Current research on hot-dip galvanized steel in case of fire

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Content

- Influence of hot-dip galvanizing on steel in case of fire
- Emissivity of steel surfaces using zinc-aluminium coatings
- Fire resistance of hot-dip galvanized composite beams made of higher and high-strength structural steels
- Large-scale fire tests on typical connection details between coated and hot-dip galvanized steel beams

Influence of hot-dip galvanizing on steel in case of fire

Dependence of galvanisation on steel alloy

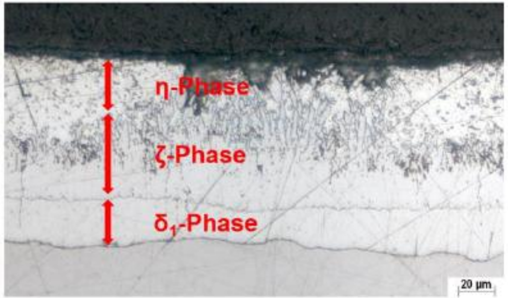
Classification of steel according to EN ISO 14713-2:2020-05

Category	Designation	Layer properties
A	Low-silicon content steel: ≤ 0.03% Si and 0.02% P	Shiny appearance with a fine texture.
B	Sebisty steel: 0.14 % < Si < 0.25 %	The coating can be shiny or matt.
C	Sandelin steel: 0.03 % < Si < 0.14 %	Appearance can be dark or matt with a coarse texture.
D	High-silicon content steel: > 0.25% Si	Matt, grey

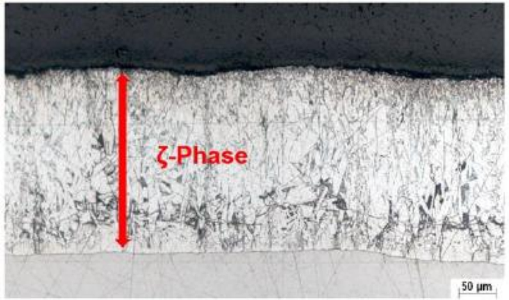
The formation of the zinc coating depends on:

- The chemical composition, particularly the silicon and phosphorus content of the steels
- The topography of the steel surface
- The galvanizing conditions (molten temperature, immersion time etc.)

Micrographs - category A



Micrographs - category D

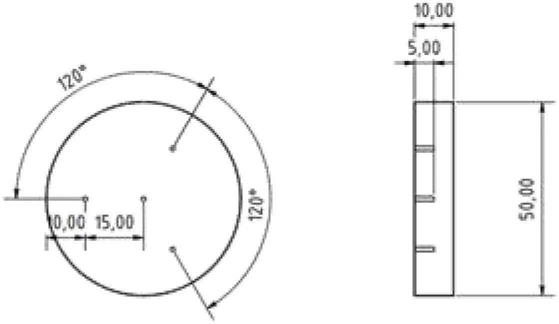


Emissivity–Performance Test (E-PT)

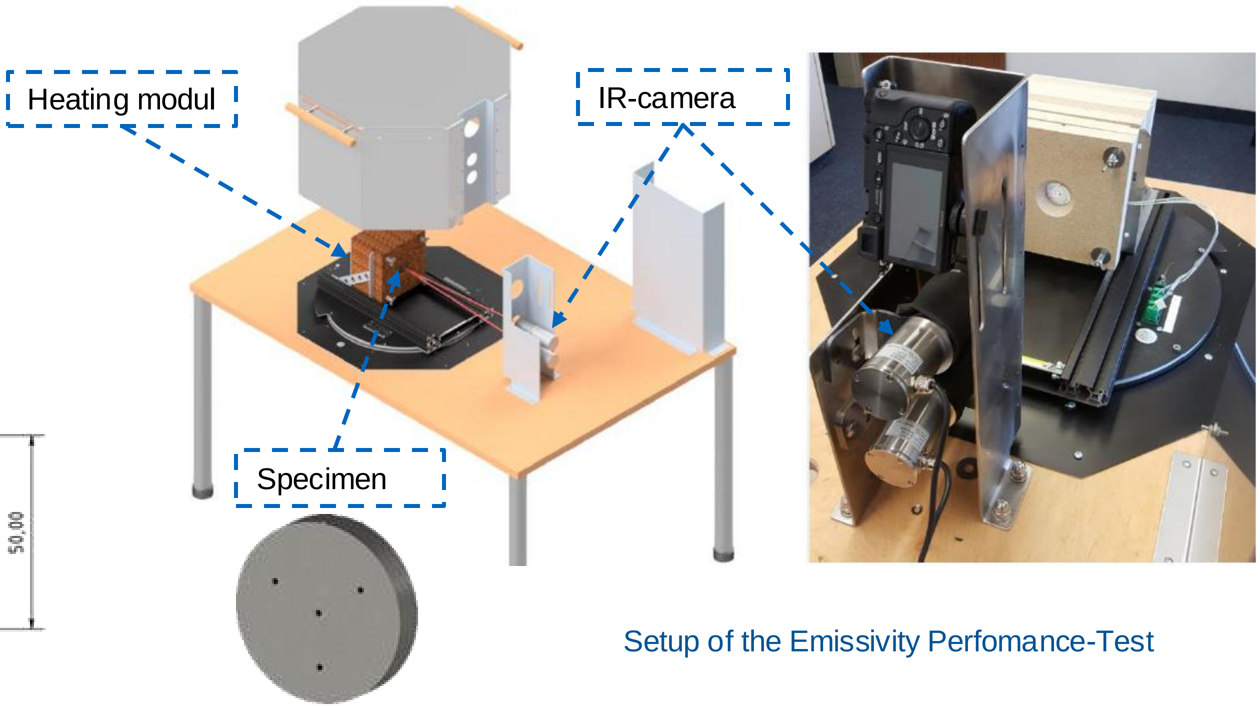
- Developed and built test setup for small fire tests from the research project 18887N “Fire resistance of hot-dip galvanized, load-bearing steel structures in the case of fire” (M. Mensinger; C. Gaigl)

Measuring system:

- Heating modul
- IR-camers
- Thermocouples
- Rotateable plate incl. stepper motor
- Radiation shield
- Specimen
- Computer incl. control software



Geometry specimen



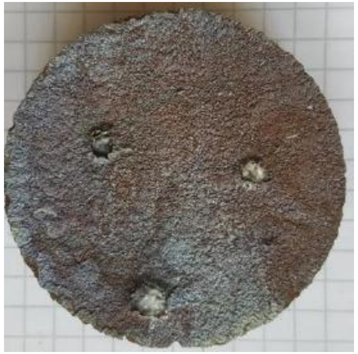
Setup of the Emissivity Perfomance-Test

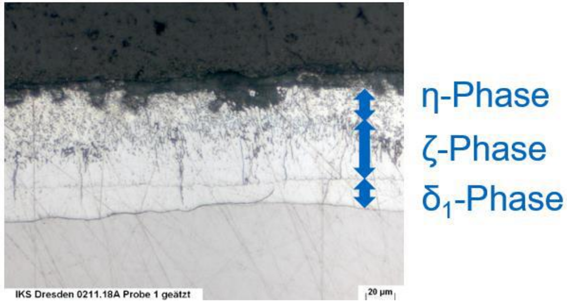
Change of surface during heating

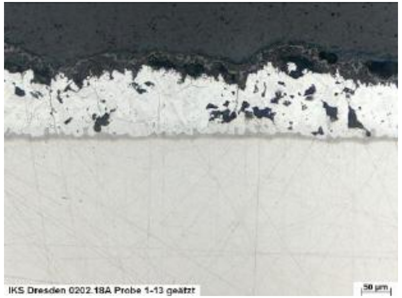
Specimen before fire test

Specimen during fire test

Specimen after fire test

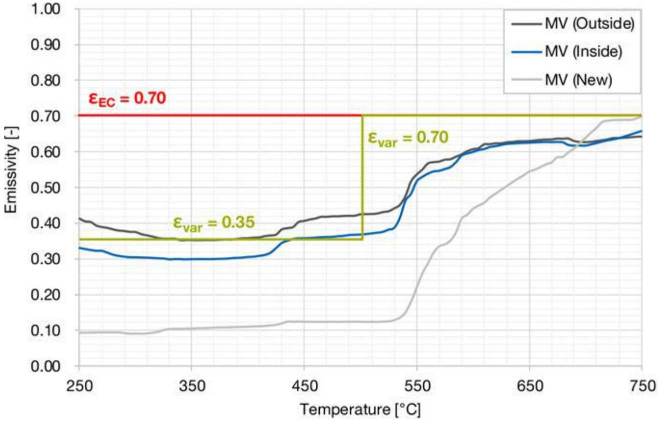


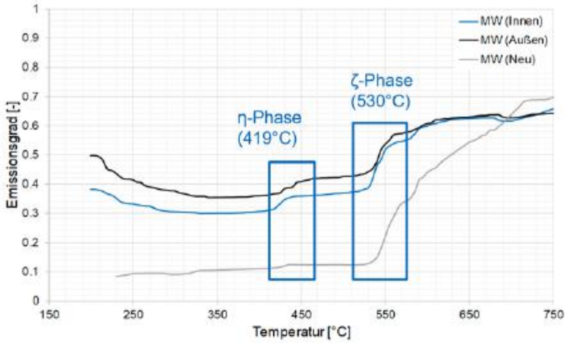




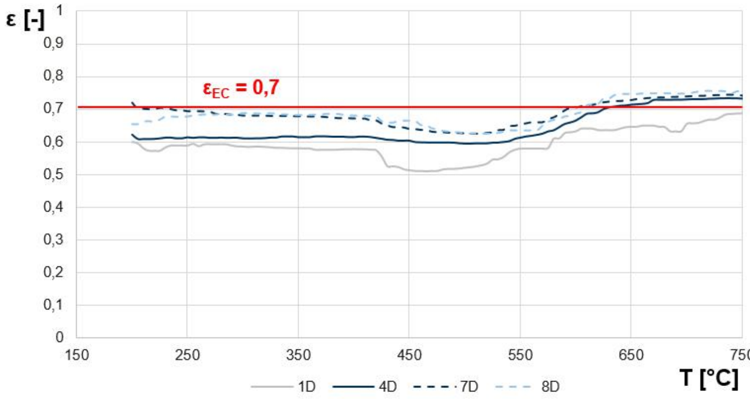
Temperature dependence of the emissivity

Category A (Si < 0,03% und 0,03% P)





Category D (Si > 0,25%)

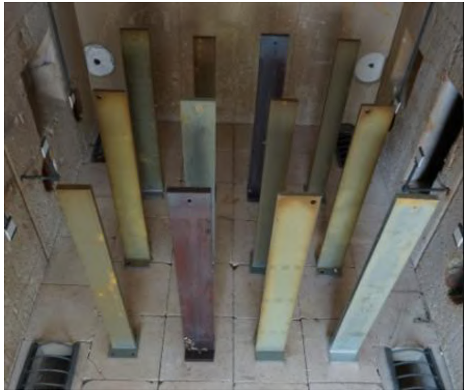


Dashed lines: stored outdoors*
Solid lines: stored indoors*

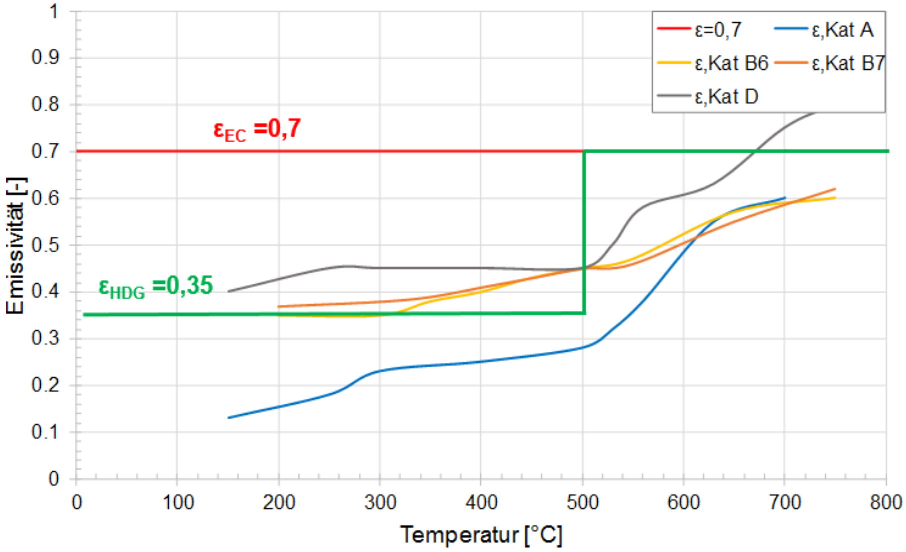
*In case of previously unfavourable storage

Real-scale fire tests

Specimens bevor and after the fire test



Determined emissivity



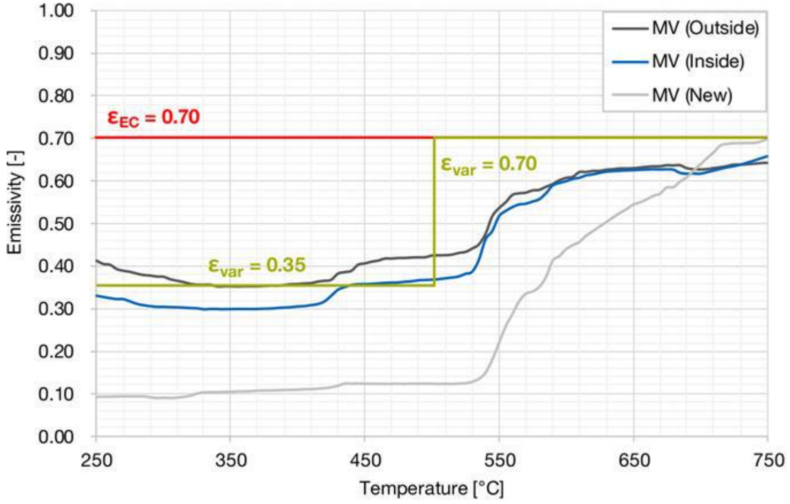
Influence of hot-dip galvanizing

- Small scale and real scale fire tests - research project “Fire resistance of hot-dip galvanized steel structures in case of fire” – TUM

- Hot-dip galvanizing - significantly improves the fire resistance of steel

- Through a combination of hot-dip galvanizing and an optimised A_m/V ratio of the steel cross-sections a fire resistance class of R30 can be achieved.

- Normative proposal: temperature-dependent two-stage emissivity ε_m - already considered in prEN 1993-1-2 and in prEN 1994-1-2 and in the DASt-Richtlinie 027 (Germany).



Type of steel	ε_m ($\theta_m \leq 500°C$)	ε_m ($\theta_m > 500°C$)
carbon steel	0,7	
stainless steel[1]	0,4	
HDG steel[2]	0,35	0,7

[1] according to annex C.

[2] Steel that has been hot-dip galvanized according to EN ISO 1461 and with steel composition according to Category A or B of EN ISO 14713-2, Table 1.

Emissivity

- Steel temperature development for unprotected steel members according to EN 1993-1-2:

$$\Delta\theta_{a,t} = k_{sh} \frac{\frac{A_m}{V}}{c_a \rho_a} \dot{h}_{net} \Delta t \quad [K]$$

- the design value of the net heat flux

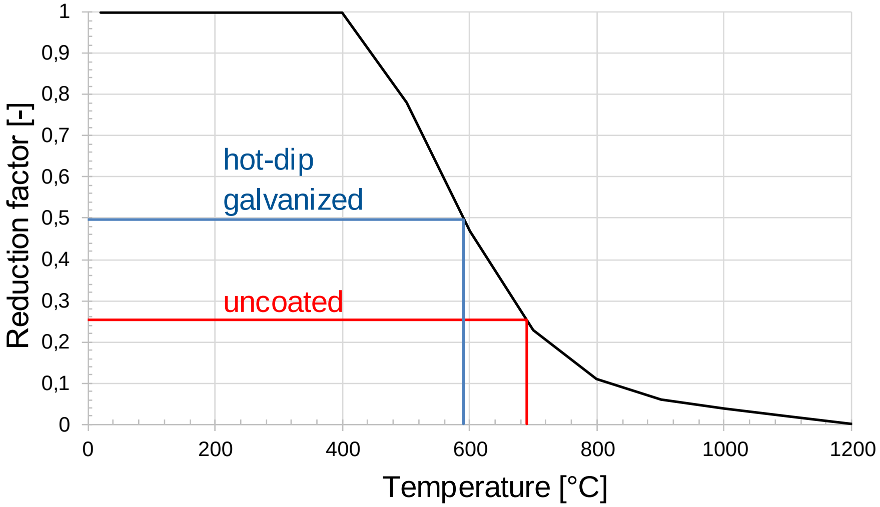
$$\dot{h}_{net} = \dot{h}_{net,c} + \dot{h}_{net,r} \quad [\mathrm{W/m^2}]$$

- the net radiative heat flux component

$$\dot{h}_{net,r} = \phi \cdot \varepsilon_m \cdot \varepsilon_f \cdot \sigma \cdot [(\theta_r + 273)^4 - (\theta_m + 273)^4]$$

ε_m - is the surface emissivity of the member
(= degree of absorption of the surface)

Example:
HEB 400, 3 sides flamed for 30 minutes



Reduction factors for the yield-strength according to EN 1993-1-2

Emissivity of steel surfaces using zinc-aluminium coatings

Project ZINQ and TUM

Overview specimens

- Number of small fire tests: 61 tests/specimens

➢ Steel category A, B and D according to EN ISO 14713-2:2020-05.

Analysed surface variants:

Batch galvanising coating according to EN ISO 1461

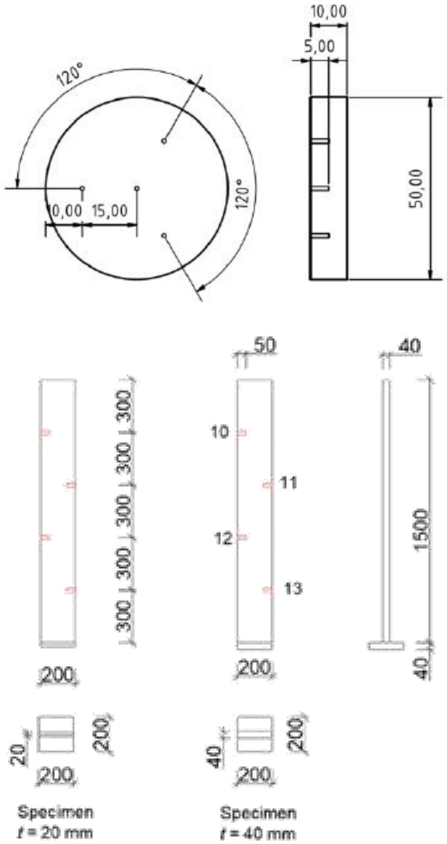
Thin-film galvanising according to DIN 50997

Influence of weathering

Influence of passivation or sealing

- Number of real-scale fire tests: 3 tests (28 specimens)

➢ Steel category B and D according to EN ISO 14713-2:2020-05.



Small scale fire tests

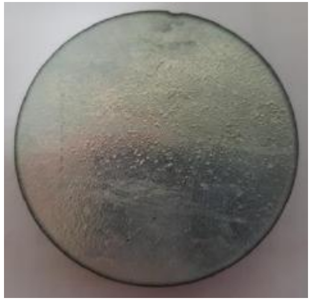
DuroZinQ
(galvanising according to DIN EN ISO 1461)

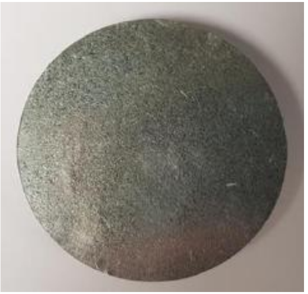
DuroZinQAl
DuroZinQ
+ additional alloy components

MicroZinQ+duropass
galvanizing according to DIN 50997 (Zn5%Al alloy)
+ passivation

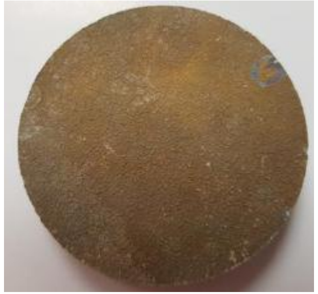
MicroZinQ+duroseal
galvanizing according to DIN 50997 (Zn5%Al alloy)
+ sealing

Before fire test

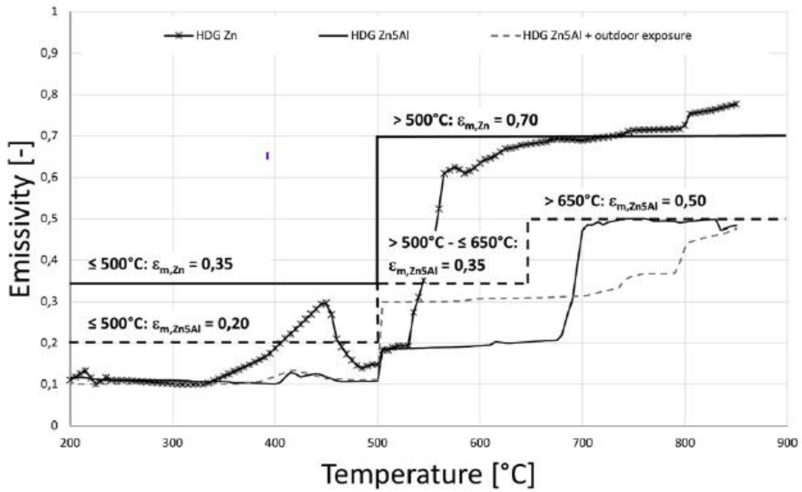




After fire test

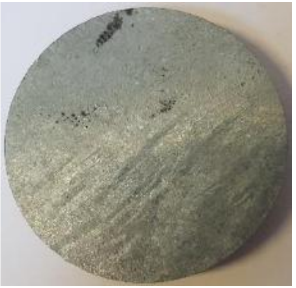


Emissivity of small scale fire tests

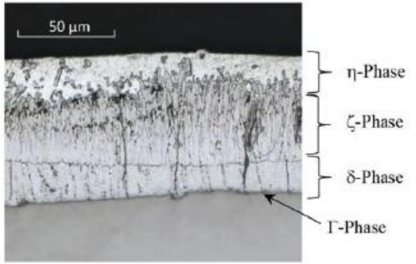


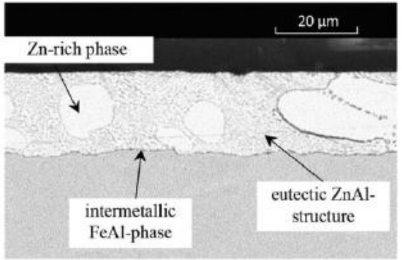
HDGZn5Al weathered

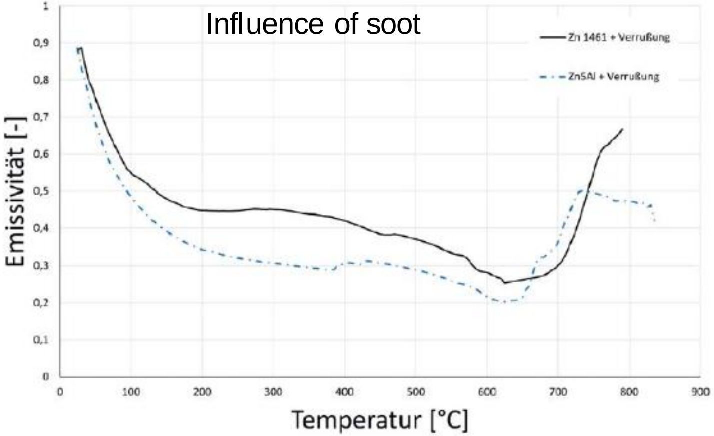
Before fire test



After fire test



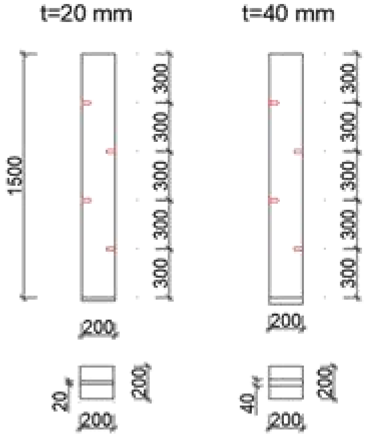




Large-scale fire tests

Test specimens before the fire test

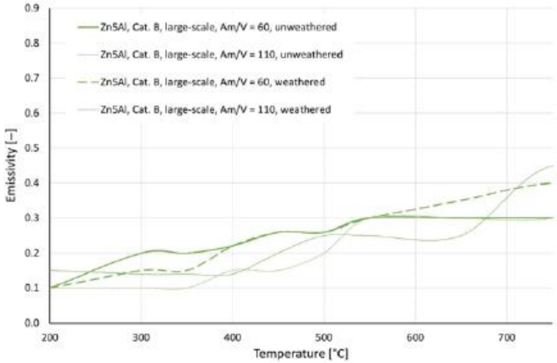
Test specimens after the fire test



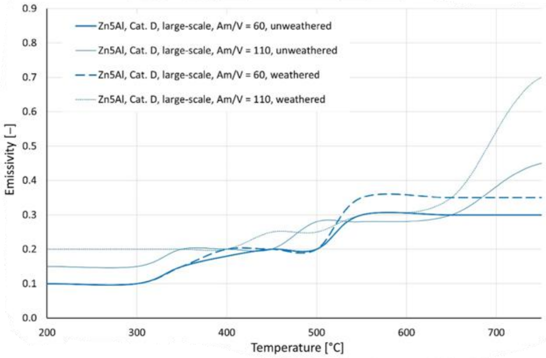
- Test specimens with thicknesses of 20 (A_m/V=100) mm and 40 mm (A_m/V=60) .
- Inside and outside stored
- Steel category: B and D
- Fire test with oil burners

Emissivity of large-scale fire tests

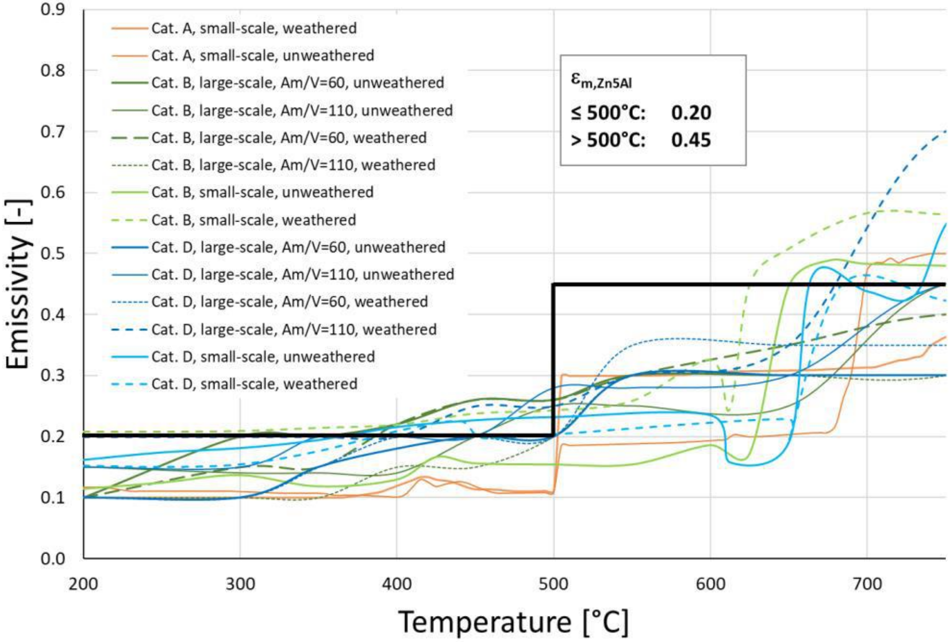
Steel category B



Steel category D



Summary of all emissivities of Zn5Al hot-dip galvanized specimens



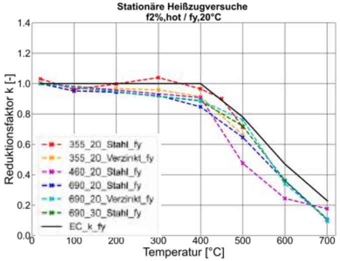
Fire resistance of hot-dip galvanized composite beams made of higher and high-strength structural steels

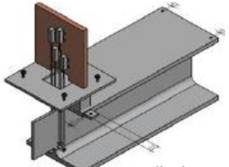
Research project in cooperation with iBMB of the TU Braunschweig and RWTH Aachen

Work package overview

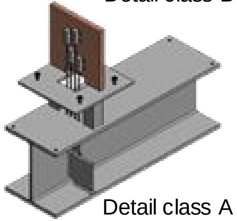
Temperature-dependent material properties → Investigations into crack-free hot-dip galvanizing (DASt-Ri. 022) → Large-scale fire tests on hot-dip galvanized composite beams → Large-scale fire tests on typical connection details between protected and hot-dip galvanized steel beams → Numerical investigations

Steady-state and transient tests: S460M and S690QL: uncoated and hot-dip galvanized

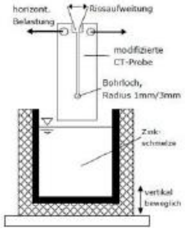




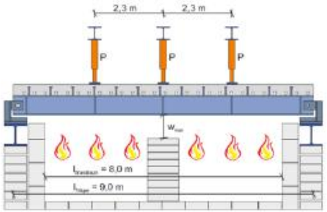
Detail class B

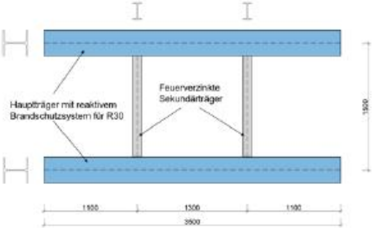


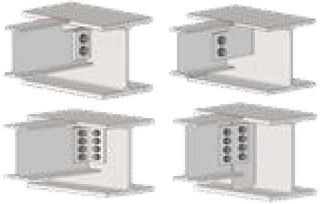
Detail class A

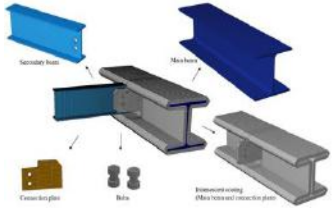


LNT-tests

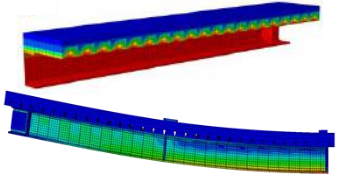




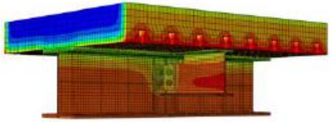




FE-Model connection details Beams: RBS-HDG



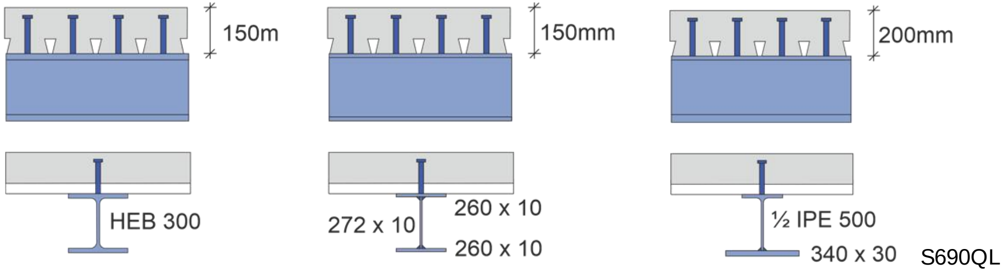
FE-Model composite beams



FE-Model connection details composite beams: HDG

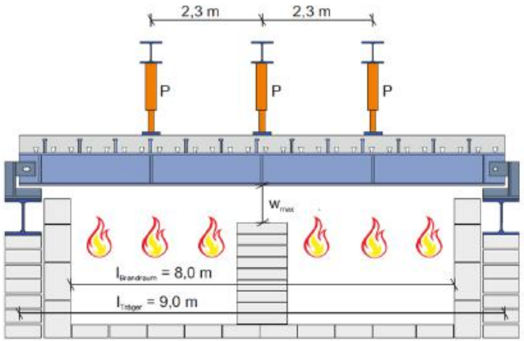
Hot-dip galvanized composite beams

- Number of hot-dip galvanized composite beams: 6
  - 2 hot-rolled standard sections (HEB 300 and HEB 450), S460M
  - 2 welded double-symmetrical sections, S690QL
  - 2 single-symmetrical sections (1/2 IPE 500 from S460M with bottom flange plate from S690QL)



- Beam length: L = 9.0 m
- Concrete deck: 100 cm x 15 cm or 20 cm
- Concrete class: C35/45
- Holorib trapezoidal sheet: HR 51/150, t = 0.88 mm
- Stud sheer connectors: Typ SD 1, ø = 22, l = 125 mm
- Secondary beam connected at mid-span

Fire test setup

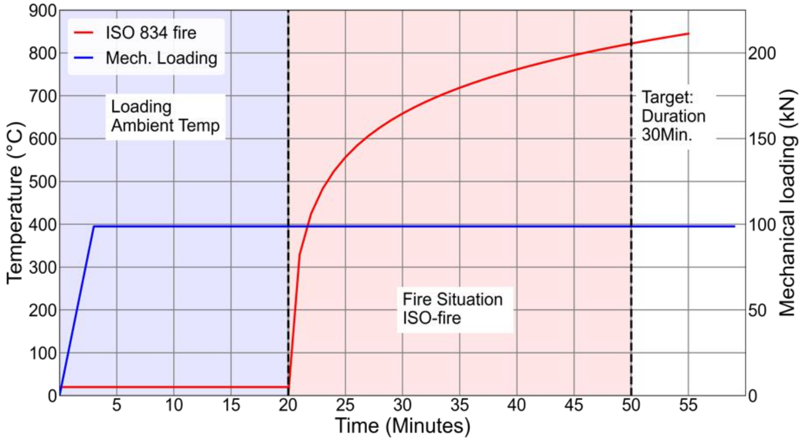


Mechanical load

- Constant loading level with 3 hydraulical presses
- Loading min. 15 min before start of fire

Temperature loading according to ISO 834

- Oil burners (ISO 834 standard fire)
- Continued constant load from hydraulical presses throughout standard fire
- Break-off criteria: approx. 40 cm deflection in the middle of the field
- Target: 30 min temp. loading
- Load of the beams: 80–100 kN per press

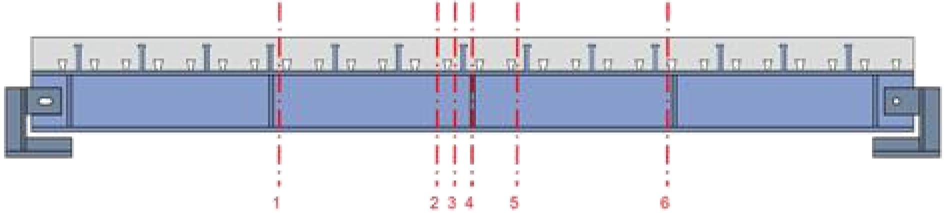


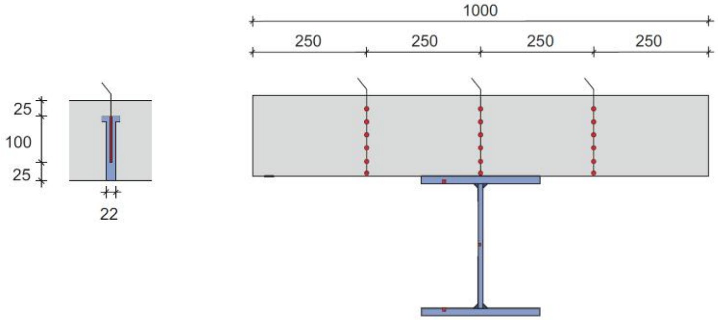
Measurements

- Temperature (steel profile, concrete deck, sheer studs)
- Displacements (vertical displacement in the middle of the field and slip at both beam ends)

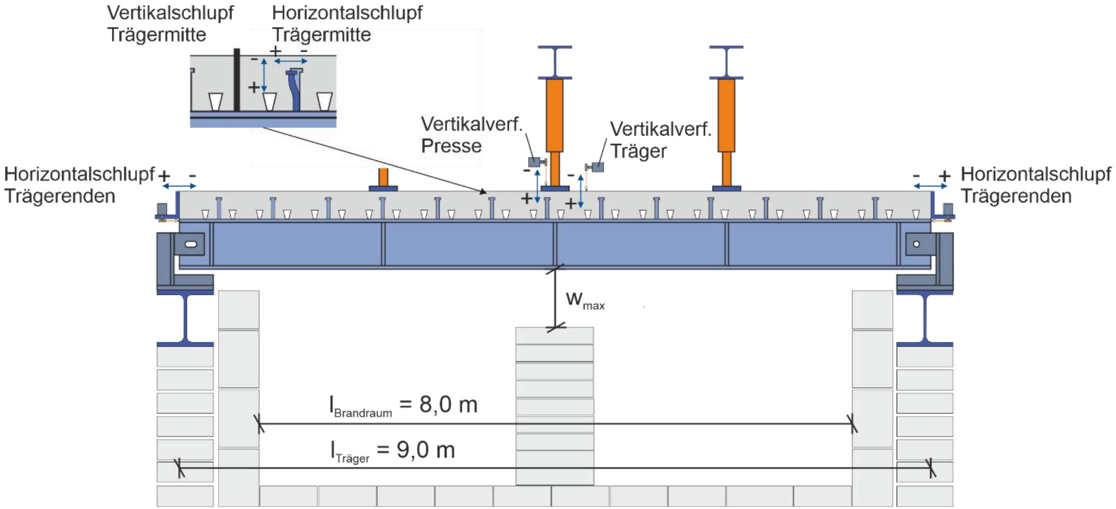
Measurements

Temperature



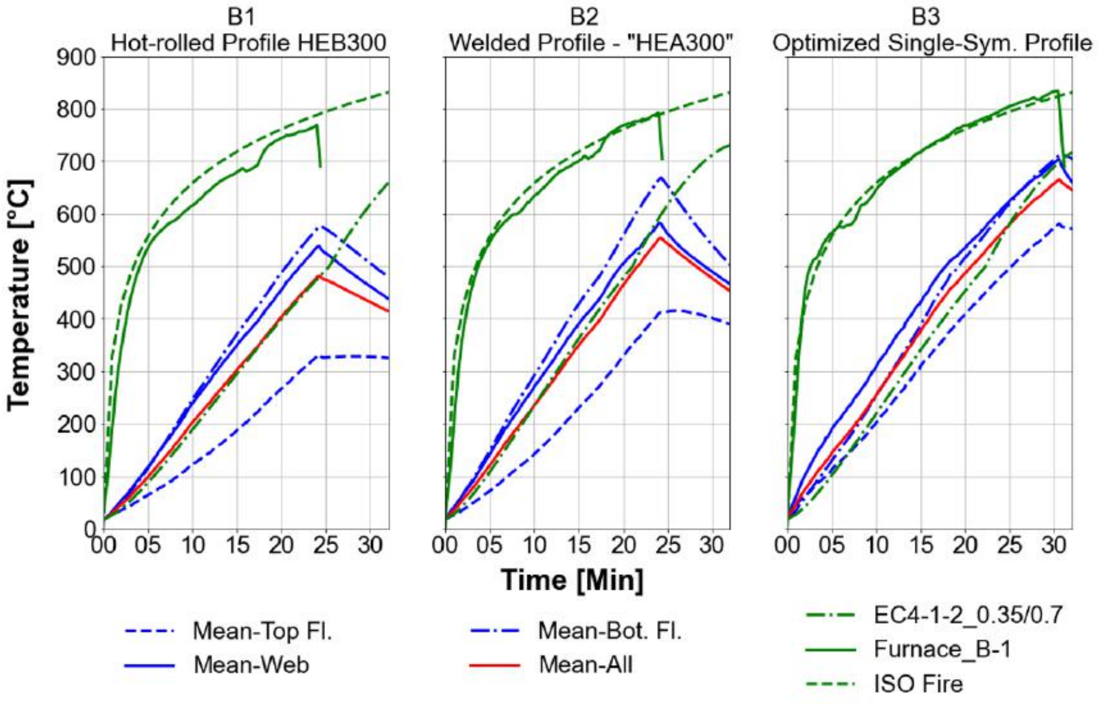


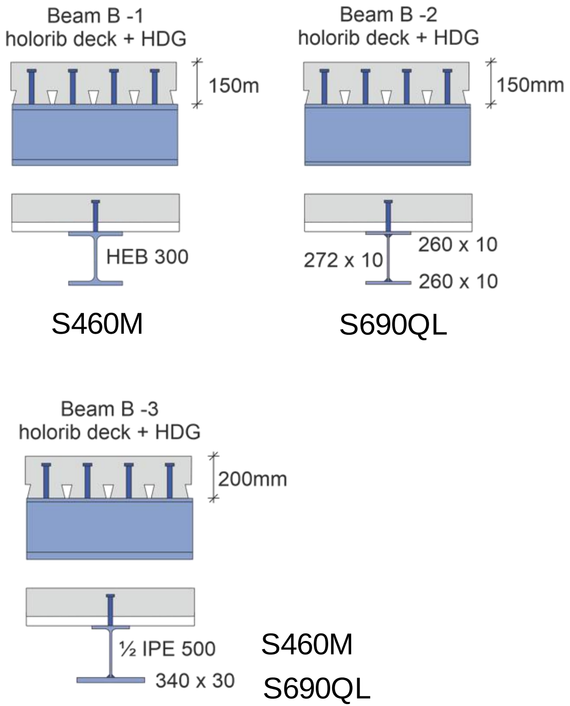
Deflections



Temperature development

- Emissivity approach 0.35/0.7 for HDG for different types of sections





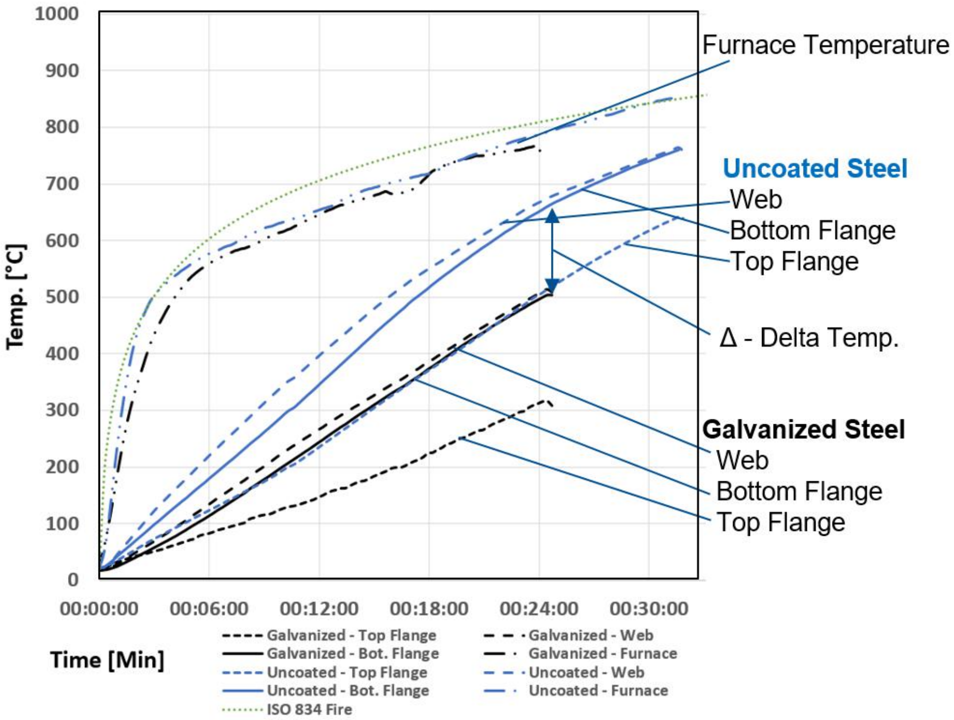
Comparison with ungalvanized steel

- Temperature development in standard steel section HEB 300 (of composite beam with trapezoidal sheet)

  - ➢ One hot-dip galvanized section HEB 300
  - ➢ Two uncoated sections HEB 300 (AiF Prj. 21403N, K. Tutzer, TUM)
  - ➢ Different trapezoidal sheets

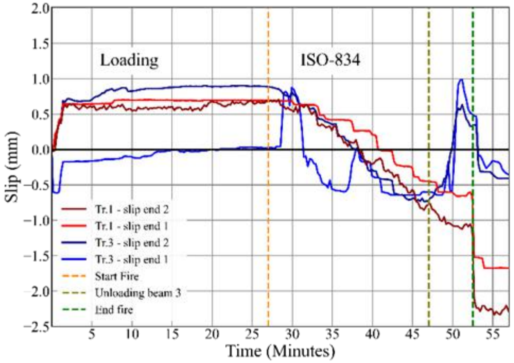
- Less heating of hot-dip galvanized section

  - ➢ Significant difference in temperature of bot. flange and web after 24 min
  - ➢ Top flange results may also vary due to different trapezoidal sheets beeing used

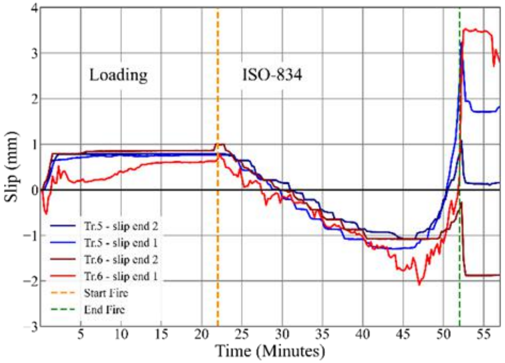


Vertical deformation and slip of the beams

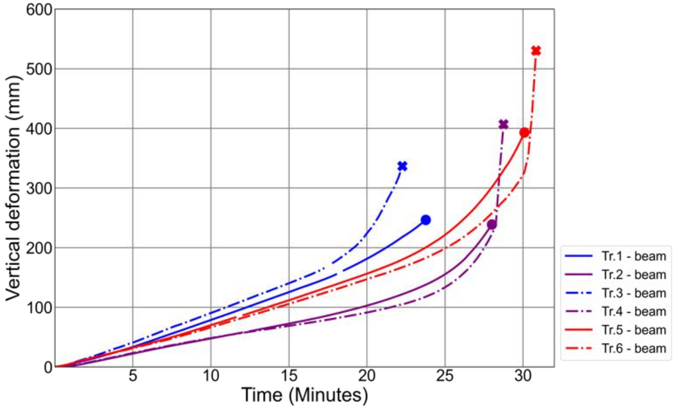
- Concrete spalling after minute 14
- Different failure modes
- Vertical deformation recorded during fire test and cooling phase
- Concrete – steel – section – slip recorded during fire test and cooling phase



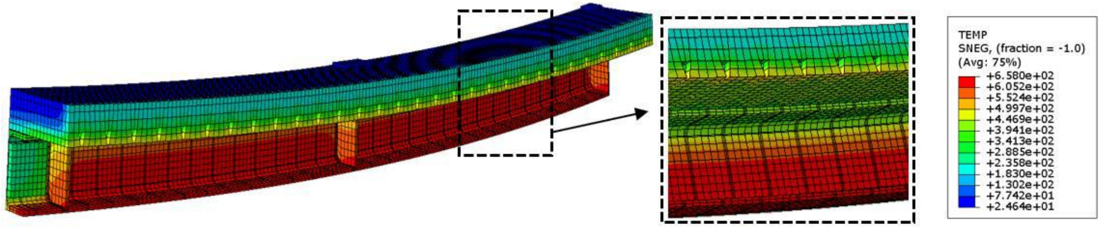
Fire test 1: Beam 1 and 3



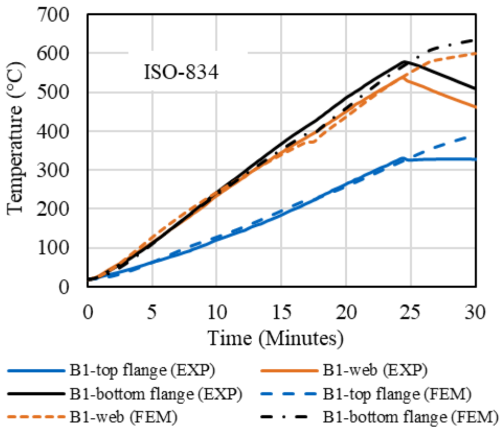
Fire test 3: Beam 5 and 6

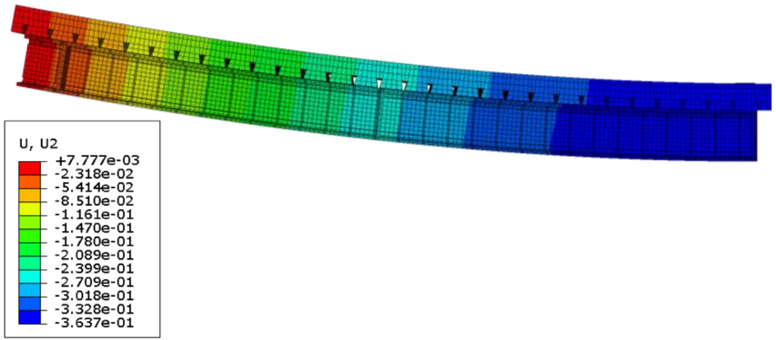


Validation FE-model for beam B-1

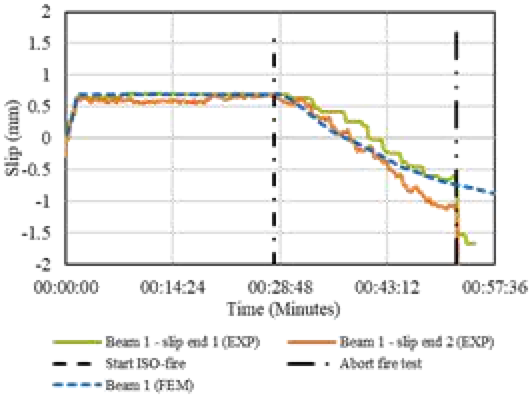


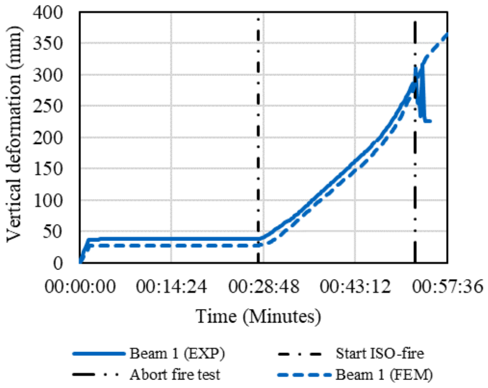
Temperature model beam B-1:
temperature development after 30 min of fire loading





Static model beam B-1:
Deformation after 30 minutes of fire test





Numerical investigations

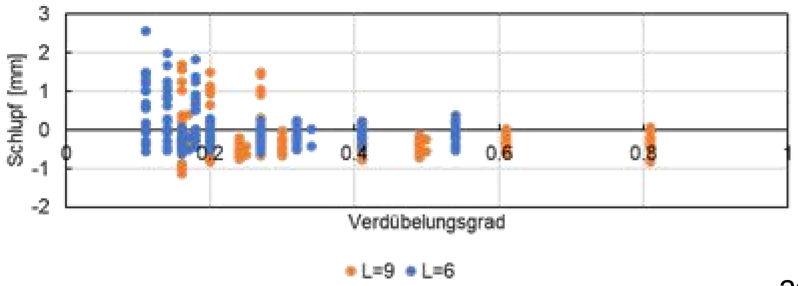
Results parametric study

- The degree of shear connection directly influences the stiffness of a composite beam.
- non-linearity can be observed for a degree of shear connection $\eta \leq 0.4$
- Slip at $\eta > 0.4$: constantly low over a wide range
- Results of the parameter study: similar behaviour for the slip as in the investigations in the research project:

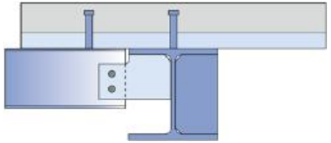
„Mensinger, M.; Pfenning, S.; Zehfuß, J. et al.: Schlussbericht zu IGF-Vorhaben Nr. 19105 N: Minimum degree of stud shear connections for composite beams in case of fire, 2018.“

Fire situation: η=1.0 independent of its degree of shear connections according to DIN EN 1994-1-1 for $\eta \geq$ 0.4 at ambient temperature.

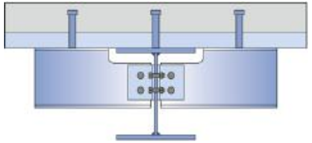
Parameter	Variation
Beam length	6 m, 9 m
Concrete chord high	14 cm, 17 cm, 20 cm
Concrete chord geometrie	Composite deck system with Holorib
Steel profile height	300 mm, 500 mm, 600 mm
Steel profile	HEA, HEB, HEM
Steel grade	S460
Concrete grade	C40/50
Distance between the studs for the degree of shear connection	15 cm, 30 cm, 45 cm (ca. 20% - 100%)
Load type	Single load at the centre of the span, 3 single loads
Protection of the steel profile	Hot-dip galvanized (Emissivität: 0,35-0,7)



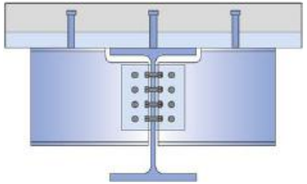
Temperature development in the joints



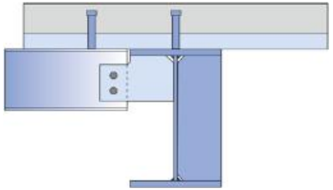
C-2



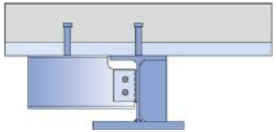
C-1



C-3



C-4



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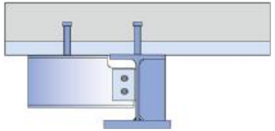
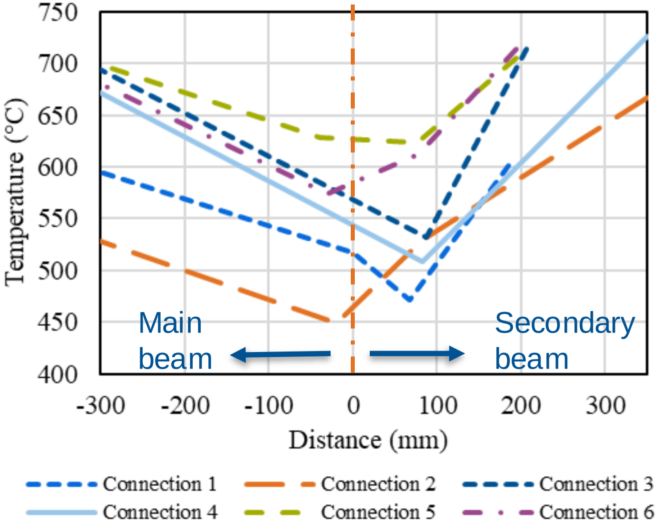
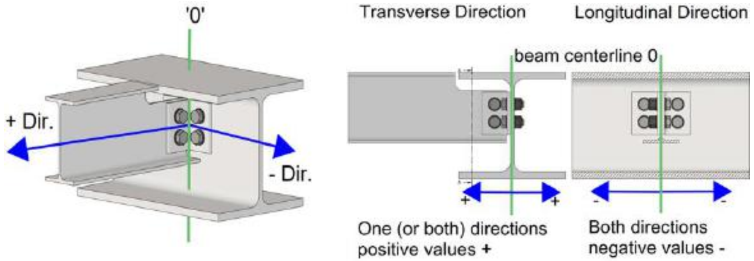


C-6





Temperature of connection details

Connection	Connection part	Temperature according to DIN EN 1993-1-2 with $\varepsilon_m = 0{,}35 - 0{,}70$ [°C]	Temperatur according to prEN 1993-1-2 [°C]	Temperature FE-Simulations [°C]	Temperature Fire tests [°C]
Connection 1 (after 24 min)	Bolt 1 (SB)	577* / 552,3**	798,8* / 781,6**	468,4	437,4[1]
	Bolt 2 (SB)	629* / 601,9**	798,8* / 781,6**	484,6	445,5[1]
	Angle (SB)	603* / 577,1**	687* / 544,4**	487,6	472[1]
Connection 2 (after 24 min)	Bolt 1 (SB)	572,1* / 547,3**	798,8*/ 781,6**	576,7	549,5
	Bolt 2 (SB)	624* / 596,9**	798,8*/ 781,6**	592,3	571,5
	Long fin plate (SB)	598* / 572,1**	766,5* / 735,4**	596,2	534,5
	Long fin plate (free standing)	766,5*	766,5*	533,03	589,6
Connection 3 (after 30 min)	Bolt 1 (SB)	569,1* / 544**	833,5* / 823,7**	516,9	475,8[1]
	Bolt 2 (SB)	-	-	-	-
	Bolt 3 (SB)	-	-	-	-
	Bolt 4 (SB)	668* / 638,6**	833,5* / 823,7**	554,6	520,6[1]
	Angle	618,6* / 591,3**	718,3* / 589,7**	543,6	531,7[1]
Connection 4 (after 30 min)	Bolt 1 (SB)	606,4* / 597,8**	836* / 832**	618,8	571,6
	Bolt 2 (SB)	661,5* / 652**	836* / 832**	633	587,4
	Long fin plate (SB)	634* / 624,9**	750,4* / 701**	637,6	601,4
	Long fin plate (free standing)	750,4*	750,4*	565,9	508,3
Connection 5 (after 30 min)	Bolt 1 (SB)	612* / 603,3**	836* / 832**	642,6	590
	Bolt 2 (SB)	667* / 657,4**	836* / 832**	653	596,8
	Short fin plate	639,5* / 630,3**	791,3* / 735,9**	658,8	623,1

Legend:

- The bolts are numbered consecutively from top to bottom within each connection, with bolt 1 always being the highest bolt
- SB – Secondary beam

[1]Average value from the measured values on both sides of the main beam (due to symmetry)

*Value with k_{sh}=1,0

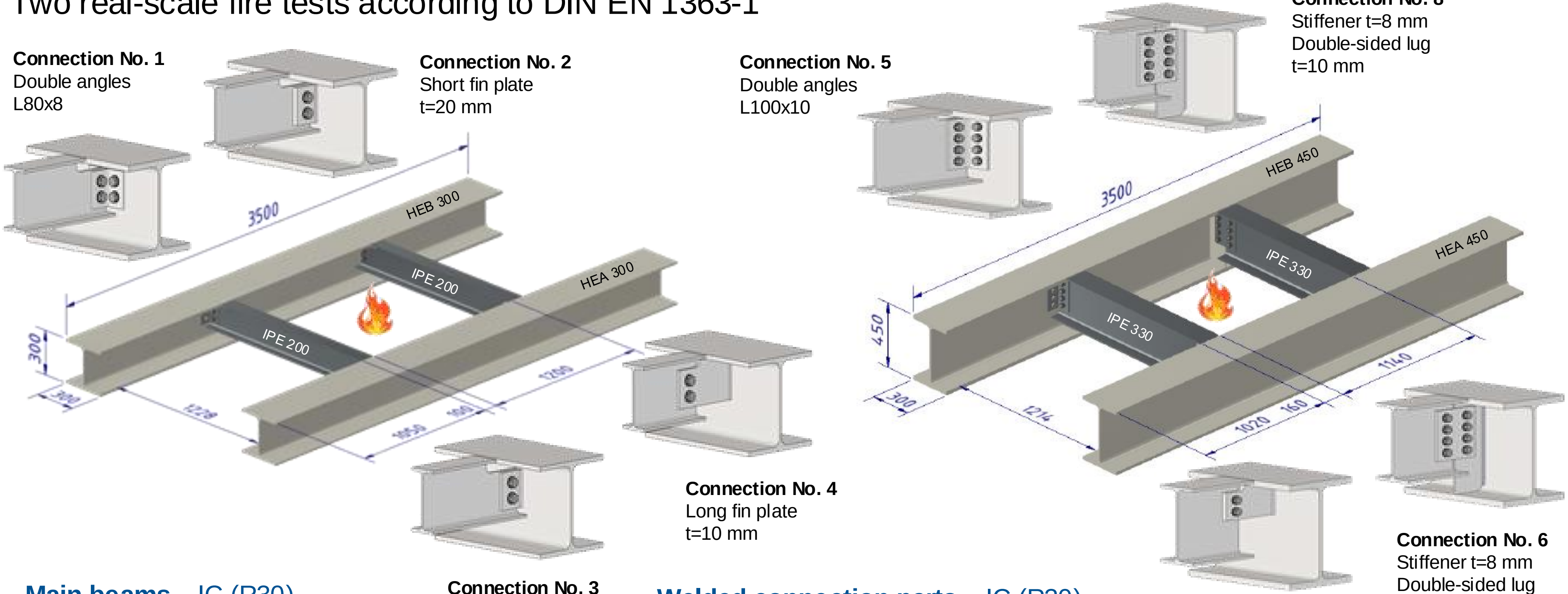
**Value with k_{sh} from the secondary beam

→ In most cases, the prEN 1993-1-2 draft standard leads to a more conservative dimensioning of the connecting parts than the current standard.

Large-scale fire tests on typical connection details between coated and hot-dip galvanized steel beams

Typical connection details between coated and hot-dip galvanized beams in case of fire

Two real-scale fire tests according to DIN EN 1363-1



Connection No. 1
Double angles
L80x8

Connection No. 2
Short fin plate
t=20 mm

Connection No. 3
Short fin plate
t=10 mm

Connection No. 4
Long fin plate
t=10 mm

Connection No. 5
Double angles
L100x10

Connection No. 6
Stiffener t=8 mm
Double-sided lug
t=10 mm

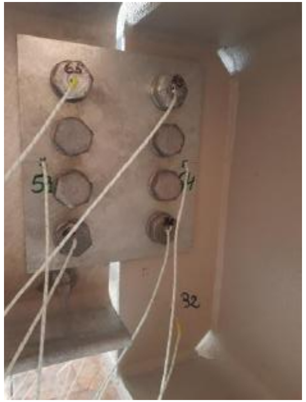
Connection No. 7
Long fin plate
t=20 mm

Connection No. 8
Stiffener t=8 mm
Double-sided lug
t=10 mm

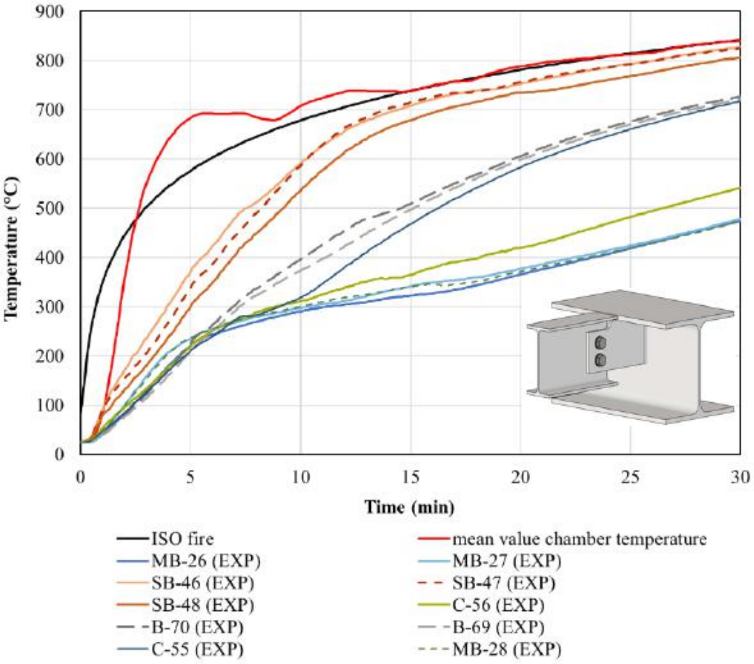
Main beams – IC (R30)
Secondary beams – HDG

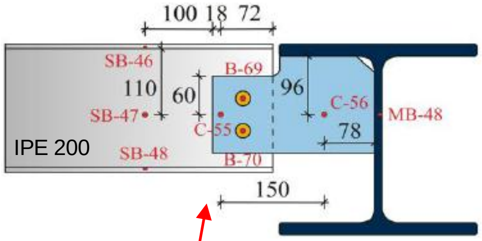
Welded connection parts – IC (R30)
Bolted connection parts – HDG

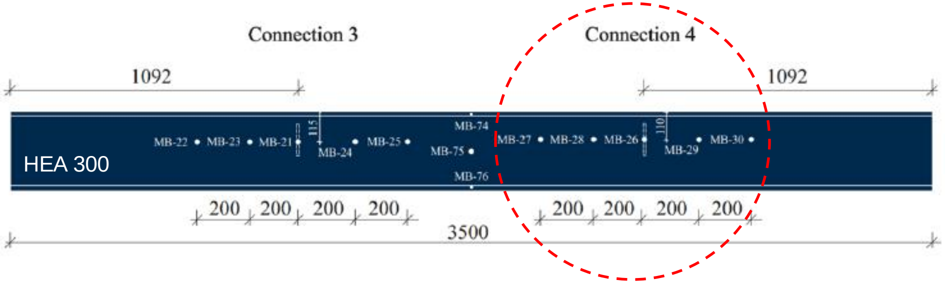
Experimental setup



Temperature development in connection detail No. 4

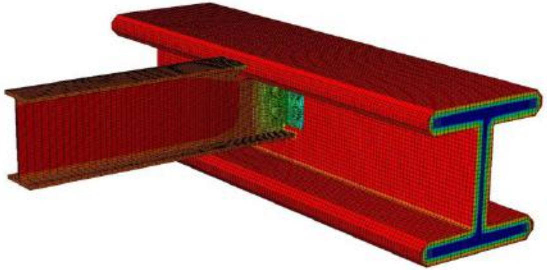


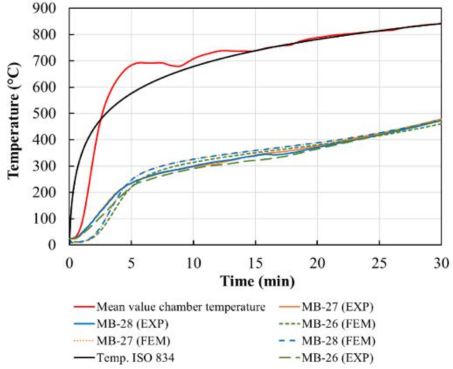


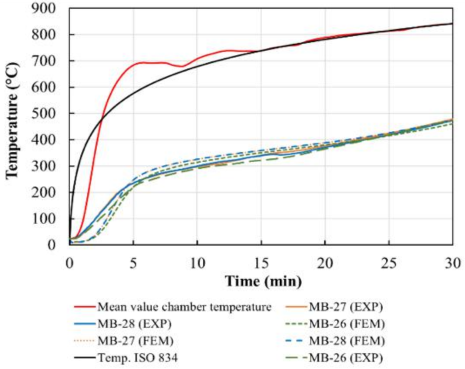


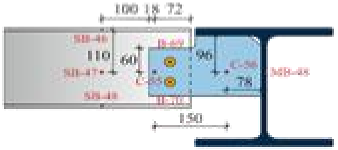
Target: Heating behavior of connections between hot-dip galvanized secondary beams to main beams protected with a reactive fire protection system

FE-Model connection details

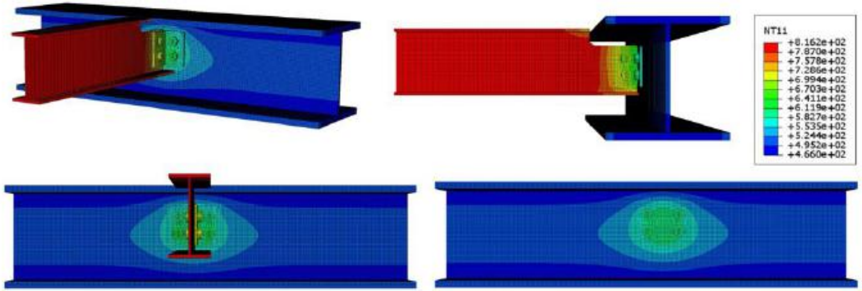




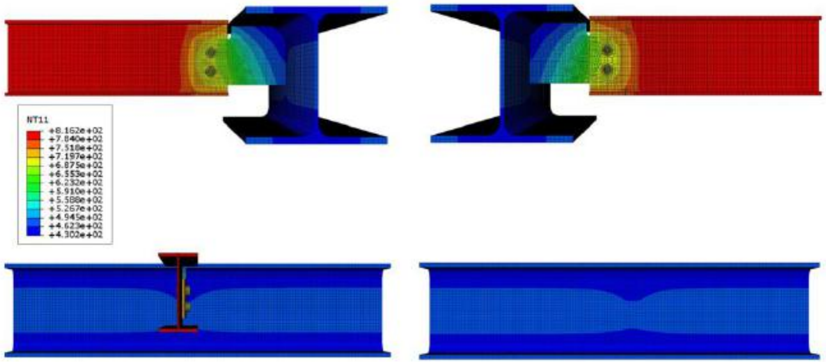




Connection No. 1 – Heating after 30 minutes of fire



Connection No. 4 – Heating after 30 minutes of fire

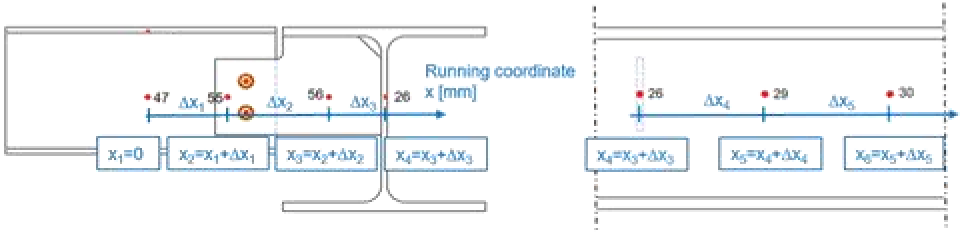


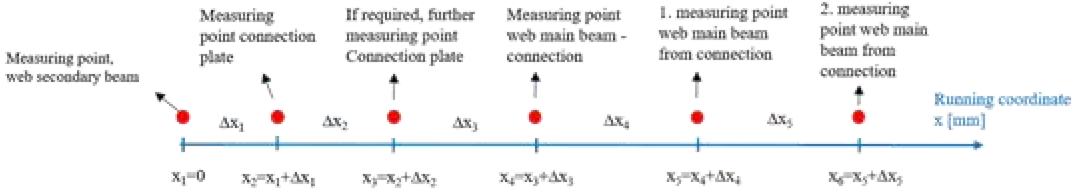
Definition of a running coordinate x

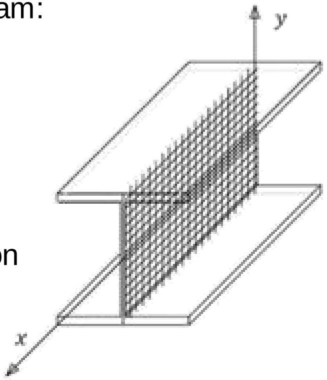
- Definition of a running coordinate x from the secondary beam to the main beam:
  Start $x_1=0$ – Measuring point web secondary beam
  End $x_i= \sum \Delta x_i$ – Measuring point web main beam

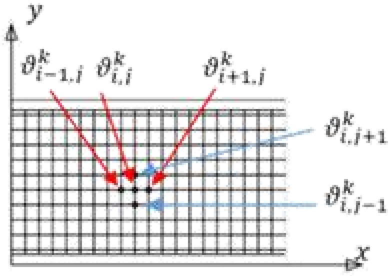
- Analytical solution using a stepwise method

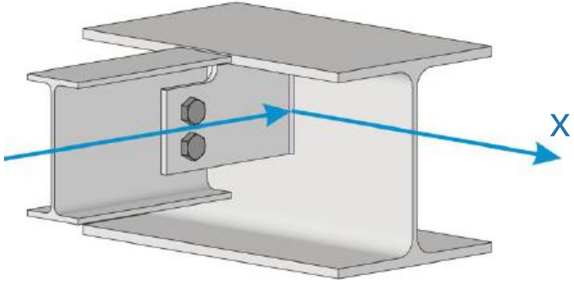
- Determination of the temperature development of a grid point using two additional grid points, at a distance of Δx_i from the point under consideration





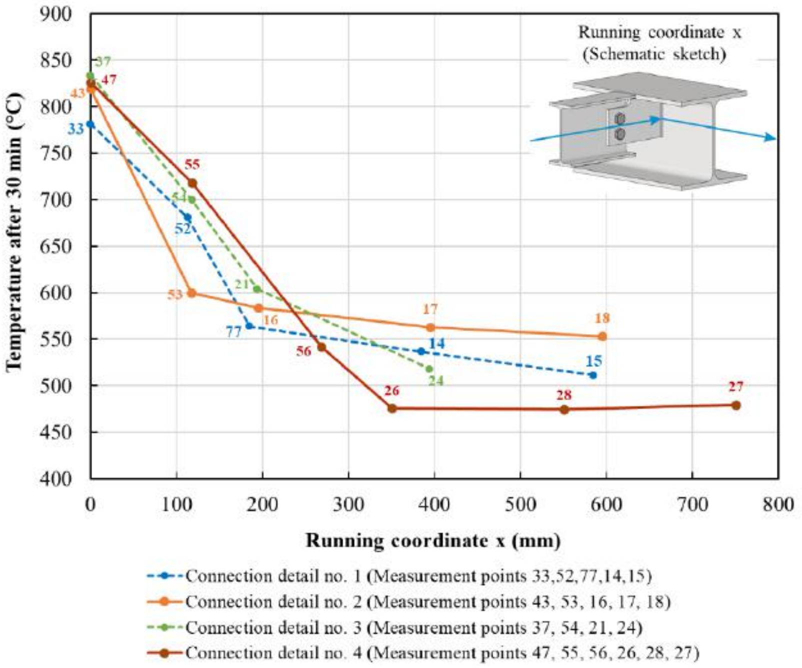




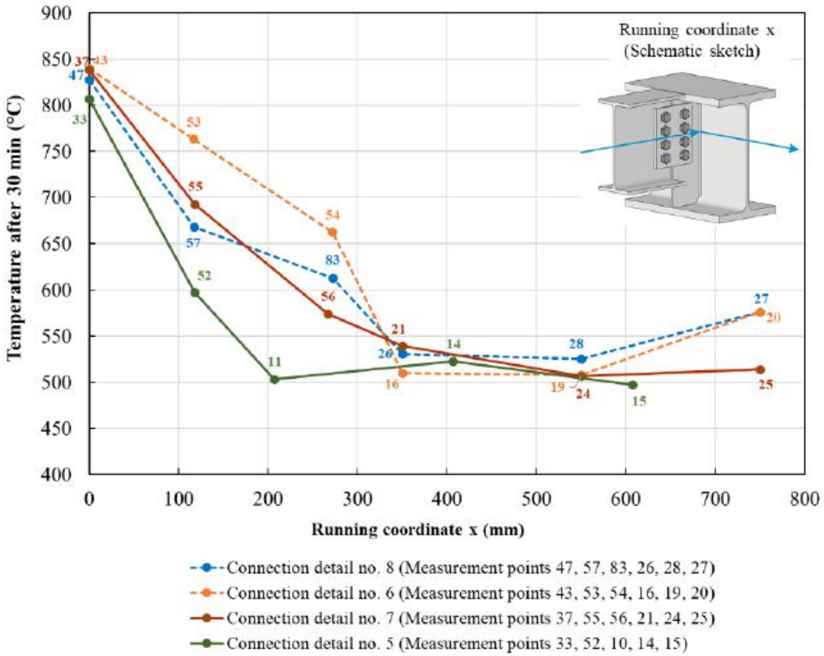


Temperaturentwicklung nach 30 min Brandfall

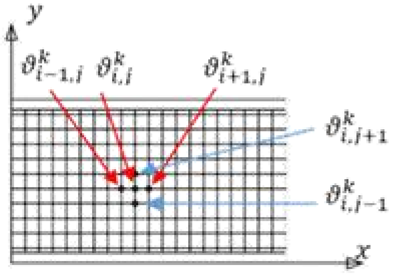
Connection details - Experimental setup no 1



Connection details - Experimental setup no 2



Analytical solution



- Temperature development of secondary beam and main beam

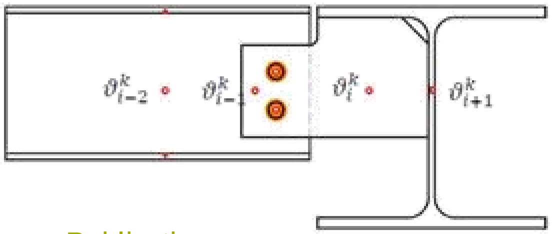
$$\vartheta_i^{k+1} = \vartheta_i^k + \Delta\vartheta_{a,t} + \Delta\vartheta_t\left(\dot{W}(x,y,t,\vartheta)\right)$$

ϑ_i^k - Initial temperature

$\Delta\vartheta_{a,t}$ - Temperature for unprotected steel or steel protected with IC

$\Delta\vartheta_t\left(\dot{W}(x,y,t,\vartheta)\right)$ - one-dimensional heat source

$$\Delta\vartheta_t = \frac{\Delta t}{c_a(\vartheta)\cdot\rho_a}\cdot\left(\frac{\vartheta^k_{web}-\vartheta^k_{i,j}}{\Delta y_{j-1}}\cdot\frac{\left[\frac{Am}{V}\right]_{web}+\left[\frac{Am}{V}\right]_i}{2}\cdot\frac{2\cdot\lambda_i^k\cdot\lambda^k_{web}}{\lambda_i^k+\lambda^k_{web}}\right)$$ - for unprotected steel



- Temperature development connection detail

$$\vartheta_i^{k+1} = \vartheta_i^k + \vartheta_{DGL} + \vartheta_{Heat\ exchange}$$

$$\vartheta_{DGL} = \frac{4\cdot a_i^k\cdot\Delta t}{V_i\cdot\Delta x}\cdot\left[\frac{\left(\vartheta^k_{i+1}-\vartheta^k_i\right)\cdot A_{i+\frac{1}{2}}}{\left(\Delta x_i+\Delta x_{i+1}\right)\cdot\left(1+\frac{\lambda_i^k}{\lambda^k_{i+1}}\right)}-\frac{\left(\vartheta^k_i-\vartheta^k_{i-1}\right)\cdot A_{i-\frac{1}{2}}}{\left(\Delta x_i+\Delta x_{i+1}\right)\cdot\left(1+\frac{\lambda_i^k}{\lambda^k_{i-1}}\right)}\right]$$

$$\vartheta_{Heat\ exchange} = \frac{\Delta t}{c_a(\vartheta)\cdot\rho_a}\cdot\left(\frac{\vartheta_{m,t}-\vartheta_i^k}{d_i}\cdot\frac{\frac{A_{i+\frac{1}{2}}+A_{i-\frac{1}{2}}}{2}}{V_i}\cdot\frac{2\cdot\lambda_i^k\cdot\lambda^k_{i,j\pm1}}{\lambda_i^k+\lambda^k_{i,j\pm1}}+\frac{\vartheta^k_{i+1}-\vartheta^k_i}{\Delta x_i}\cdot\frac{A_{i+\frac{1}{2}}}{V_i}\cdot\frac{2\cdot\lambda_i^k\cdot\lambda^k_{i+1}}{\lambda_i^k+\lambda^k_{i+1}}+\frac{\vartheta^k_{i-1}-\vartheta^k_i}{\Delta x_i}\cdot\frac{A_{i-\frac{1}{2}}}{V_i}\cdot\frac{2\cdot\lambda_i^k\cdot\lambda^k_{i-1}}{\lambda_i^k+\lambda^k_{i-1}}\right)$$

Publication:
Firan, Maria-Mirabela; Ghanbari-Ghazijahani, Tohid; Cheung, Jinhong; Mensinger, Martin: *Experiments on Fire-Protected and Hot-Dip Galvanised Steel Bolted Connections.* Fire Safety Journal 146, 2024.

Equation for temperature in the connection detail

Time-dependent equation for temperature in the connection detail

$$\Delta\theta = \frac{A \cdot \Delta t}{V \cdot c_{steel} \cdot \rho_{steel}} \cdot \left[\dot{q}_{comb,steel} \cdot k_{reduction} + \dot{q}_{cond} \cdot (1 - k_{reduction})\right]$$

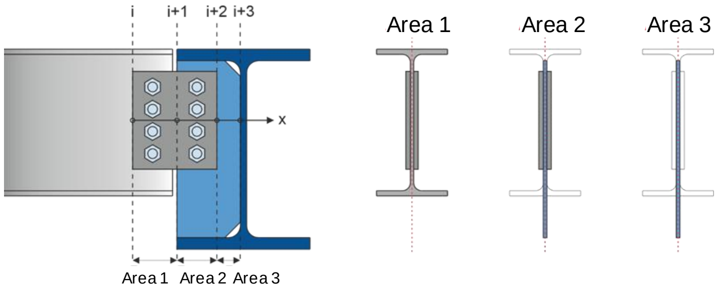
Temperature curve in the connection area

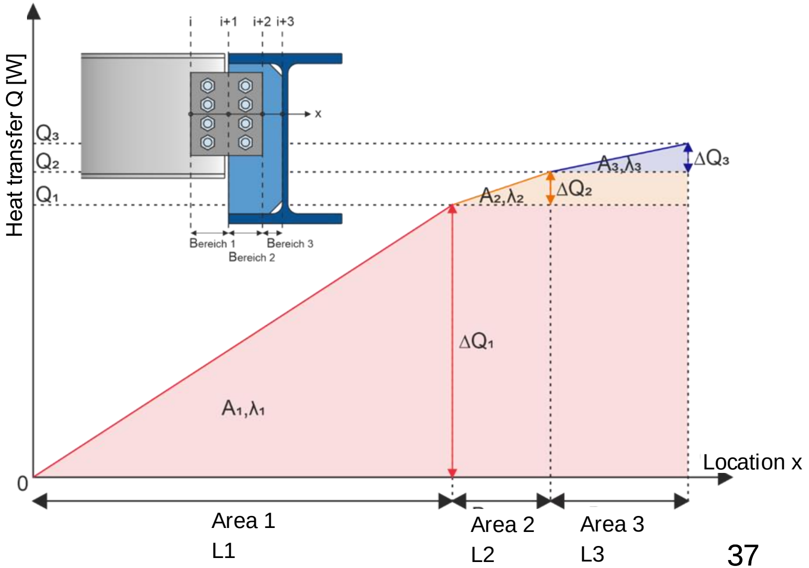
$$\theta = \theta_{unprotected} \cdot f_{unprotected} + \theta_{protected} \cdot f_{protected}$$

Location-dependent equation for determining the temperature in the connection area

$$T(x) = \theta_{start} - \dot{Q} \cdot \left(\sum_{i=1}^{n} \frac{L_i}{A_i \cdot \lambda_i} \cdot \frac{1}{1 + e^{-k_i \cdot \left(x - \left(\sum_{j=0}^{i} L_{j-1} + \frac{L_i}{2} \right) \right)}} \right)$$

- Good agreement between calculations with the equations, experiments and FEM.
- Simplified function for temperature determination in the connection detail - in progress.
- Publication in progress with development of the equations

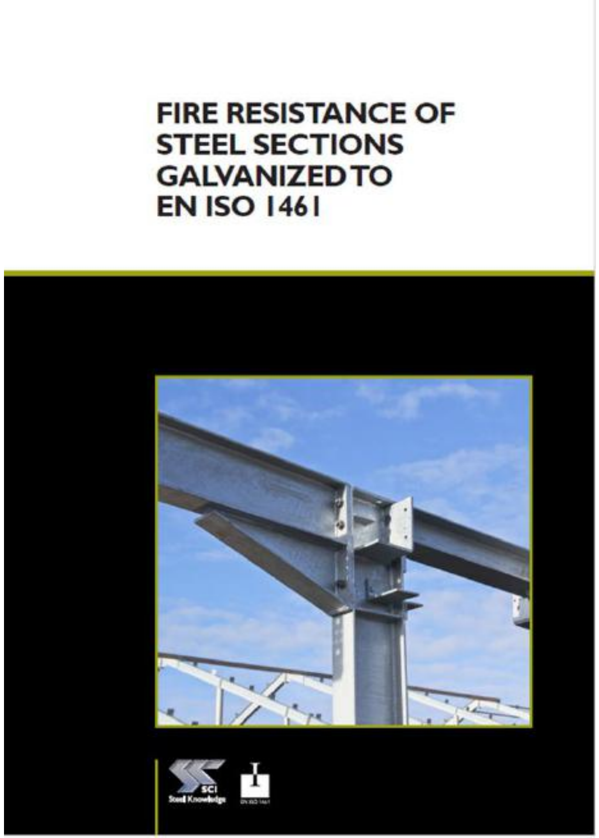




Conclusion

- Galvanizing has a positive effect on the temperature development of the steel. The two-stage emissivity approach (ε_m = 0,35 – 0,7) proved to be applicable.
- No irregularities in the steel beams as a result of the fire tests: two S460M rolled sections and one single-symmetrical beam (S460M and S690QL, larger flange width).
- Further investigations are required for hot-dip galvanised steel made of the material S690QL in the case of fire - see final report of the research project.
- Connection details between unprotected secondary beams on protected main beams: The tests showed that the heat transfer from the galvanized secondary beams to the protected main beams was low, depending on the type and geometry of connection.
- In some cases, it may be necessary to locally increase the dry film thickness or adjust the design of the beam. This means that it may be sufficient to protect only the main beams, resulting in considerable cost savings.
- An analytical solution was used to develop a simplified formula to determine the temperature in the connection area.

Design Guide – SCI (UK)



CONTENTS

WORKED EXAMPLES

Design Example 1 - Composite beam in a car park

Consider a simply supported galvanized steel composite beam which is used as a secondary beam in an open sided multi-storey car park located in Sheffield, UK. The structure has a total height of 20 m. The composite beam consists of a UB 533x165x66 section, in steel grade S355 supporting a solid concrete slab with strength class C25/30, a depth h_c = 130 mm and an effective width b_{eff} = 3600 mm. The steel beam has enough shear studs to assume a full shear connection with the concrete slab. Determine the sagging moment resistance in the fire situation for the appropriate fire exposure period assuming that vertical shear is sufficiently low so that no reduction to the moment resistance of the beam is required. Compare the results obtained with a similar composite beam of the same dimensions and strength but made of non-galvanized steel.

SOLUTION:

According to the UK Building Regulations[15], an open sided multi-storey car park with a height of 20 m should be designed for a minimum period of fire resistance of 15 minutes. — Approved Document B, Table B4

The relevant cross-sectional properties of a UB 533x165x66 are:

- Depth, h = 524.7 mm
- Width, b = 165.1 mm
- Web thickness, t_w = 8.9 mm
- Flange thickness, t_f = 11.4 mm
- Root radius, r = 12.7 mm
- Cross-sectional area, A_a = 8370 mm²

Verification of the fire resistance of the galvanized composite beam

For a hot rolled structural steel section S355 with thickness of less than 40 mm, f_y = 355 MPa. — EN 1993-1-1, Table 3.1

A UB 533x165x66 steel beam of grade S355 is classified as Class 2 in the fire situation. Therefore, the resistance of the composite beam in the fire situation can be determined using the tables given in this publication. — EN 1993-1-2, clause 4.2.2

At room temperature, the UB 533x165x66 steel beam is classified as Class 1. Therefore, the design bending resistance of the composite cross-section is given by the plastic moment resistance, $M_{pl,Rd}$. That is: — EN 1993-1-1, clause 5.5

$$M_{Rd} = M_{pl,Rd}$$

The design strength of the concrete is given by:

$$f_{cd} = \frac{f_{ck}}{\gamma_c}$$

EN 1994-1-1, clause 2.4.1.2(2)

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Design Guide – ECCS – Still in progress!

Partnerships and support

- Technical University of Munich, Germany:
  Prof. Martin Mensinger, Maria-Mirabela Firan M.Sc.
- GAV/Industrieverband Feuerverzinken e.V.: Mark Huckshold
- CTICM, France: Gisèle Bihina, Bin Zhao
- Czech Technical University in Prague: Prof. Frantisek Wald
- University of Naples Federico II, Italy:
  Prof. Eng. Emidio Nigro, Dr. Eng. Donatella De Silva
- UK: SCI
- EGGA: Vasile Rus, Murray Cook

Chapters Guide

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2. Hot dip galvanizing
3. Establishing the surface emissivity for galvanized steel by laboratory and full-scale testing
4. Fire resistance classification
5. Material properties of carbon steel at elevated temperatures
6. Structural fire design according to EN 1993-1-2
7. Resulting design rules for hot dip galvanized steel in prEN 1993-1-2
8. Overview about research activies
9. Influences on the emissivity of hot-dip galvanised
10. Additional National Regulations and Standards
11. Design tools
12. Calculation examples
13. Case studies
14. Recomandation of execution

Thank you for your attention!

Publications – zinc-aluminium coatings

Pinger, Thomas; Firan, Mirabela; Mensinger, Martin: *Behavior of Zn5Al hot-dip galvanized steel members under fire exposure.* Journal of Structural Fire Engineering, 2024. doi:10.1108/jsfe-11-2023-0042.

Pinger, Thomas; Mensinger, Martin; Firan, Maria-Mirabela: *Emissivität von Zink-Aluminiumüberzügen unter Brandlast und Wirkung auf den Feuerwiderstand.* Bauphysik 45 (2), 2023, 122-131. doi:10.1002/bapi.202300101.

Pinger, Thomas; Mensinger, Martin; Firan, Maria-Mirabela: *Behavior of hot-dip zinc-aluminum coated steel under elevated temperature in case of fire.* Journal of Structural Fire Engineering, 2022. doi:10.1108/jsfe-02-2022-0005.

Pinger, Thomas; Mensinger, Martin; Firan, Maria-Mirabela: *Emissivität von Zink-Aluminiumüberzügen unter Brandlast und Wirkung auf den Feuerwiderstand.* Bautechnik 99 (8), 2022, 594-603. doi:10.1002/bate.202200055.

Publications – Fire resistance of HDG composite beams made of higher and high-strength structural steels

Mensinger M.; Firan M.-M.; Zehfuß J.; Frenz J.; Feldmann M.; Kühne R.; Nonn J.: Schlussbericht zu IGF-Vorhaben 21536N: *Feuerwiderstand von feuerverzinkten Verbundträgern aus höher- und hochfesten Baustählen.* 2024.

Firan, Maria-Mirabela; Ghanbari-Ghazijahani, Tohid; Cheung, Jinhong; Mensinger, Martin: *Experiments on Fire-Protected and Hot-Dip Galvanised Steel Bolted Connections.* Fire Safety Journal 146, 2024. doi:10.1016/j.firesaf.2024.104130.

Maria-Mirabela Firan, Justus Frenz, Annika Kapfhammer, Jochen Zehfuß, Martin Mensinger: *Validation of numerical simulations for hot-dip galvanized composite beams and connection details with experimental data.* Proceedings of the 13th International Conference on Structures in Fire - SiF 2024, University of Coimbra, Portugal, 983-994. ISBN 978-989-35292-2-5.

Publications – Fire resistance of HDG composite beams made of higher and high-strength structural steels

Mensinger, Martin; Firan, Maria-Mirabela: *Erwärmung des Anschlusses eines feuerverzinkten Sekundärträgers an einen mit reaktivem Brandschutzsystem geschützten Hauptträger im Brandfall. Teil 1: Brandversuche an unterschiedlichen An-schlussdetails*. Stahlbau, 2023. doi:10.1002/stab.202200072.

Mirabela Firan; Kurt Tutzer; Martin Mensinger; Justus Frenz; Jochen Zehfuß: *Temperature development in the cross section of composite beams with galvanized steel compared to uncoated steel.* Proceedings of the 12th International Conference on Structures in Fire, The Hong Kong Polytechnic University, 2023, 180-191. E-ISBN: 978-962-367-869-8.

Ronny Kühne; Prof. Markus Feldmann; Maria-Mirabela Firan; Prof. Martin Mensinger; Justus Frenz; Prof. Jochen Zehfuß: *Hot-dip galvanizing of high strength steel compo-nents and its impact on the fire resistance of steel structures*. Proceedings of the 12th Asia Pacific General Galvanizing Conference, 2023, 209 – 221.

Publications – Fire resistance of HDG composite beams made of higher and high-strength structural steels

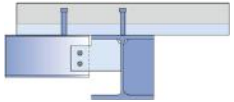
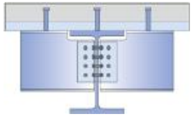
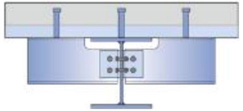
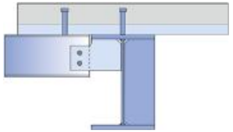
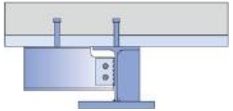
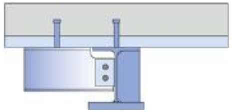
Justus Frenz; Jochen Zehfuß; Maria-Mirabela Firan; Martin Mensinger: *Temperature increase throughout hot-dip galvanized steel sections and connections of composite beams in the fire situation.* Proceedings of IFireSS 2023 - International Fire Safety Symposium, ALBRASCI, 2023, 507-516. E-ISBN: 978-65-00-82533-6.

Maria-Mirabela Firan, Martin Mensinger, Justus Frenz, Jochen Zehfuß, Ronny Kühne, Markus Feldmann: *Fire resistance of hot-dip galvanized HSS composite girders and connections between protected and hot-dip galvanized steel girders.* Intergalva 2022. Rome, Italy.

Firan, M.; Frenz, J.; Mensinger, M.; Zehfuß, J.; Feldmann, M.; Kühne, R.: *Feuerwiderstand von Feuerverzinkten Verbundträgern aus höher- und hochfesten Baustählen und Verbindungen von geschützten zu feuerverzinkten Stahlträgern.* 8th Symposium Structural Fire Engineering. TU Braunschweig, Tagungsband, 2022.

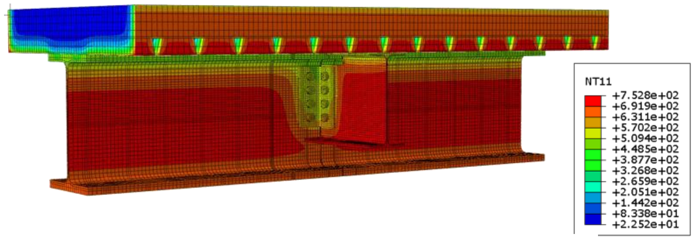
Back-up

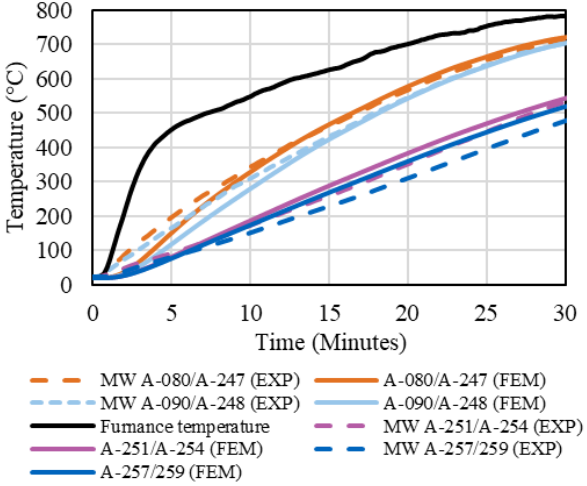
Overview composite beams

Beam-no. (Test-no.)	Profile main beam	Profile secondary beam	Connection type and no.	Concrete deck	Sketch
1 (T1)	HEB 300 S460M	IPE 200 S355J2	C2-long fin plate t=10 mm	100x15 cm	
2 (T3)	HEB 450 S460M	IPE 330 S355J2	C3-double angles L100x10	100x15 cm	
3 (T1)	Welded section Flange: 16 x 260 Web: 10 x 268 mm S690QL	IPE 200 S355J2	C1-double angles L80x8	100x15 cm	
4 (T3)	Welded section Flange: 20 x 300 Web: 10 x 410 mm S690QL	IPE 200 S355J2	C4-long fin plate t=20 mm	100x15 cm	
5 (T2)	Single Sym. 1/2 IPE500 (S460M) + bottom flange 30 x 340 mm (S690QL)	IPE 200 S355J2	C5-short fin plate t=10 mm	100x20 cm	
6 (T2)	Single Sym. 1/2 IPE500 (S460M) + bottom flange 30 x 250 mm (S690QL)	IPE 200 S355J2	C6-short fin plate t=20 mm	100x20 cm	

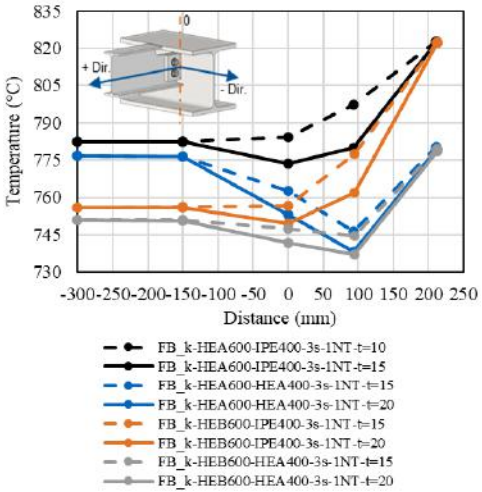
Numerical investigations connection details

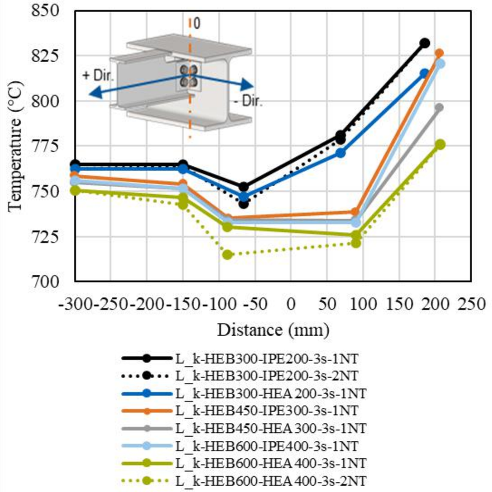
Connection detail C3

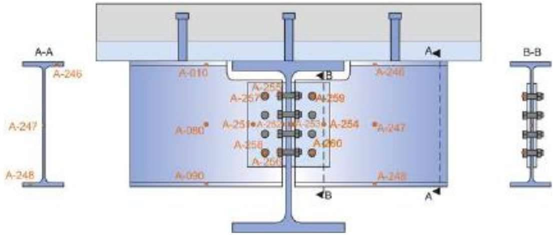


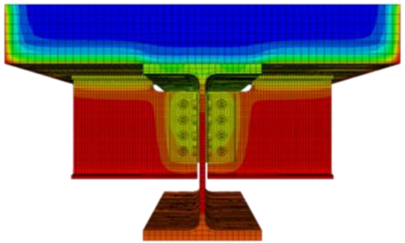


Parametric study





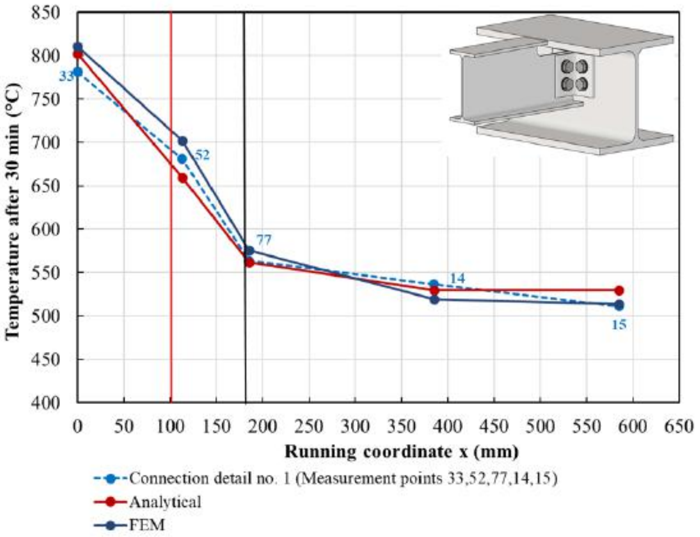




Temperature development after 30 min

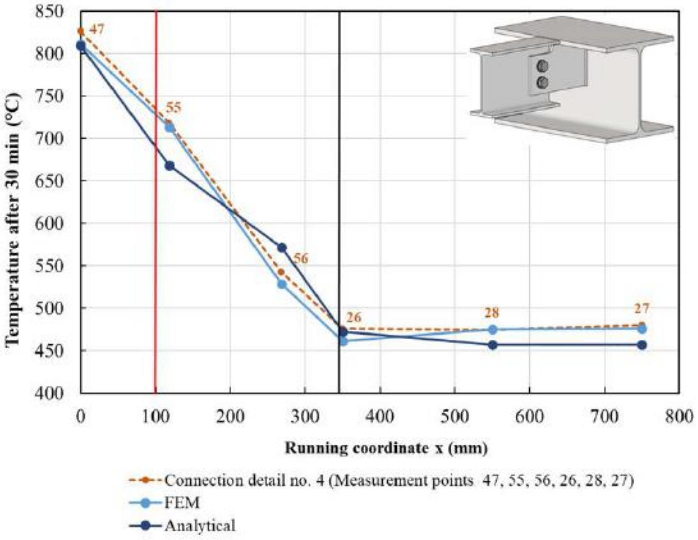
Connection detail No. 1

Comparison between test data, analytical solution and FE simulations



Connection detail No. 4

Comparison between test data, analytical solution and FE simulations



Time-dependent equation for temperature in the connection detail

General formula for determining the temperature of a steel structure with a symmetrical cross-section (for unprotected and protected steel):

$$\Delta\theta = \frac{A \cdot \Delta t}{V \cdot c_{steel} \cdot \rho_{steel}} \cdot \left[\dot{q}_{comb,steel} \cdot k_{reduction} + \dot{q}_{cond} \cdot (1 - k_{reduction})\right]$$

$k_{reduction}$ - reduction factor as ratio of material properties between steel and the existing surface coating (IC)

$$k_{reduction} = \frac{\lambda_{surf} \cdot c_{surf} \cdot \rho_{surf}}{\lambda_{steel} \cdot c_{steel} \cdot \rho_{steel}}$$ with $k_{reduction}$ = 1 for unprotected steel

The area-specific heat flux density $\dot{q}_{cond}$ due to heat conduction for the multi-layer steel beam is determined as follows:

$$\dot{q}_{cond} = \frac{\lambda_p}{d_p} \cdot \left(\theta_{surf} + \Delta\theta_{surf} - \theta_{steel}\right)$$

The change in surface temperature is calculated by taking into account the area-specific heat flux density $\dot{q}_{comb}$ and the cross-section value A:

$$\Delta\theta_{surf} = \frac{\dot{q}_{comb} \cdot A}{c_p \cdot \rho_p \cdot V} \cdot \Delta t$$

$\dot{q}_{comb}$ - Area-specific heat flux density $(\dot{h}_{net})$ with $\dot{q}_{comb} = \dot{q}_{conv} + \dot{q}_{rad}$

Time-dependent equation for temperature in the connection detail

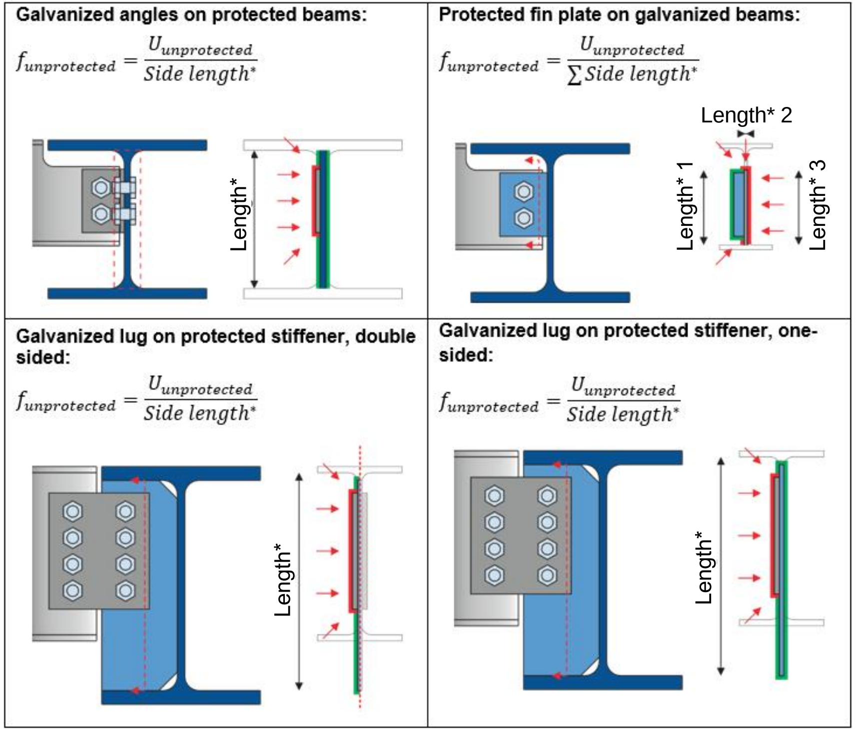
Temperature curve in the connection area

$$\theta = \theta_{unprotected} \cdot f_{unprotected} + \theta_{protected} \cdot f_{protected}$$

The scaling factor *f* only takes into account the non-uniform temperature distribution along the y-axis (cross-sectional direction).

$$f_{unprotected} = \frac{U_{unprotected}}{U^*} \begin{cases} \geq 0{,}5 \\ \leq 0{,}65\ (experiment\ fire\ temperature) \\ \leq 0{,}6\ (ETK) \end{cases}$$

$f_{protected}$ = 0,5



Location-dependent equation for determining the temperature in the connection area

General equation as a function of the location x, the cross-section A and the thermal conductivity λ for the **connection area**

$$T(x) = \theta_{start} - \dot{Q} \cdot \left(\sum_{i=1}^{n} \frac{L_i}{A_i \cdot \lambda_i} \cdot \frac{1}{1 + e^{-k_i \cdot \left(x - \left(\sum_{j=0}^{i} L_{j-1} + \frac{L_i}{2} \right) \right)}} \right)$$

$$\theta_{area\,1}(x = 0) = \theta_{start}$$

$\dot{Q}$ – the rate of heat transfer through the connections

$$\dot{Q} = k \cdot A \cdot (T_1 - T_n)$$

$$\dot{Q} = \left(\frac{x_{i+1} - x_i}{\lambda_{mean,i+\frac{1}{2}} \cdot A_{mean,i+\frac{1}{2}}} + \cdots + \frac{x_n - x_{n-1}}{\lambda_{mean,n-\frac{1}{2}} \cdot A_{mean,n-\frac{1}{2}}} \right)^{-1} \cdot (T_1 - T_n)$$

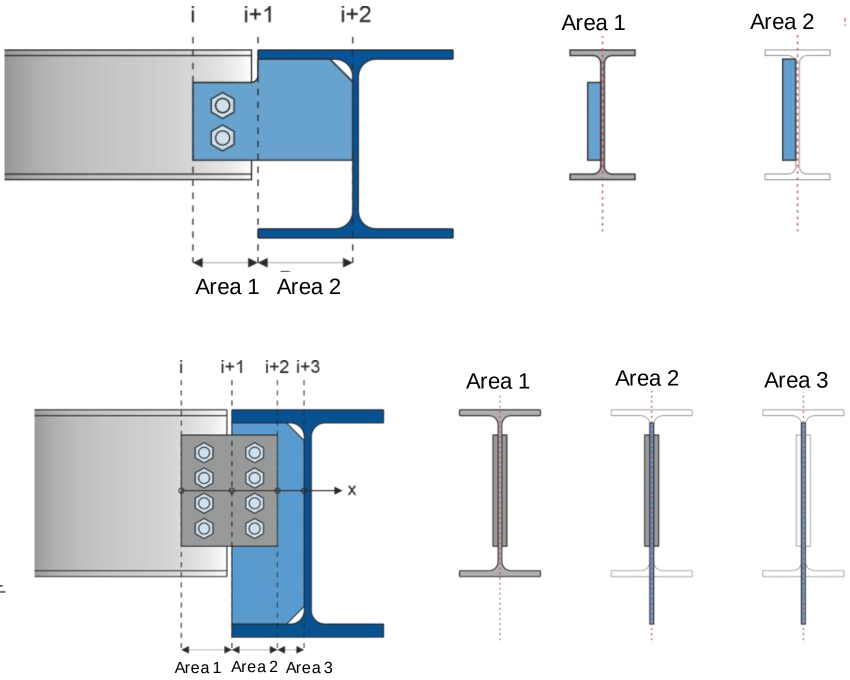
A linear temperature gradient can be determined within the individual areas as follows:

$$T_{i+1}(x_i) = T_i - \frac{x_i}{\lambda_{mean,i+\frac{1}{2}} \cdot A_{mean,i+\frac{1}{2}}} \cdot \dot{Q}$$

with

$$A_{mean,i+\frac{1}{2}} = \frac{A_i + A_{i+1}}{2}$$

$$\lambda_{mean,i+\frac{1}{2}} = \frac{\lambda_i + \lambda_{i+1}}{2}$$



Area partitioning in the connection cross-section

Location-dependent equation for determining the temperature in the connection area

General equation as a function of the location x, the cross-section A and the thermal conductivity λ for the **connection area**

$$T(x) = \theta_{start} - \dot{Q} \cdot \left(\sum_{i=1}^{n} \frac{L_i}{A_i \cdot \lambda_i} \cdot \frac{1}{1 + e^{-k_i \cdot \left(x - \left(\sum_{j=0}^{i} L_{j-1} + \frac{L_i}{2} \right) \right)}} \right)$$

L_i – length of a defined area: $\theta_{area\ 1}(x_1 = L_1)$; $\theta_{area\ 2}(x_2 = L_2)\dots$

λ_i – thermal conductivity of a defined area

A_i – cross-section of a defined area

k_i – heat conduction gradient within a defined area

The gradient parameter k in the n^{th} range must be calculated separately:

for $i \neq n$: $k_i = \frac{\lambda_{i+1} - \lambda_i}{L_i}$

for $i = n$: $k_n = \frac{\lambda_n - \lambda_{n-1}}{L_n/2}$