HAZ with a reduced load-carrying capacity of over 15 % below the tensile strength of the high-strength steel [4], [5]. At present, according to regulations there is no need for a separate verification of a full penetration butt-welded connection, but rather it is assumed that the verification for the base material according to EN 1993-1-1 [6] is sufficient and the butt weld is always stronger. For butt-welded mixed connections, the verification according to EN 1993-1-8 [7] specifies that the load-carrying capacity is equal to the strength of the weaker connected component. In addition, it is specified that the filler metal needs to have the minimum strength of the base material. It is not defined to what steel grade this refers in case of mixed connections. The new draft FprEN 1993-1-8 [8] contains a new design concept that allows a safe and user-friendly design of high-strength butt-welded connections with different filler metal strengths and is valid up to S700. The new version prEN 1993-1-12 [9] will extend the rules up to S960.

Within the scope of the ongoing research project [10], extensive experimental investigations were conducted up to steel grade S960 to examine the load-carrying capacity and deformation behaviour of mixed connections. Furthermore, it was investigated whether the formation of a soft zone in the HAZ of the high-strength steel in mixed connections is relevant for the load-carrying capacity of the welded connections.



https://doi.org/10.1002/cepa.2262 wileyonlinelibrary.com/journal/cepa

**Table 1** Variables of the test matrix

| Base material | Plate thickness | Filler metal | Weld bevel | Heat input |
|---|---|---|---|---|
| - EN 10025-2-**S355J2+N** (1.0577)<br>- EN 10025-6-**S690QL** (1.8928)<br>- EN 10149-2-**S700MC** (1.8974)<br>- EN 10025-6-**S960QL** (1.8933) | - 10 mm<br>- 20 mm | - ISO 14341-A **G 46** 5 M21 4Si1<br>- ISO 16834-A **G 69** 6 M21 Mn4Ni1,5CrMo<br>- ISO 16834-A **G 79** 5 M21 Mn4Ni1,5CrMo<br>- ISO 16834-A **G 89** 6 M21 Mn4Ni2CrMo<br>- ISO 18276-A **T 69** 6 Mn2NiMo M M21 2 H5<br>- ISO 18276-A **T 89** 4 Z M M21 3 H5 | - V-weld<br>- DV-weld | - low ($t_{8/5,target}$ = 5 s)<br>- high ($t_{8/5,target}$ = 8 or 12 s) |

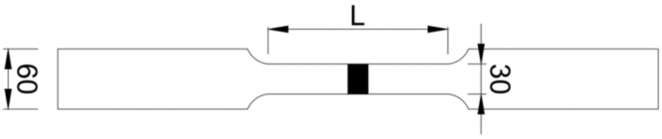
## 2 Experimental investigations

### 2.1 Experimental programme

A large experimental programme of mixed connections has been set up with 180 test specimens as part of the ongoing research project [10]. An S355J2+N was used as the normal-strength material while S690QL and S700MC was used as the high-strength material as well as S960QL with regard to prEN 1993-1-12 [9]. The variables of the test matrix are given in Table 1, and the test matrix of mixed connections is specified in Table 2. For each configuration G46 solid wire electrode was used on the one hand, and a solid wire electrode as well as tubular metal cored electrodes matching the high-strength steel on the other: G/T69 for S690, G79/G69 for S700 and G/T89 for S960. Since T79 is uncommon to use in practice, a G69 is used instead for S700. The filler metal strength class "89" was used as "matching" for steel grade S960 since it is the maximum strength class available for standardized filler materials. Each combination given in Table 2 was executed both with single-V groove (V) and double-V groove (DV). Furthermore, each configuration was welded with a high and a low heat input. By this, the variations in production that occur in practice are represented by the experimental tests.

**Table 2** Test matrix of mixed connections

| Plate thickness in mm | Base material 1 | Base material 2 | Filler metal |
|---|---|---|---|
| 10 | S355J2+N | S690QL | G46 |
| | | | G69 |
| | | | T69 |
| | | S700MC | G46 |
| | | | G79 |
| | | | G69 |
| | | S960QL | G46 |
| | | | G89 |
| | | | T89 |
| 20 | S355J2+N | S690QL | G46 |
| | | | G69 |
| | | | T69 |
| | | S960QL | G46 |
| | | | G89 |
| | | | T89 |




for $t$ = 10 mm: $L$ = 130 mm
for $t$ = 20 mm: $L$ = 180 mm

**Figure 1** Welded test specimen for tensile tests, depending on the thickness of the specimen [mm]

Three test specimens were cut out from the centre of the welded plates for each configuration, resulting in a total of 180 specimens for tensile tests on butt-welded mixed connections. The specimen geometry is shown in Figure 1. The parallel length depending on the plate thickness was $L$ = 130 mm for $t$ = 10 mm and $L$ = 180 mm for $t$ = 20 mm thick specimens. The total length of the test specimens including the clamping area was approximately 600 mm. Furthermore, high-resolution microhardness mappings were made of selected combinations of the test matrix to examine the hardness distribution, especially in the HAZ.

In addition, 44 mixed connections on plates with thickness $t$ = 3 mm were welded and tested within the research project [10]. These investigations, as well as 32 connections on butt welds of the same grade with $t$ = 3 mm are presented in [11].

### 2.2 Welding of samples

Prior to the welding, the joint preparation was made by milling. Taking into account the materials used, an appropriate preheating temperature was determined according to EN 1011-2 [12] and carried out in an oven or by using induction heating. The welded specimens were produced by gas metal arc welding (GMAW) using solid wire electrode (135) or metal cored electrode (138). The welding was performed fully mechanised using a robot, see Figure 2. A mixed gas in accordance with ISO 14175 – M21 – ArC – 82/18 was used as shielding gas.

The $t_{8/5}$-time is specified as cooling time of the weld from 800 to 500 °C after welding and it was used as parameter to specify the different high and low heat inputs during welding. The target cooling time was $t_{8/5}$ = 5 s to represent low heat input welding and $t_{8/5}$ = 12 s for S690QL and S700MC or $t_{8/5}$ = 8 s for S960QL within the meaning of high heat input welding, respectively.

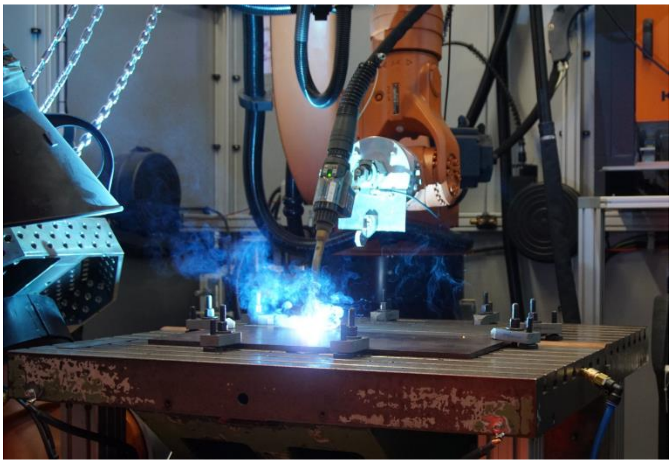


**Figure 2** Welding of samples using a 6-axis robot handling system (Kuka KR60HA)

GMAW welding process with varying wire feed rates (7,5 to 12,5 m/min) and arc modes (short, pulsed and spray) were used to obtain the target cooling times (± 20 %). The welding speed for all specimens was set to 45 cm/min, therefore the resulting mean arc energies were in the range of 0,5 to 1,2 kJ/mm depending on the target cooling time, preheating temperature and the used welding consumable.

The actual required number of weld beads to achieve a full penetration butt weld depends on the welding parameters as well as the groove type and plate thickness. The joints with $t$ = 10 mm plate thickness were multipass welded with up to eight runs in two to four layers. The thicker $t$ = 20 mm test specimens were welded with up to fourteen passes in four to six layers.

### 2.3 Tensile tests on welded specimens

Quasi-static transverse tensile tests were carried out displacement controlled until failure with a constant testing speed of 2 mm/min for the 10 mm samples and 3 mm/min for the 20 mm thick specimens according to ISO 6892-1 [13]. Testing of the specimens is carried out with a 1000 kN testing machine, see Figure 3.

The optical measuring system used was ARAMIS from Carl Zeiss GOM Metrology GmbH, that was also synchronized to the force output of the testing machine [14]. For this purpose, a grey-scale pattern was applied to the test specimens, that was distorted during the tests and allowed to follow the deformation of the surface optically. With the software of the system, the local strains during testing could be determined, displayed in colour and assigned to the corresponding force. The experimental test setup, a grey-scale pattern as well as a display of the strains with colour are shown in Figure 3.

## 3 Results and discussion

### 3.1 Hardness mappings

High-resolution ultrasonic hardness mappings were made to examine the strength distribution of the connections. A close investigation was made of the characteristics of the HAZ and especially the soft zone.

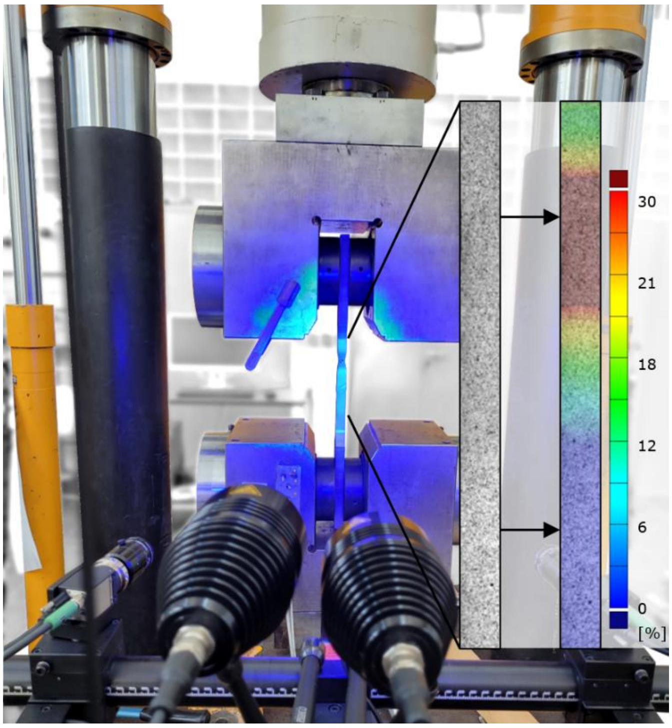



**Figure 3** Experimental setup: 1000 kN testing machine, optical measuring system ARAMIS and random grey-scale pattern with evaluated strain

The mappings were carried out in Vickers microhardness range HV 0,1. A BAQ UT-200 hardness tester with the ultrasonic contact impedance method (UCI) was used. To validate the measurement methodology comparative measurements were carried out with Struers Durascan optical hardness tester, which provided good agreement [15].

A hardness mapping of a mixed connections from normal-strength steel S355J2+N and high-strength steel S700MC with a thickness of $t$ = 10 mm welded with G79 is shown in Figure 4 a). The welding was performed with a high heat input. It is clearly evident that a pronounced soft zone occurred in the HAZ of the S700MC. Figure 4 b) shows the width of the soft zone in relation to the height of the specimen. This shows that the width of the soft zone varies over the height of the specimen. The mean width of the soft zone was 1,7 mm for an execution with single-V groove for steel grade S700MC, as listed in Table 3.

For mixed connections with a thickness of $t$ = 20 mm, hardness mappings of high-strength steels S690QL with filler metal G69 as well as S960QL with filler metal G89 are shown in Figure 5 a) and b). Both test specimens were welded with high heat input and single-V groove. The two high-strength steels developed a soft zone in the HAZ. The width of the soft zone is shown in Figure 5 c). It can be observed that the steel grade S960QL resulted in a wider soft zone compared to S690QL. This is also clearly represented in Table 3 by the mean width given.

Table 3 also gives the mean hardness values of the soft zone, the high-strength steel, the weld metal and the normal-strength steel. On average, the normal-strength steel S355J2+N has a hardness of 182 HV 0,1 (UCI). Consequently, the softening in the HAZ of the used high-strength steels was sufficiently small, with a lowest value of 251 HV 0,1 (UCI), that no risk of premature failure was expected. The softening in the HAZ compared to the base material was between 8 % and 16 %, depending on the high-strength steel used. The average hardness in the weld was greater than the hardness in the high-strength base material for the welded combinations examined in Figure 4 and Figure 5. For a rough estimation, the measured hardness values can be converted into tensile strengths according to ISO 18265 [15][16].

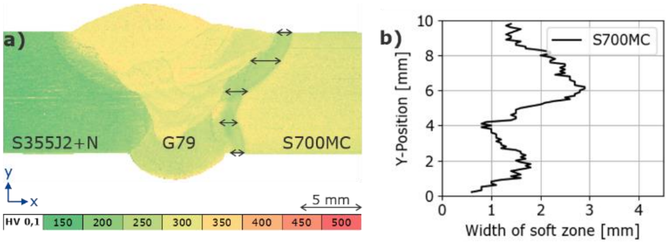



**Figure 4** Hardness mappings HV 0,1 (UCI) on mixed connection with high heat input during welding, $t$ = 10 mm, V-weld: a) S355J2+N – G79 – S700MC; b) width of soft zones

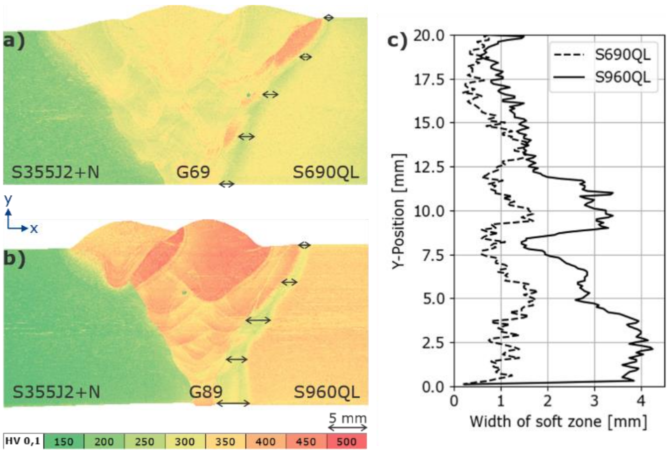



**Figure 5** Hardness mappings HV 0,1 (UCI) on mixed connection with high heat input during welding, $t$ = 20 mm, V-weld: a) S355J2+N – G69 – S690QL; b) S355J2+N – G89 – S960QL; c) width of soft zones

**Table 3** Evaluation of hardness mappings for different butt-welded connections

| | **S700MC G79 $t$ = 10 mm** | **S690QL G69 $t$ = 20 mm** | **S960QL G89 $t$ = 20 mm** |
|---|---|---|---|
| **Mean width of soft zone** | 1,7 mm | 1,0 mm | 2,3 mm |
| **Mean hardness of soft zone** | 251 HV 0,1 (UCI) | 280 HV 0,1 (UCI) | 304 HV 0,1 (UCI) |
| **Mean hardness of high-strength steel** | 292 HV 0,1 (UCI) | 306 HV 0,1 (UCI) | 360 HV 0,1 (UCI) |
| **Mean hardness of weld metal** | 305 HV 0,1 (UCI) | 315 HV 0,1 (UCI) | 391 HV 0,1 (UCI) |
| **Mean hardness normal-strength steel** | 179 HV 0,1 (UCI) | 186 HV 0,1 (UCI) | 180 HV 0,1 (UCI) |

## 3.2 Load-carrying capacity

The maximum load-carrying capacity $\sigma_{max}$ of the tested butt-welded mixed connections is obtained from Eq. (1) with the maximum achieved force $F_{max}$ and the initial cross-sectional area at the point of failure $S_0$. The weld reinforcement was removed from all specimens before testing. Nevertheless, the cross-section was measured at several locations in order to take into account variations in the plate thickness or specimen width.

$$\sigma_{max} = \frac{F_{max}}{S_0} \tag{1}$$

The results of the load-carrying capacity tests are given for $t$ = 10 mm in Figure 6 and for $t$ = 20 mm in Figure 7. The figures show the results of full penetration butt-welded mixed connections. The load-carrying capacity is shown on the vertical axis. The tensile strength of the normal-strength base material S355J2+N according to the acceptance test certificates is shown with a horizontal red line.

The experimental results of butt-welded mixed connections show that the different parameters investigated had no effect on the load-carrying capacity of the welded connections. All full penetration butt-welded connections reached the load-carrying capacity of the normal-strength base material S355J2+N. Failure always occurred in the unaltered normal-strength base material S355J2+N. The soft zone detected by the hardness mappings (see section 3.1) had no significant influence on the load-carrying capacity of the entire connection or the failure location. This assumption was already made from the hardness investigations, see Table 3, and is thereby confirmed by the transverse tensile tests.

Thus, it can be concluded that for the examined mixed connections the load-carrying capacity of the butt-welded joints is not depending on the varied parameters. The load-carrying capacity of the normal-strength steel S355J2+N (tensile strength) was achieved for all connections. Consequently, it is not necessary to use a filler metal matching with the high-strength steel, but rather it must fulfil the requirements for a welded normal-strength steel according to FprEN 1993-1-8 [8].

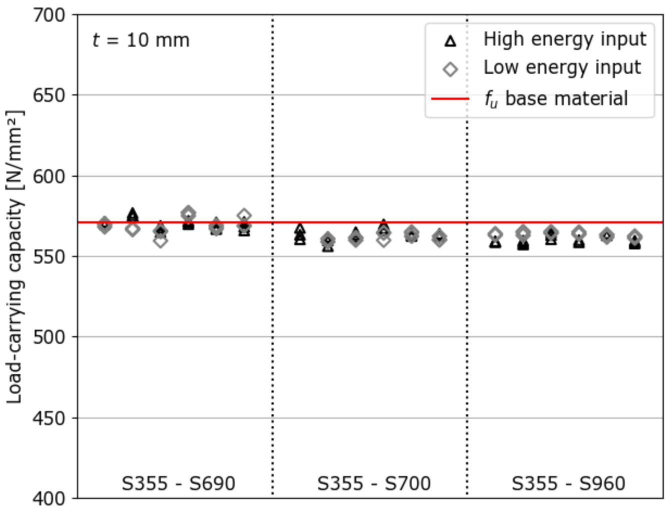



**Figure 6** Results of load-carrying capacity test of mixed connections with $t$ = 10 mm

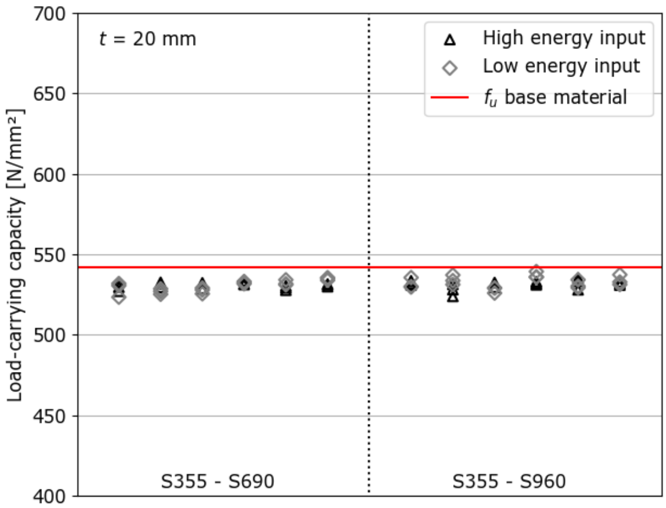



**Figure 7** Results of load-carrying capacity tests of mixed connections with $t$ = 20 mm

### 3.3 Deformation behaviour

By using the ARAMIS measurement system, the local strain during testing could be visualised in the corresponding software. Figure 8 shows an evaluation of a transverse tensile test on a butt-welded mixed connection. In Figure 8 a) an evaluation of strain is given and in b) the corresponding stress-strain graph is shown.

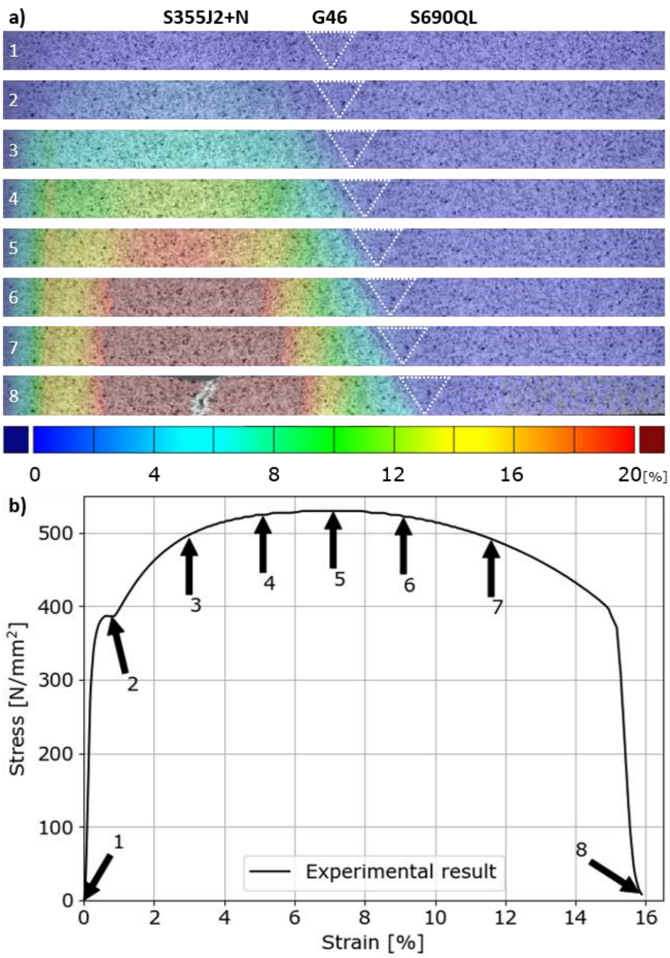



**Figure 8** Experimental results from S355J2+N – G46 – S690QL with high heat input during welding and V-weld with $t$ = 20 mm; a) deformation behaviour during testing; b) stress-strain graph

During the test, strain occurred almost exclusively in the normal-strength steel S355J2+N. The strain continues to concentrate as the test progressed until necking and finally fracture of the specimen occurred. In Figure 8 a), the weld seam is marked and no significant strain can be detected in the soft zone of the high-strength steel S690QL next to the weld seam. The stress-strain diagram shows the behaviour of a normal-strength steel exhibiting a typical yield phenomenon and gives an upper yield strength of about $R_{eH}$ = 385 N/mm² and subsequent strain-hardening until the tensile strength is reached. The specimen then constricted until failure. A similar behaviour was observed for all tested specimens.

Consequently, it can be said that the examined parameters do not influence the deformation behaviour of butt-welded mixed connections. Furthermore, no significant deformation was visible in the soft zone of the HAZ zone in the high-strength steels.

## 4 Conclusions

Within the research project [10], 180 experimental tests were carried out on full penetration butt-welded mixed connections of normal-strength steel and high-strength steel with different thicknesses $t$ = 10 and 20 mm. Further investigations on mixed connections within the research project were carried out with plate thickness $t$ = 3 mm and they are presented in [11].

Here a S355J2+N was used as normal-strength steel and S690QL, S700MC or S960QL as high-strength steel. In addition, further parameters such as the filler metal, the groove type and the heat input during welding were varied. The following conclusions are made:

a) For butt-welded mixed connections of normal-strength steel S355J2+N and high-strength steel S690QL, S700MC or S960QL the tensile strength of the connected normal-strength steel is reached.
b) There is no need of using a matching filler metal regarding the high-strength steel to achieve the full load-carrying capacity of the connection. The filler metal used must only meet the requirements for a welded connection with normal-strength steel.
c) The failure of the butt-welded connections occurred exclusively on the normal-strength steel and no relevant deformations were detected in the high-strength steel and the soft zone in particular.
d) The examined parameters given in Table 1 did not influence the load-carrying capacity or the deformation behaviour of the welded connections.
e) The high-strength steels formed a soft zone in the HAZ. The softening and the size of the soft zone depended on the steel grade.
f) The mean hardness in the soft zone of the high-strength steels S690QL, S700MC or S960QL was higher than the hardness of the connected normal-strength steel S355J2+N.

## 5 Acknowledgement

The IGF project "Effective design concepts for welded mixed connections in steel structures" [10] (21412 BG/P 1507) of the Research Association for Steel Application e. V. (FOSTA), Sohnstraße 65, 40237 Düsseldorf, Germany, is a sub-project of the FOSTA joint research program HOCHFEST and was funded by the Federal Ministry for Economic Affairs and Climate Action via the AiF within the framework of the program for the promotion of joint industrial research and development (IGF) on the basis of a resolution of the German Bundestag. Special thanks go to the industrial partners of the project committee for their support of the research project.

**References**

[1] Maurer, W.; Ernst, W.; Rauch, R.; Vallant, R; Enzinger, N. (2015) *Evaluation of the factors influencing the strength of HSLA steel weld joint with softened HAZ*. Weld World 59, 809-822. https://doi.org/10.1007/s40194-015-0262-z

[2] Ran, M.-M.; Sun, F.-F.; Li, G.-Q.; Kanvinde, A.; Wang, Y.-B.; Xiao, R. Y. (2019) *Experimental study on the behaviour of mismatched butt welded joints of high strength steel*. Journal of Constructional Steel Research 153, 196-208. https://doi.org/10.1016/j.jcsr.2018.10.003

[3] Amraei, M.; Afkhami, S.; Javaheri, V.; Larkiola, J.; Skriko, T.; Björk, T.; Zhao, X.-L. (2020) *Mechanical properties and microstructural evaluation of the heat-affected zone in ultra-high strength steels*. Thin-Walled Structures 157. https://doi.org/10.1016/j.tws.2020.107072

[4] Bergmann, J. P.; Hildebrand, J.; Kuhlmann, U.; Spiegler, J.; Keitel, S.; Mückenheim, U. (2020) *Tragfähigkeit von Stumpfnähten höherfester Stähle im Stahlbau.* (engl.: *Load-carrying capacity of butt welds made of high-strength steel*.) Research report, AiF; IGF-Nr. 19.470 BG; DVS-Nr. 09.083. ISBN: 978-3-96870-458-6

[5] Spiegler, J. (2022) *Tragfähigkeit von Kehl- und Stumpfnahtverbindungen höherfester Baustähle.* Dissertation. Mitteilung Institut für Konstruktion und Entwurf No. 2022-2, University of Stuttgart. http://dx.doi.org/10.18419/opus-12207

[6] DIN EN 1993-1-1:2010-12 (2010) *Eurocode 3: Design of steel structures - Part 1-1: General rules and rules for building*; German version EN 1993-1-1:2005 + AC:2009.

[7] DIN EN 1993-1-8:2010-12 (2010) *Eurocode 3: Design of steel structures - Part 1-8: Design of joints*; German version EN 1993-1-8:2005 + AC:2009.

[8] FprEN 1993-1-8:2023 (2023) *Eurocode 3 – Design of steel structures – Part 1-8: Design of joints*. Formal Vote Version. European Committee for Standardization.

[9] CEN/TC 250/SC 3/WG 12 N139 (2023) *prEN 1993-1-12 Eurocode 3: Design of steel structures – Part 1-12: Additional rules for the extension of EN 1993 up to steel grades S960*, Working Draft (unpublished), European Committee for Standardization.

[10] Kuhlmann, U.; Bergmann, J. P.; Flügge, W.; Hildebrand, J.; Gericke, A.; von Arnim, M.; Eichler, S.; Brätz, O. (ongoing Project) *Effiziente Nachweiskonzepte für Mischverbindungen im Stahlbau.* (engl. *Effective design concepts for mixed connections in steel structures.)* German Federation of Industrial Research (AiF); IGF-Nr. 21412 BG; FOSTA-Nr. P 1507.

[11] Eichler, S.; von Arnim, M.; Brätz, O.; Hildebrand, J.; Gericke, A.; Bergmann, J. P.; Kuhlmann, U.; Henkel, K.-M. (2023) *Heat management and tensile strength of 3 mm mixed and matched connections of butt joints.* EUROSTEEL, Amsterdam.

[12] DIN EN 1011-2:2001-05 (2001) *Welding – Recommendations for welding of metallic materials – Part 2: Arc welding of ferritic steels.* German version EN 1011-2:2001.

[13] DIN EN ISO 6892-1:2020-06 (2020) *Metallic materials – Tensile testing – Part 1: Method of test at room temperature.* German version EN ISO 6892-1:2019.

[14] Carl Zeiss GOM Metrology GmbH (2022) *GOM Correlate Pro*. ARAMIS Adjustable 12M. https://www.gom.com/en/products/zeiss-quality-suite/gom-correlate-pro

[15] von Arnim, M.; Eichler, S. Brätz, O.; Hildebrand, J.; Gericke, A.; Kuhlmann, U.; Bergmann, J. P.; Flügge, W. (2022) *Effiziente Nachweiskonzepte für geschweißte Mischverbindungen im Stahlbau*. Stahlbau 91, H. 10, 660-670. https://doi.org/10.1002/stab.202200046

[16] DIN EN ISO 18265:2014-02 (2014) *Metallic materials – Conversion of hardness values.* German version EN ISO 18265:2013.