TESTS ON 10.9 BOLTS UNDER COMBINED TENSION AND SHEAR

Anne K. Kawohl*, Jörg Lange

Institute for Steel Structures and Materials Mechanics, Technische Universität Darmstadt, Darmstadt, Germany

* corresponding author: kawohl@stahlbau.tu-darmstadt.de

Abstract. Prior investigations of the load-bearing capacity of bolts during fire have shown differing behaviour between bolts that have been loaded by shear or by tensile loads. A combination of the two loads has not yet been examined under fire conditions. This paper describes a series of tests on high-strength bolts of property class 10.9 both during and after fire under a combined shear and tensile load.

Keywords: structural fire design; steel structures; material behaviour; high-strength bolts; experimental study; connections.

1. Introduction

In steel structures, connections are essential for the stability of the entire structure. They not only join one load-bearing member to another but they also transfer the load and influence the internal forces through their rigidity. The failure of a connection can lead not only to the failure of individual connected members but also, for example, to a change in buckling length within the structure and, as a consequence, to its collapse. In the load case of fire, connections are not only additionally strained by thermal exposure, but thermal exposure of the connected members leads to a change in the strain within the connection over the duration of the fire. At the beginning of a fire, while the temperature is still rising, the thermal expansion of the connected members leads to compression in the connection, which is commonly designed to carry shear and moment forces at ambient temperatures. In a later stage of the fire, at high temperatures, the connected steel members have lost most of their resistance, which again leads to massive deflections of the members and, in consequence, to large tensile and shear forces in the connection. After the fire, during the cooling phase, as the thermal expansion of the bearing members is reversed, the connection is strained by large tensile forces. In the case of a fire load, ductility of the connections is therefore essential. In recent years, the behaviour of joints in fire has been the focus of numerous investigations. Al-Jabri et al. [1] and Burgess et al. [2] give a good overview of research in this field.

All of these investigations have in common that they examine the connections as a whole. Within a connection there are many effects that come together and influence the load-bearing and deflection behaviour at elevated temperatures. To understand these different effects, it is important to have a thorough knowledge of the load-bearing behaviour of the individual elements of the connection, for example the bolts that are used. Appendix D of Eurocode 3 Part 1–2 [3] states reduction factors for the strength of bolts at elevated temperatures. These reduction factors are independent of the property class of the bolts. As high-strength bolts of property classes 8.8 and 10.9 ($f_u = 800\,\text{N/mm}^2$ or $f_u = 1000\,\text{N/mm}^2$) obtain their enhanced strength through different heat treatments, the assumption that these bolts behave in the same way as bolts of property classes 4.6 and 5.6 ($f_u = 400\,\text{N/mm}^2$ or $f_u = 500\,\text{N/mm}^2$) at elevated temperatures must be questioned. Furthermore, EC 3 [3] states nothing about the deflection behaviour of bolts at elevated temperatures.

There have been fewer studies on the load-bearing behaviour of bolts at elevated temperatures than on complete connections, but the number of studies has increased in recent years. The tests conducted on bolts so far have focused either on pure tension or on pure shear. Studies that have included tests both under pure tension and under pure shear show deviating reductions of the load-bearing capacity of the bolts in reference to the temperature, depending on whether the bolts were loaded by tension or by shear. The above-mentioned reduction factors for bolt strength at elevated temperatures are based on an extensive series of tests by Kirby [4] on bolts of property class 8.8. Kirby conducted steady-state tests on bolt sets under pure tension and under pure shear. As stated in the ECCS Model Code on Fire Engineering [5], the reduction factors stated in EC 3 [3] are based on the results of the pure tension tests by Kirby, as his results lead to more conservative values. There was less strength loss with pure shear tests. Another study that includes both tension tests and shear tests at elevated temperatures is by Kodur et al. [6] on A325 and A490 bolts ($f_u = 830\,\text{N/mm}^2$ and $f_u = 1030\,\text{N/mm}^2$). The test results also show deviating strength reduction depending on the strain on the bolts and the temperature. The absolute value of the shear strength for A325 bolts lies above the absolute value of the tensile strength in the temperature range between
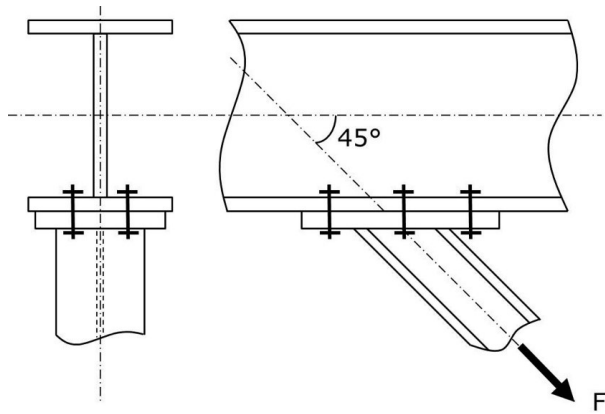
FIGURE 1. Example of a connection in which the bolts are loaded by a combination of tension and shear.

450 °C and 550 °C. For A490 bolts, the absolute shear strength values are above the absolute tensile strength, beginning at a temperature of approximately 550 °C. The effect of different strength reduction depending on strain was also observed by González [7] in his tests on bolts of property class 10.9. For bolts tested under pure shear, the reduction factors given by EC 3 overestimated the load-bearing capacity only in the temperature range between 400 °C and 600 °C. For bolts tested under pure tension, on the other hand, the factors from EC 3 overestimate the strength of the bolts from temperatures of 450 °C onward.

As described above, in the event of fire the bolts in a connection are loaded by a combination of tension and shear. However, there are also connections in which the bolts are by design already loaded by interacting tensile and shear stresses at ambient temperatures. An example is shown in Figure 1. A closer examination of the load-bearing behaviour of high-strength bolts under a combination of tension and shear at elevated temperatures is therefore of interest. A preliminary series of tests by the authors [8] investigated the post-fire performance of bolts of property class 10.9 under various combinations of tension and shear. It confirms the assumption that at least the post-fire performance depends on the type of strain. A more comprehensive series of tests of the load-bearing behaviour of these bolts under combined tension and shear after fire and also during fire is presented in this paper.

2. TEST SET-UP

In the above-mentioned preliminary test series [8], test rigs were used that had been designed for a very extensive series of tests on threaded and shank bolts under combined tension and shear at ambient temperature. Figure 2 shows the test rig assembled for an angle of 45°. Renner [9] designed a total of three different test rigs with which, depending on the assembly, each bolt can be stressed under two different angles or shear-to-tension ratios. The strain is applied by pulling on each of the two parts of the test rig.
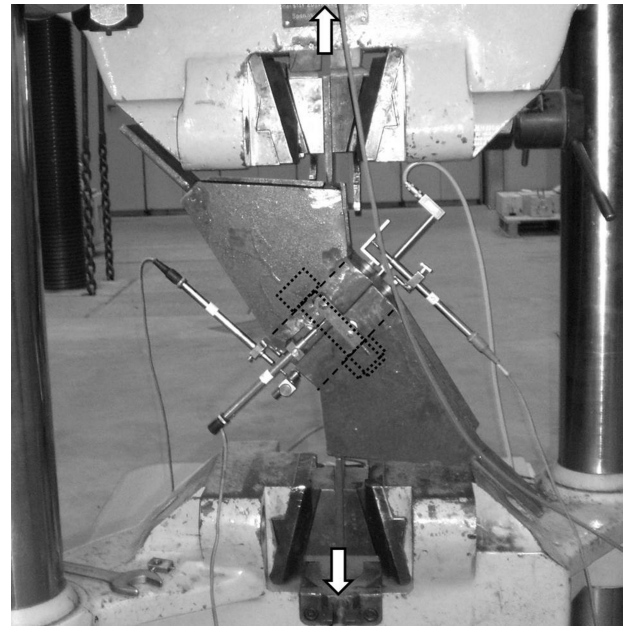

FIGURE 2. Test rig for angles 0° and 45°, assembled for a test with an angle of 45°.

The test rigs designed by Renner [9] are not practical for the tests described in this paper, due to the boundary conditions of the furnace that is required for the fire tests. However, the basic idea of applying the load in only one direction was to be retained, while thereby straining the bolt both by tension (in the bolt axis) and by shear (perpendicular to the axis of the bolt) through a suitable test rig. New test rigs based on this idea were designed, while at the same time taking into account that the furnace used for the tests only allows compression to be applied. The design combines the principles of a compact test rig by Godley et al. [10], where tension tests on bolts were performed by applying compression to the test rig, with the use of different angles as in the test rigs used by Renner [9]. Figure 3 shows the newly-designed test rigs for angles of 0° (left), 30° (centre) and 45° (right). The bolt is stressed by applying compression on the bottom and top plate of each test rig, causing tension and – for angles of 30° and 45° – also shear in the bolt.

The test rigs are made of NIMONIC® 80 A nickel-based alloy, a high-temperature alloy, to ensure that only the bolt that is being tested receives deflection and ultimately fails. The tested bolts are M20 zinc-coated shaft bolts of property class 10.9. The test layouts for the tests at elevated temperatures and for post-fire performance are described in greater detail below.

2.1. TESTS AT ELEVATED TEMPERATURES

The tests are conducted as steady-state tests with the temperature rising until the exposed bolt reaches the specified temperature. The temperature is kept constant, and after a stabilising time the bolt is loaded
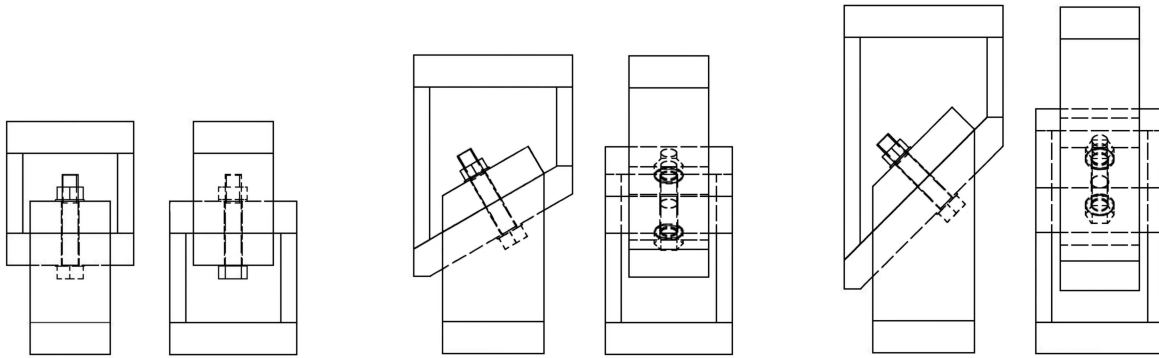
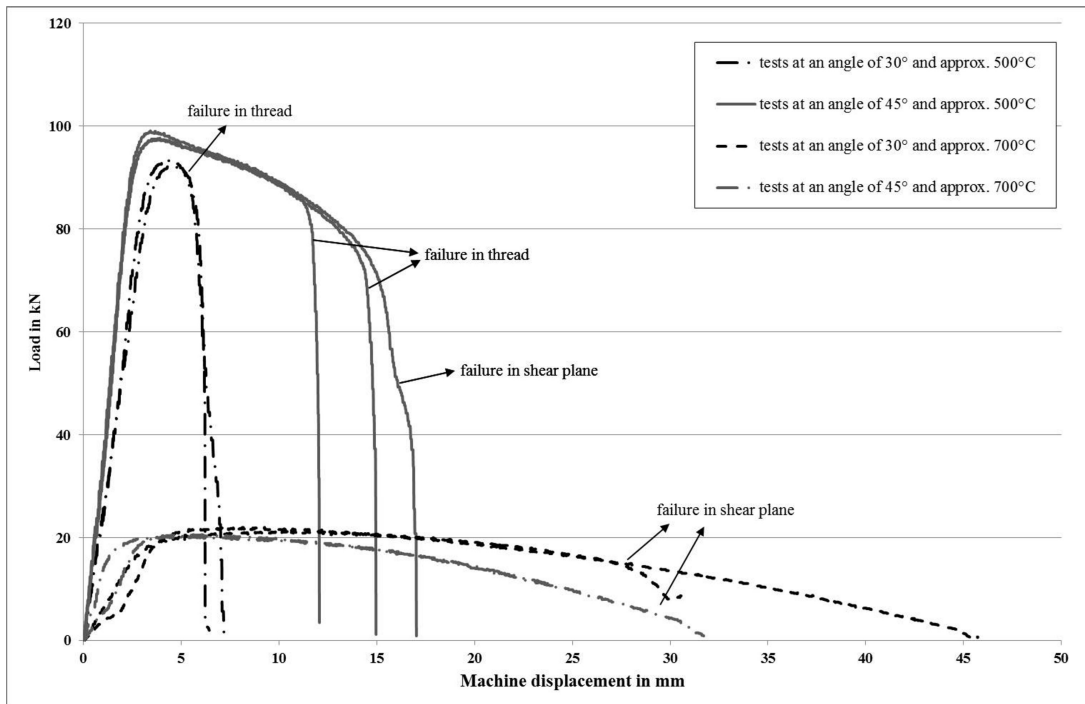Figure 3. Test rigs for an angle of 0° (left), 30° (centre) and 45° (right).

Figure 4. Load-deflection diagram of the fire tests with an angle of 30° and 45°.

until failure. A 4-zone electric furnace with a maximum temperature of 1000 °C is used for the fire tests. The furnace is fitted with a 3 MN compression machine. Type K thermocouples are installed to monitor the temperature on the surface of the test rig and also the temperature of the bolt. In order to ensure that the specified temperature is reached throughout the entire bolt, the surface temperature of the bolt is measured in the shear plane, where the surrounding mass of the test rig is highest. The furnace has a heating rate of approximately 10 K/min. During the heating phase, the temperature is monitored carefully to ensure that the bolt is uniformly heated. After the stabilising time at the specified temperature, the load is applied in a displacement-controlled manner at a rate of 1.5 mm/min. Since experimental studies in fire are both time-consuming and expensive, only two temperatures are specified - approximately 500 °C and 700 °C. As the temperature of the test rig, and

therefore also the temperature of the bolt, is not the same as the air temperature in the furnace, it is very difficult to meet the specified temperature exactly; it can only be reached approximately. The initial plan was to conduct 3 tests each for every combination of temperature and angle. However, after the first three tests (angle 45°, temperature 500 °C) showed very good compliance, it was decided to conduct only two tests for each combination.

2.2. Post-Fire Performance Tests
The same test rigs are used for the tests on the post-fire performance of the bolts as for the tests at elevated temperatures. As these tests are less time-consuming and less expensive, a larger number of temperatures are tested. The bolts are heated to 500 °C, 600 °C, 700 °C, 800 °C and 900 °C without any additional mechanical loading, and are then cooled slowly to ambient temperature. Once the bolts have reached the
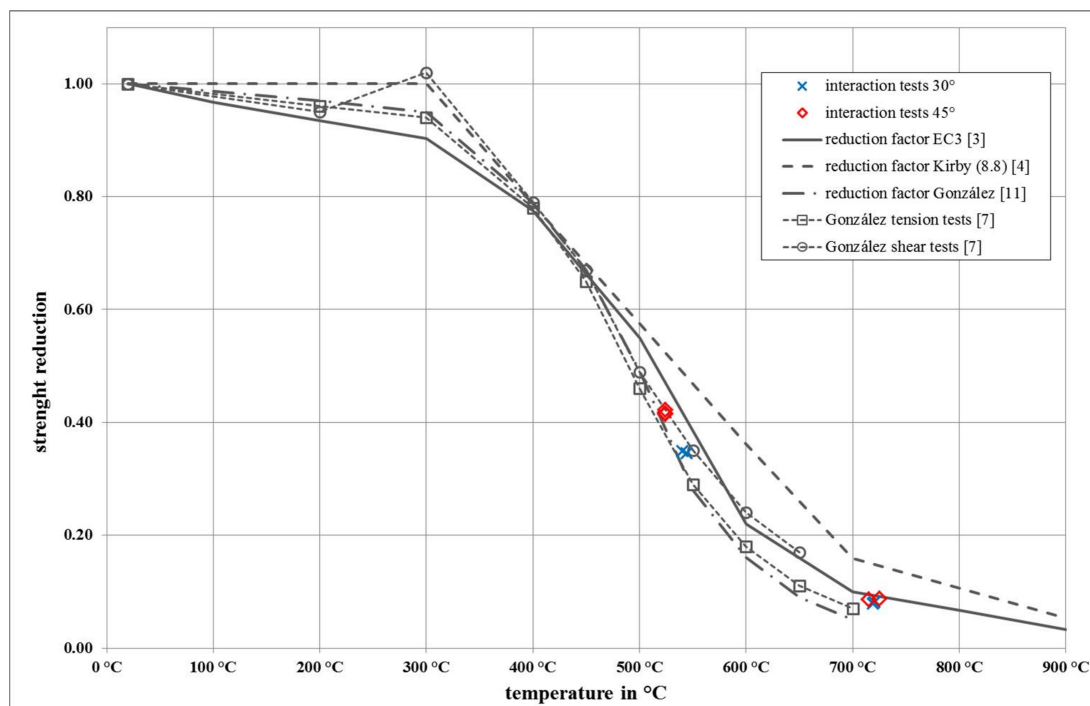
Figure 5. Results of the fire tests in reference to the reduction factors from EC 3 [3], Kirby [4] and Lange and González [11] and also the test results by González [7].

target temperature, the temperature is kept constant for 30 min to ensure that the temperature is reached throughout the bolt section. A compression machine with a maximum load of 1 MN is used for the tests. They are carried out in a displacement-controlled manner at a rate of 1.5 mm/min, and the bolts are loaded until failure. Five tests are done for each combination of angle and temperature. In the planning phase of the tests a large scatter of results was assumed, but this has not been confirmed thus far. In addition, five bolts from the same batch are tested without further heat treatment, as references.

3. Results

The tests have not as yet been completed. Up to now, the tests for angles of 30° and 45° have been carried out. The results of these fire tests and the post-performance tests will be presented in the following.

3.1. Results of the fire tests

In the tests at approximately 500 °C, the bolts tested at an angle of 45° and those tested at 30° show widely differing load-deflection behaviour, see Figure 4. The bolts tested at an angle of 45° show quite a large deflection after reaching the maximum load, while at the same time the load decreases. The bolts tested at an angle of 30°, on the other hand, fail quite suddenly after reaching the maximum load. The temperature in the bolts tested at an angle of 30° was about 20 °C higher than in the bolts tested at an angle of 45°. Disregarding this, the absolute value of the maximum load would have been higher at an angle at 30° than at an angle of 45°, as the amount of tension is greater

at this angle. However, the differing temperature in the bolts is not the reason for the differing failure behaviour. The temperature of approximately 500 °C is within the critical temperature range of LME (liquid metal induced embrittlement), where the liquid zinc flows into the micro cracks along the grain boundaries due to the tensile stresses and consequently leads to failure of the microstructure. The failure mode of the bolts seemed to indicate failure due to LME. The bolts tested at both angles at ambient temperature fail in the shear plane. In the fire tests, both bolts tested at an angle of 30° failed in the thread; and of the bolts tested at an angle of 45° only one bolt failed in the shear plane, although failure in the shear plane was imminent. The thread is especially prone to LME, as the thread acts more or less as a series of notches. The failure surfaces were investigated with an EDX-analysis to verify this assumption. For both angles, zinc was found within the fracture surface. At an angle of 30° the amount of zinc was much higher and was also detected further into the cross-section than for an angle of 45°.

The other investigation temperature of approximately 700 °C is outside the critical temperature range for LME failure. As predicted, all bolts failed within the shear plane but showed large necking of the cross section. The maximum load reached in these tests is only about one fifth of the load in the tests at 500 °C, see Figure 4. However, the bolts show a very large deflection. The elongation of the bolts is about a third of the original bolt length.

Figure 5 shows the results of the current tests in comparison with the reduction factors for the bolt
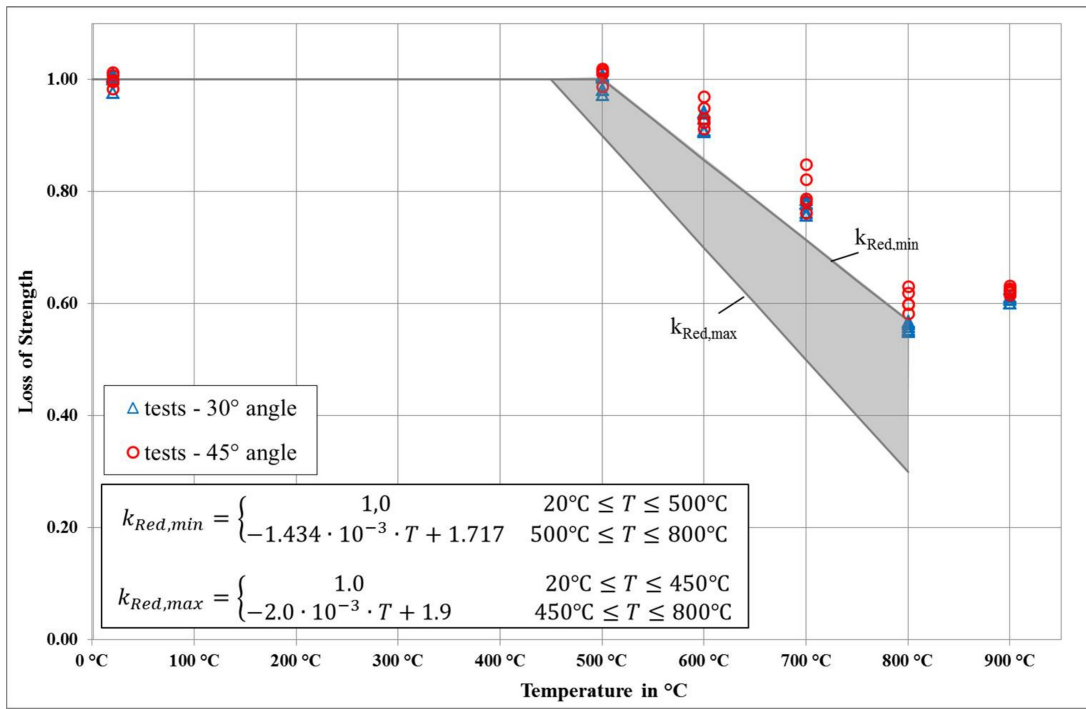
FIGURE 6. Results of the post-fire tests in comparison with the post-fire reduction factors by González [7].

strength at elevated temperatures given by Eurocode 3 Part 1–2 Appendix D [3] for all property classes, the reduction factors given by Kirby [4] from his tests on 8.8 bolts, and the reduction factors given by Lange and González [11] for bolts of property class 10.9. The Figure also shows González's test results on pure tension and pure shear tests applied to 10.9 bolts [7]. All test results lie below the reduction factor given by Appendix D of the Eurocode 3 part 1–2. González has shown that the reduction factor stated in Eurocode 3 is not applicable for bolts of property class 10.9, as the strength reduction at temperatures above 450 °C is much higher than for bolts of property class 8.8. The tests conducted at an angle of 30° and 45° lead to tension and shear in the bolts. The failure loads of the tests, therefore, lie as predicted between the test results of González under pure tension and pure shear. At an angle of 45° the amount of shear stress in the bolt is higher, which in turn has a positive effect on the ultimate strength of the bolts.

3.2. RESULTS OF THE POST-FIRE PERFORMANCE TESTS

The investigation of the post-fire performance of high-strength bolts is quite sensitive, as these bolts obtain their enhanced strength through carefully controlled heat treatment. The uncontrolled heating and cooling in the event of fire can consequently lead to a complete change in material properties. In his dissertation, González [7] states two reduction factors for evaluating the post-fire strength of bolts of property class 10.9. The minimum reduction factor $k_{\text{Red,min}}$ is based on tension tests carried out on specimens and bolts that were heated without an additional mechanical load.

The maximum reduction factor $k_{\text{Red,max}}$ is based on tension tests, where the specimens were loaded by both thermal and mechanical loading. The post-fire reduction of the strength of a 10.9 bolt should usually in the following bounds:

$$k_{\text{Red,min}} = \begin{cases} 1.0 & 20\,°\text{C} \leq T \leq 500\,°\text{C}, \\ -1.434 \cdot 10^{-3}T \\ \quad + 1.717 & 500\,°\text{C} \leq T \leq 800\,°\text{C}, \end{cases}$$

$$k_{\text{Red,max}} = \begin{cases} 1.0 & 20\,°\text{C} \leq T \leq 450\,°\text{C}, \\ -2.0 \cdot 10^{-3}T \\ \quad + 1.9 & 450\,°\text{C} \leq T \leq 800\,°\text{C}. \end{cases}$$

(see the shaded area in Figure 6). Both reduction factors are based on pure tension tests of specimens and bolts. In the current series of tests, the tested bolts were heated to each specified temperature without additional mechanical loading. Thus the values lie nearer to the reduction factor $k_{\text{Red,min}}$, see Figure 6. As with the tests during fire, the higher ratio of shear with an angle of 45° has a positive influence on the load-bearing capacity of the bolts. The above-stated reduction factors are also applicable for the tested batch of 10.9 bolts and for a combination of tension and shear.

In addition to the tests on whole bolt sets, specimens milled from the bolts were tested under pure tension to obtain the stress-strain relations. The unaltered bolts (20 °C) and the bolts heated to 500 °C show very close compliance with each other. Up to 600 °C, the stress-strain relations show no yielding, which is typical for quenched and tempered steels. The specimens taken from bolts heated to 900 °C have a lower proportional

limit than the bolts heated to 800 °C, but the ultimate stress value is higher. Micrographs show a change in microstructure to a coarser microstructure in the bolts heated to 900 °C.

4. CONCLUSIONS

The tests presented in this paper are intended to give a better understanding of the load-bearing behaviour of high-strength bolts of property class 10.9 under a combination of tension and shear during and after fire. Although the test programme has not yet been completed, initial conclusions can be drawn.

The load-bearing capacity of bolts of property class 10.9 at elevated temperatures degrades more than the load-bearing capacity of bolts of property class 8.8. However, the 10.9 bolts behave in a very ductile manner even after reaching the maximum load and with quite a large rate of shear stress. This is a positive characteristic for the stability of a connection in a steel structure during fire. As was pointed out in the introduction, connections encounter great deformation over the course of a fire.

The positive effect of a combination of tension and shear is also true for the post-fire performance of bolts of property class 10.9. The reduction factors stated by González [7] can also be used for combined stress. In order to draw final conclusions, further tests need to be conducted.

REFERENCES

[1] Al-Jabri, K.S., Davison, J.B., Burgess, I.W.: Performance of beam-to-column joints in fire – A review, Fire Safety Journal 43 (2008), p. 50-62. DOI:10.1016/j.firesaf.2007.01.002

[2] Burgess, I.W., Davison, J.B., Dong, G., Huang, S.-S.: The Role of Connections in the Response of Steel Frames to Fire, Structural Engineering International 4 (2012), p.449-461. DOI:10.2749/101686612X13363929517811

[3] DIN EN 1993-1-2: Eurocode 3: Design of steel structures, Part 1-2: General rules – Structural Fire design, German Version; EN 1993-1-2, 2:2005 + AC:2009

[4] Kirby, B.R.: The Behaviour of High-strength Grade 8.8 Bolts in Fire, Journal of Constructional Steel Research, 33 (1995), p. 3-38. DOI:10.1016/0143-974X(94)00013-8

[5] European Convention for Constructional Steelwork / Technical Committee Fire Safety of Steel Structures ECCS, Model Code on Fire Engineering. ISBN: 92-9174-000-65

[6] Kodur, V., Kand, S., Khaliq, W.: Effect of Temperature on Thermal and Mechanical Properties of Steel Bolts, Journal of Materials in Civil Engineering, 24 (2012), p-765-774. DOI:10.1061/(ASCE)MT.1943-5533.0000445

[7] González Orta, F.: Untersuchungen zum Material- und Tragverhalten von Schrauben der Festigkeitsklasse 10.9 während und nach einem Brand, Dissertation, Technische Universität Darmstadt, 2011. ISBN: 978-3-939195-24-5

[8] Kawohl, A., Renner, A., Lange, J.: Experimental Study of Post Fire Performance of High-strength Bolts under Combined Tension and Shear, 8th International Conference on Structures in Fire, June 11-13 2014, Shanghai, China, 2014. p. 89-96, ISBN: 978-7-5608-5494-6

[9] Renner, A., Lange, J.: Load-bearing behaviour of high-strength bolts in combined tension and shear, Steel Construction, 5 (2012), p. 151-157. DOI:10.1002/stco.201290033

[10] Godley, M.H.R., Needham, F.H.: Comparative tests on 8.8 and HSFG bolts in tension and shear, The Structural Engineer, 60 (1982), p. 94-99. UDC: 624.078.0001.4

[11] Lange, Jörg; González, Fernando: Behavior of High-Strength Bolts under Fire Conditions, Structural Engineering International, 4 (2012), p. 470-475. DOI:10.2749/101686612X13363929517451