Fire resistance of hot-dip galvanized HSS composite girders and connections between protected and hot-dip galvanized steel girders

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Abstract

Current research shows that hot-dip galvanizing can significantly improve the fire resistance duration of structural steel elements. The standards EN 1993-1-2 and EN 1994-1-2, which are valid for structural design of steel and composite sections in the fire situation are currently being revised to consider the positive effect of hot-dip galvanizing in the case of fire. The following topics are investigated in a current research project: the temperature distribution in the steel profile of a hot-dip galvanized composite beam, the material behaviour of high-strength steels at high temperatures, the possibility of liquid metal embrittlement of high-strength steels in case of fire, the required minimum degree of dowelling in case of fire for hot-dip galvanized composite beams for double and single symmetrical steel profiles and recommendations for the formation of optimised single-symmetric hybrid cross-sections of the steel profile made of high-strength steels. In addition, the heating behaviour of connections between hot-dip galvanized beams in case of fire and the heating behaviour of connections with hot-dip galvanized components in combination with coated components will be analysed.

Keywords: Fire Protection, Hot-Dip Galvanizing, Intumescent Coating, High Strength Steels, Composite Beams, Connections

Introduction

The emissivity of steel is considered in heating due to radiation. Research from the Technical University of Munich and other studies in Europe on hot-dip galvanized steel show lower emissivity values (ε_m = 0.35 up to a component temperature of 500 °C and ε_m = 0.7 over a component temperature of 500 °C) compared to non-galvanized steel (constant ε_m = 0.7). The lower the emissivity, the slower the heating of the component progresses. Hot-dip galvanizing has a positive influence on the emissivity. The higher the temperature gradient between the component surface and the fire room temperature, the higher the influence of emissivity. A positive effect occurs mainly at the beginning of the fire and with small profile factors (A_m/V ratio).

Hot-dip galvanized composite beams can achieve R30 fire resistance with significantly increased material efficiency, especially with the use of high-strength steels (S460M or S690Q). The load bearing capacity of hot-dip galvanized composite beams with high-strength steel is experimentally examined in the fire situation. The test regime consists of six large-scale steel girders with a composite slab ranging from hot-rolled standard steel profiles to welded sections. Therefore several sections as single-symmetrical, hybrid welded sections, such as from a halved rolled section of S460M with an optimised (A_m/V ratio) lower flange of S690Q in combination with hot-dip galvanization are investigated to provide fire resistance of R30 in a very economical way. Every beam is loaded and exposed to the ISO 834 standard fire for 30 min, and the load is held constant until failure of the composite beam. During the experiments, both displacement and heating of the hot-dip galvanized high-strength steel and concrete section is continuously recorded to establish the load capacity and evaluate the influence of the galvanization on the fire resistance duration.

For the investigation of the heating behaviour of connections of hot-dip galvanized beams to beams protected with a reactive fire protection system, large-scale fire tests were carried out on two constructions with a total of eight different connection types. The constructions each consist of two main beams coated with a reactive fire protection system and two hot-dip galvanized secondary beams with four different connection types. The results of the tests and subsequent simulations will provide a simplified calculation method for the heat transfer from hot-dip galvanized beams to protected beams.

Large-scale fire tests on typical connection details

For the investigation of the heating behaviour of connection details between protected main beams to hot-dip galvanized secondary beams, were performed two fire tests at the Technical University in Munich. For this, two constructions consisting of different profiles with four connection details each were planned. The main beams with the welded connecting parts were coated with an intumescent coating (R30) and the secondary beams and the loose connecting parts were hot-dip galvanized. The eight connection parts consist of short and long angles, short and long flag plates in different thicknesses and butt joint with splice plate in combination with one-sided or double-sided flag plates. The main beams have a length of 3.5 m and the secondary beams 1.5 m. The construction of the first test structure consists of the main beams HEB 300 and HEA 300 and the two secondary beams made of IPE 200. Connection detail 1 consists of hot-dip galvanized short double angles L80x8. Connection details 2, 3 and 4 consist of flag plates welded to the main beam and also coated with the reactive fire protection system.

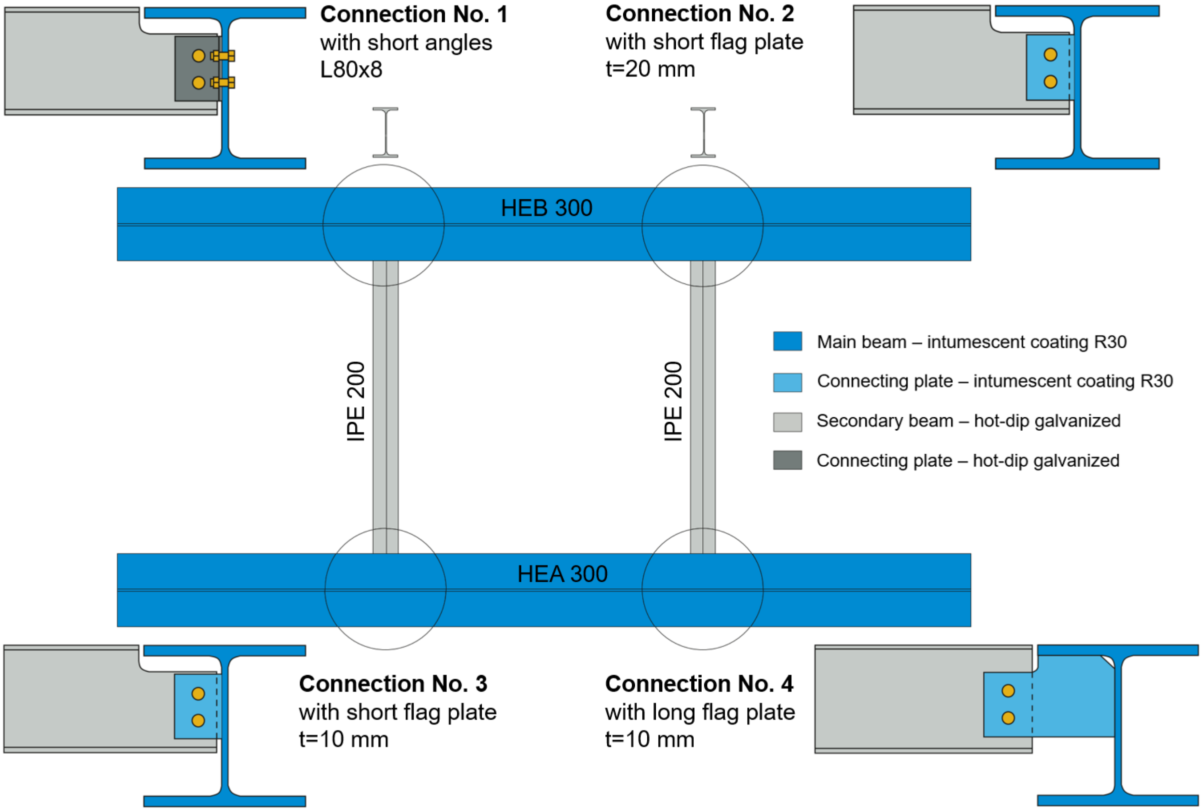

Figure 1: Connection details 1 to 4 for the fire test

The construction of the second test structure consists of the main beams HEB 450 and HEA 450 and the secondary beams of IPE 330. Connection detail 5 consists of hot-dip galvanized long double angles L100x10. Connection details 6 and 8 consist of splice plates welded to the main beam and also coated with the reactive fire protection system, in combination with hot-dip galvanized flag plates. Connection detail 7 was formed with a long flag plate.

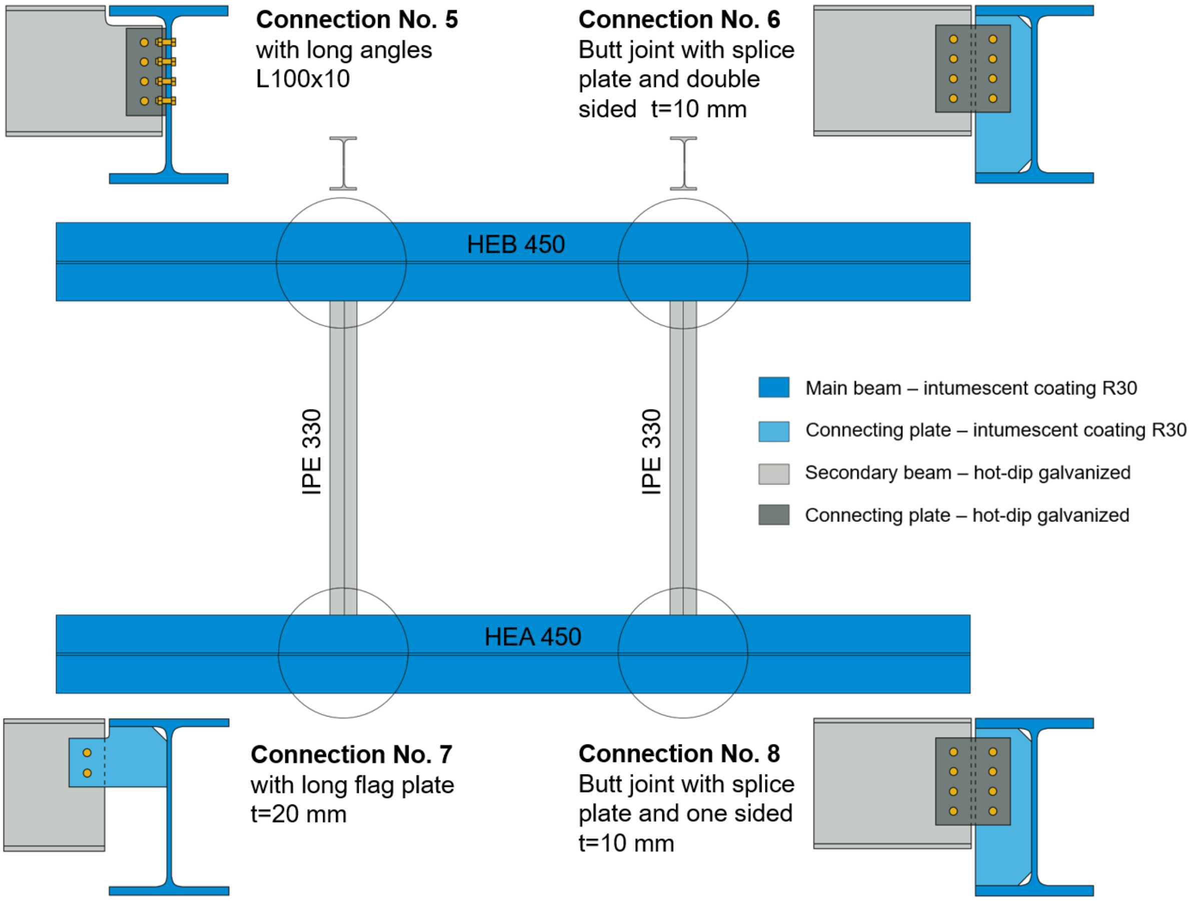

Figure 2: Connection details 5 to 8 for the fire test

For the temperature measurements, measuring points were provided on the main beams, on the secondary beams, in the connecting parts and in the bolts. On the main beams, five measuring points were defined in the web in the area of the connections: one measuring point directly behind the connection part and four further measuring points at a distance of 200 mm from each other. The measuring points in the secondary beams were placed in the web and in both flanges at a distance of 100 mm from the edge of the connection plate. An additional measuring point on the secondary beam was made at the same position as the measuring point in the connection plate. The measuring point in the connection plate was positioned centrally between the edge and the axis of the bolts. The temperature measurement in the bolts was carried out at a borehole depth of 18 mm from the bolt head.

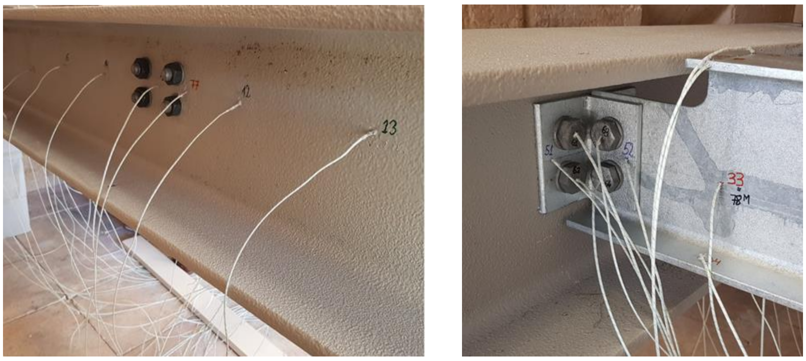

Figure 3: Measuring points for the temperature at the main beam, secondary beam and at the connecting parts for connection detail No. 1

The main beams were supported on aerated concrete blocks to a height of 1.0 m, so that the construction could be positioned approximately at the middle height of the furnace. The burning in the furnace according to ISO fire (according to ISO 834) was carried out with the help of four oil burners, which were arranged on the top and bottom of the side walls. There was no direct flaming of the construction and no mechanical load.

Figure 4: Position of the beams in the furnace

Temperature development in connection detail no.1 with short angle L80x8

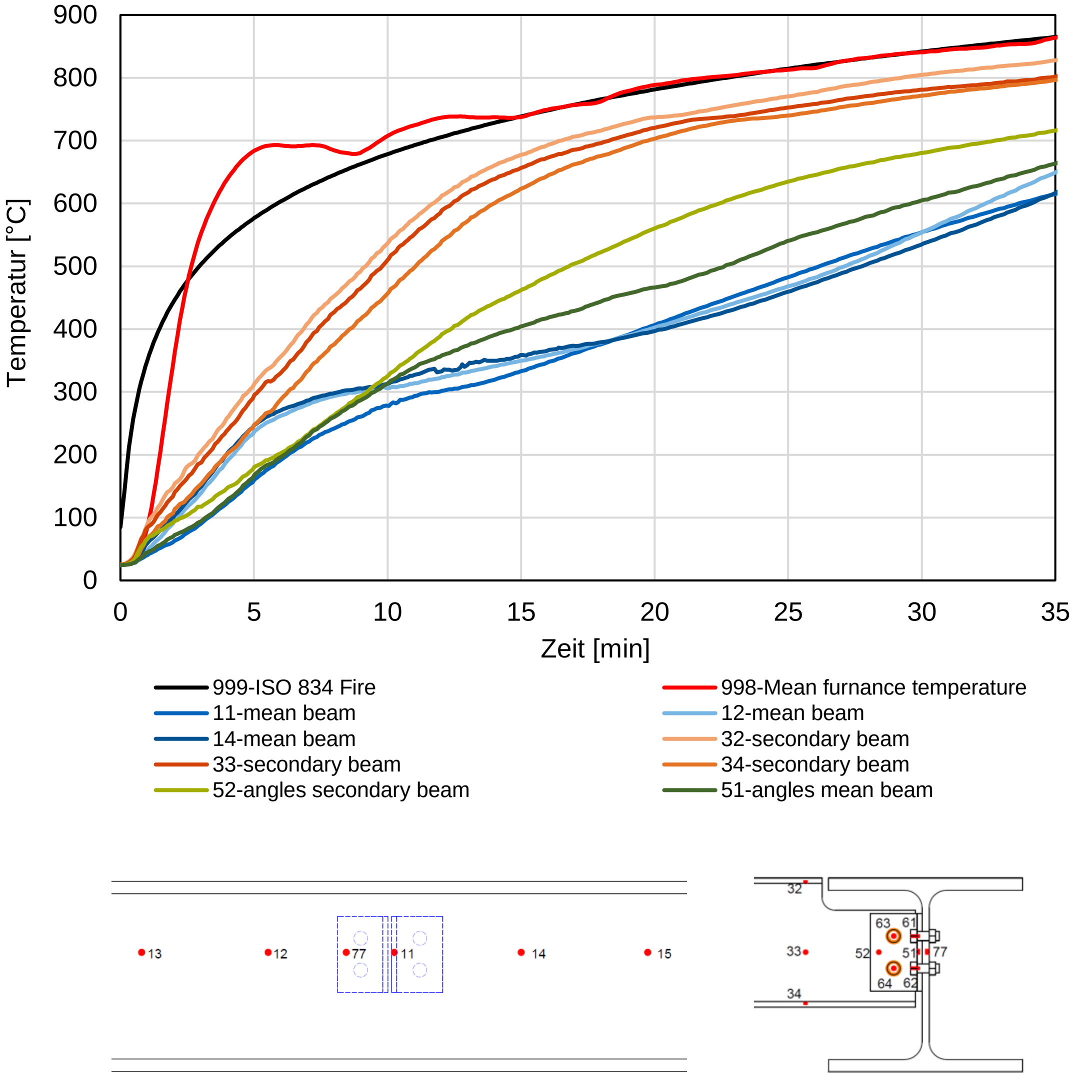

Figure 5: Temperature development in connection detail no.1

In general, there was a slow heating of the protected beam. For the secondary beams, IPE 200 and IPE 330 profiles were used, which have a large A_m/V ratio. Since most of the heating at the beginning of the test takes place via convection and because of the A_m/V ratio, there is a small visible influence of the galvanization, which is considered in the radiation. Realistic beam dimensions were chosen for the investigation of heat transfer through the connections into the main beams. Because the temperature curves are dependent on the positions, different measuring points are compared in the main beam. As a result of the tests carried out, temperature data are available for eight different connection details. The next step is the development of FE models. The validation of the models for the different connection configurations is carried out with the recorded data of both fire tests and is not yet completed. With the help of the tests carried out and the FE models, an analytical function for a simple calculation of the temperature development in different connection configurations will be developed.

Large-scale fire tests of hot-dip galvanized composite beams with high-strength steel sections

At TU Brunswick, Germany, large-scale fire tests of hot-dip galvanized composite beams with high-strength steel sections were conducted. All beams were produced with a length of 9.0 m, concrete deck (concrete class: C35/45) width of 1.0 m and thickness ranging between 0.15 to 0.2 m. Stud sheer connectors SD 1, D = 22 mm, L = 125 mm and Holorib trapezoidal sheets HR 51/150, t = 0.88 mm, were used for all beams.

A variety of six steel sections served as the sample ranging from hot-rolled standard sections and welded double-symmetrical sections to single symmetrical sections of a halved standard section with an optimised bottom flange. In addition, the steel grade was varied between S460M and S690QL. All steel elements were hot dip galvanized.

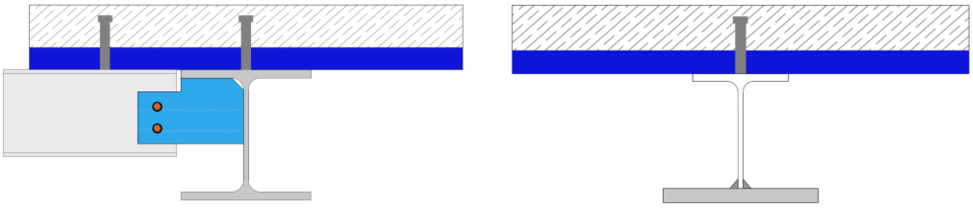

Figure 6: Composite section (HEB300) and connection detail at mid-span

Additionally, each beam had a secondary beam located at mid-span. Here the same connections details were investigated as previously at TU Munich to record the corresponding heat transfers between galvanized secondary to galvanized main beam.

For the fire tests, the furnace was fitted with oil burners to produce the standard fire according to ISO 834 while three presses per beam mechanically loaded the beam. The supports at either end of each beam allowed for rotations and change in length. Temperature data from the concrete section, sheer studs, main steel beam as well as secondary beam and connection was recorded for the analysis of the heating process of the composite beam. Also, beam deformation, end rotation and slip between concrete deck and steel section was observed during the fire tests. Videos from both outside and inside the furnace were taken.

Figure 7: Large-scale fire test setup: furnace and composite beams

All composite beams were tested in pairs of similar height and load bearing resistance capacity.

Figure 8: Composite beams before and during fire test

The mechanical loading of the beams, for the fire test program, was realized with three hydraulical presses per beam. The loading occurred a minimum of 15 min before the start of the fire. The loading level was chosen so that the hot beams were at 90 % utilization of their load bearing capacity in the hot state after 30 min of standard fire ISO 834.

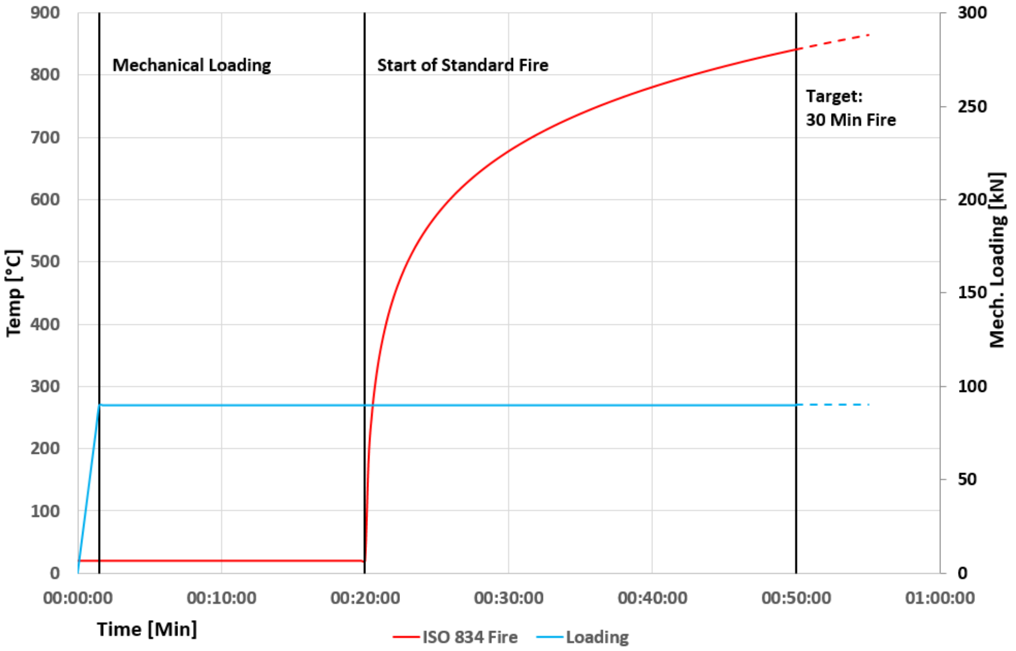

Figure 9: Loading programme

In addition to the large-scale fire tests, concrete cube compression was tested (solely cold state) from the same concrete batches of beam production at the concrete plant. Steel tension tests of the same steel materials (at hot state, both stationary and transient) are part of this research project in a different work package to produce corresponding material input data for all following simulations.

The vertical deformation showed an almost linear increase during a certain amount of time in the standard fire. Then, deformation at mid-span increased more quickly and even suddenly in some cases. Concrete spalling was seen at around minute 14 for all composite beams.

For the temperature development, the results from the hot-dip galvanized beams could be compared to data from a different research project (IGF-Nr. 21403, TUM, Prof. Mensinger/ K. Tutzer) in which uncoated beams (same standard section) were tested in the same furnace with the same test programme. In the hot-dip galvanized section, the heating occurred significantly slower so that a difference in temperature could be observed throughout the fire test duration, especially for the web and bottom flange.

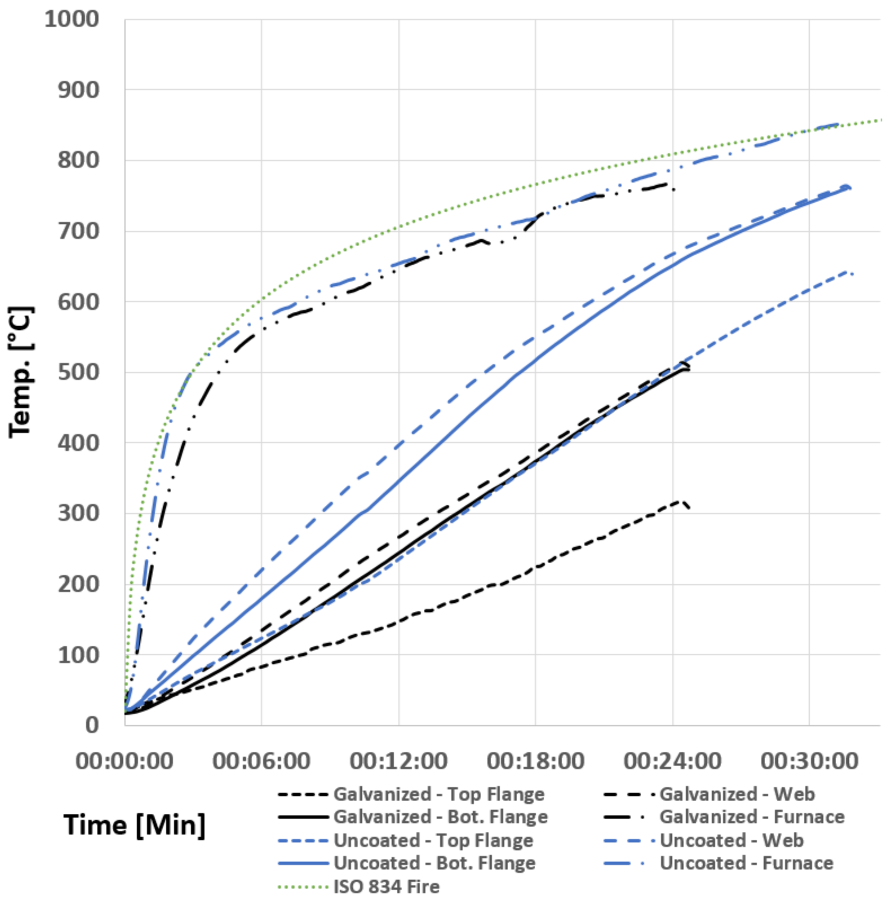

Figure 10: Comparison of temperature development in galvanized and uncoated HEB300 beams

The same analysis is conducted between all the hot-dip galvanized sections so that the influence of varying sizes, thickness of steel profiles as well as the impact of different zinc coating thicknesses can be identified.

Some parts of the concrete deck are going to be stripped to examine the sheer studs after the fire. Also, further steel samples were taken from the beam for the investigation of the surface constitution before and after the fire.

With all the result data, FEM-models are developed and verified to run a full analysis of numerous parameters and sensitivities. The models will use the symmetry of the composite beams, so that only one quarter of the total structure will need to be numerically calculated. In the modeling, DC3D8-elements (one temperature degree of freedom) and C3D8L/C3D8-elements (multiple degrees of freedom) will be used for the thermal transient and the static-mechanical analysis respectively.

Execution of LNT-tests

The first aim of this part is to determine the susceptibility to cracking of high-strength steels by hot-dip galvanizing. The second aim is to contribute the examination of whether high-strength steels can be used, so that the advantages known from hot-dip galvanizing of normal-strength steels can also be transferred to high-strength steels in order to use them for fire assessment.

For the experimental investigation, Long Notch Tension (LNT) specimens were manufactured from the steel grades S355J2 and S460M and then individually hot-dip galvanized. During hot-dip galvanizing, the specimens are mechanically loaded and the resulting expansions and applied forces are measured. The goal was to investigate the influence of the steel grade on the crack resistance. Furthermore, with the help of numerical investigations, it is possible to determine the plastic equivalent strain and to check the sensitivity to liquid metal embrittlement (LME).

The concept of the LNT specimen is based on the compact-tension specimen (CT specimen) known from fracture mechanics. In contrast to the CT specimen, the length of the legs of the LNT specimen is extended, see Figure 11. This allows the specimen to be immersed sufficiently deep into the molten zinc and at the same time there is an adequate safety distance between the molten metal and the test equipment.

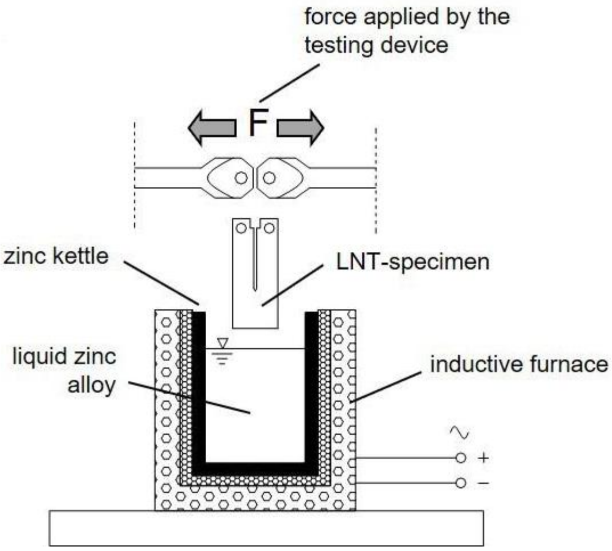

Figure 11: Experimental setup of the LNT test procedure

In order to numerically recalculate the experimental investigation, the finite element method programme ANSYS-Mechanical is used. Symmetries are used to shorten the computing time and keep the memory requirements low. In the LNT sample, the shape is divided in the x- and z-direction in the middle in each case, resulting in the symmetry axes, see Figure 12. The aim is to determine the limit strains at the time of fracture at the notch base by determining the temperature-related strains. In principle, the values are determined taking into account previously experimentally determined flow curves and heat transfer coefficients. Here, yield curves for the steels S355 and S460 were used with the help of the software SYSWELD and then transferred to the existing script.

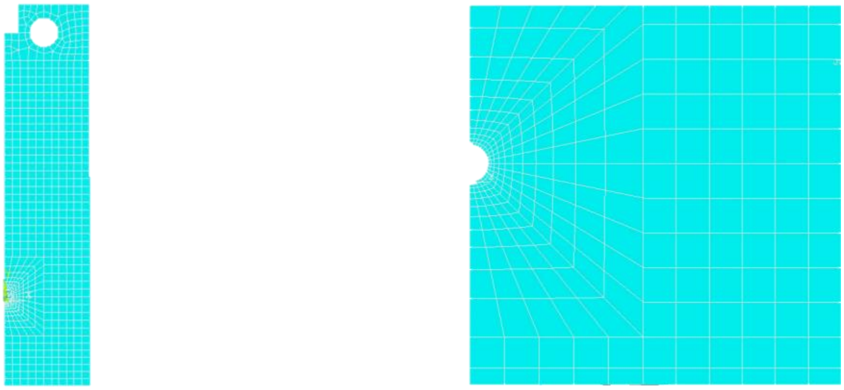

Figure 12: Left: model of a LNT sample; right: meshing around the hole

The results for the material S355 are shown in Figure 13. The highest maximum force in these tests is 13.6 kN. The different expansions at the break-off points are noticeable. This is due to the fact that the tests were terminated manually. The curves are similar and the force maxima do not show a large variation.

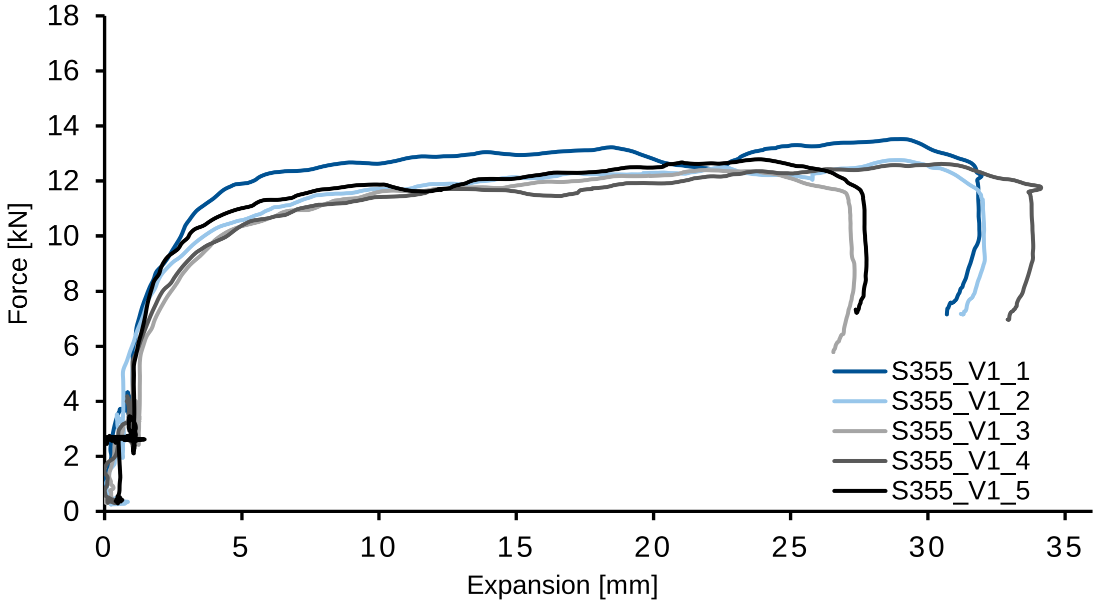

Figure 13: Results of the LNT tests for the S355J2

Figure 14 shows the force-expansion curves for the material S460. The highest maximum force is 17.9 kN. This is an increase of about 32 % compared to the maximum force absorbed by S355. Specimen S460_V1_5 shows a pop-in because of a slip of the clip gauges.

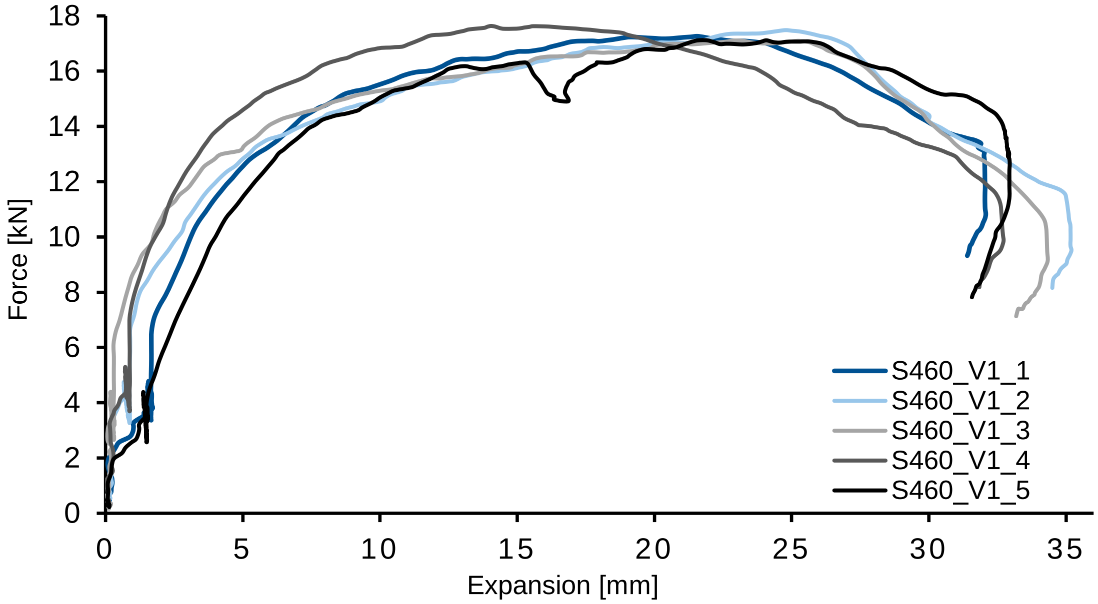

Figure 14: Results of the LNT tests for the S460M

Due to the temperature loading stress and strain develop over time. Starting from a preload the specimen is modelled as a component sinking in the zinc bath, see Figure 15 left. With the effective heat transition coefficient of 3,000 W/m²K for the zinc bath class 1 according to DASt-Ri 022 is considered. Figure 15 right shows the resulting plastic equivalent strain of a tested specimen simulated with a flow curve of S460M.

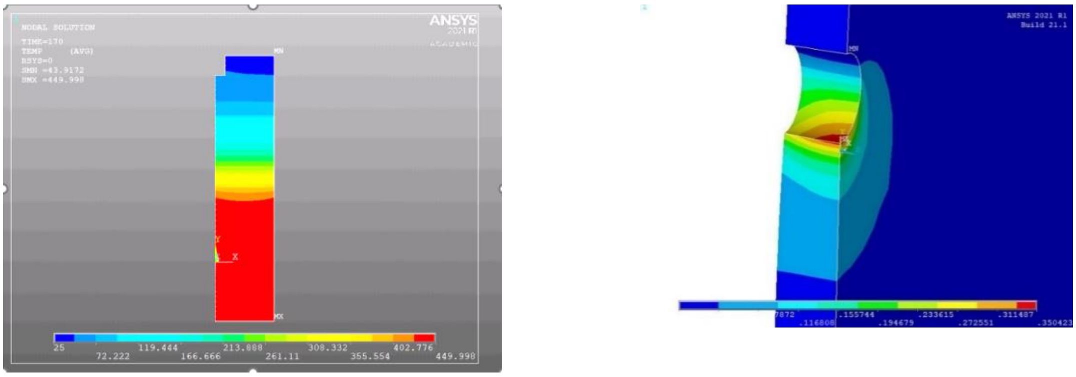

Figure 15: Left: temperature gradient of the LNT sample; right: plastic equivalent strain (von Mises) for S460M

Three different flow curves were used to compare all materials of this project. At this stage, the flow curves are out of the program SYSWELD because the real tensile tests will be tested soon. With those results the realised LNT tests can be recalculated and compared with the plastic equivalent strain at breakage.

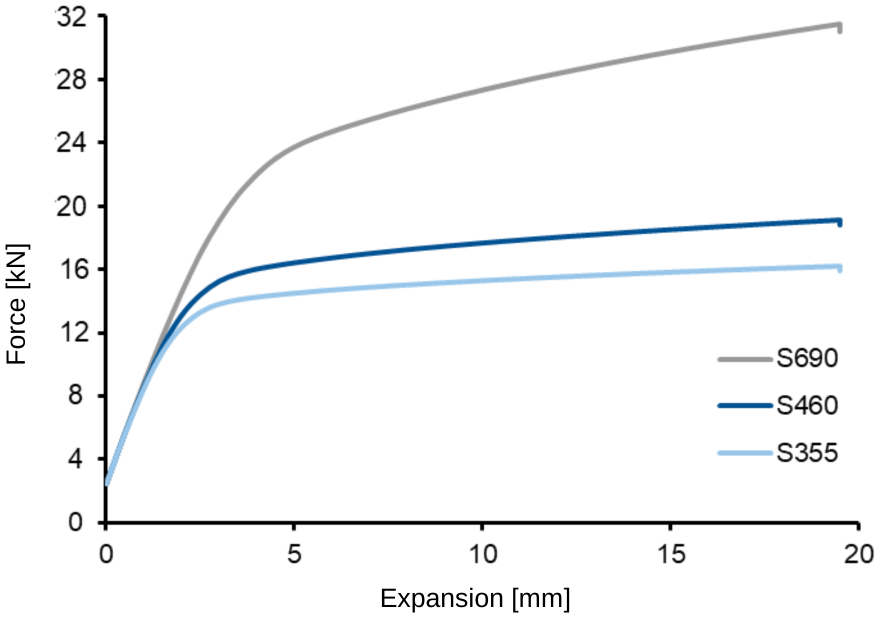

Figure 16: Results of the simulations of the LNT tests

Conclusions

The measured temperatures of the galvanised steel profiles show a first evaluation that the approach with a temperature dependent emissivity, which is reduced with $\varepsilon_m = 0.35$ until a component temperature of 500 °C is reached and only then increased to $\varepsilon_m = 0.7$ is applicable.

With the help of the measurement data from the composite beams, FE-models are created and calibrated so that a broad parameter study and sensitivity analysis of the individual parameters can be carried out. Within the context of the parameter study, the influence of hot-dip galvanizing on the heating behaviour of the steel cross-section, the influence of the geometry and an asymmetrical steel cross-section, the influence of the degree of dowelling and the influence of a composite deck system are to be investigated.

With the new results of the tensile tests the LNT tests can be recalculated and evaluated. S690Q will be tested, too. This leads to a overall evaluation of a possible use for high strength steels in the future.

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