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Experimental investigations on the load-bearing behavior of shear studs in trapezoidal sheet in fire

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Abstract

Composite slabs, consisting of a steel section, profiled sheet and concrete, have been used successfully in composite construction for many years. In order to increase the maximum span widths, trapezoidal sheets with deeper ribs are increasingly being used. The use of modern deep steel decking changes the load-bearing behaviour of the shear studs towards greater flexibility and ductility, but also towards a lower load-bearing capacity. In recent years, a significant amount of research has been carried out into the load bearing behaviour of shear studs in profiled sheets, resulting in the development of a new design approach in the draft prEN 1994-1-1. Compared to the Ultimate Limite State (ULS), scarce research has been conducted for elevated temperature. It is therefore difficult to evaluate the compatibility of the new design approach from the draft with the existing regulations from EN 1994-1-2. In order to fill this gap in knowledge, push-out tests have been carried out on trapezoidal sheets under elevated temperature. The focus of this paper is to describe the experimental approach and the first results.

Keywords

Shear studs, push-out test, fire test, trapezoidal deck

1 Introduction

Composite floors made of profiled steel sheets and concrete have been used successfully in composite construction for many years. In order to increase the span widths and the cost-effectiveness of the construction method, modern profiled sheets with comparatively deep and narrow ribs are increasingly being used. Due to the use of deeper and more narrow ribs, the load-bearing behavior of the shear studs required for the composite action is changing towards greater ductility, but also towards lower load-bearing capacity [1]. In this context, there is a large body of research on design at ambient temperature, which is well summarised in [2].

Recent investigations [2, 3, 4, 5] into the load-bearing behavior of shear connectors used with profiled steel sheeting have shown that the current normative approaches to determine the shear connector load-bearing capacity for slender profiled sheet metal geometries can lead to unsafe results. Based on the research results in context of DISCCO project [6], new application limits for the use of the known formulations in [7] were introduced in the draft for the prEN 1994-1-1 [8]. In the following, the approaches from EN 1994-1-1 [7] for the determination of the shear resistance in transverse deck sheets are given.

$$P_{Rd} = k_t \cdot 0.8 \cdot f_u \cdot \pi \cdot \frac{d^2}{4} / \gamma_v \tag{1}$$

$$P_{Rd} = k_t \cdot 0.29 \cdot \alpha \cdot d^2 \cdot \sqrt{f_{ck} \cdot E_{cm}} / \gamma_v \tag{2}$$

$$with\colon k_t = \frac{0.7}{\sqrt{n_r}} \cdot \frac{b_0}{h_p} \cdot \left(\frac{h_{sc}}{h_p} - 1\right) \tag{3}$$

In addition to the established method for determining the shear resistance for trapezoidal deck sheets (Formula 1, 2, 3), three new calculation approaches are presented in [2, 4, 5]. One of these, the so-called "cantilever model", has been proposed by CEN/TC250/SC4 for the revision of EN 1994-1-1 [7] and has been included in the Annex G of prEN 1994-1-1 [8] for trapezoidal sheets outside the regular application limits. Vinegri [5] shows that the new calculation approach provides accurate results for modern profiled steel sheeting orientated transverse to the supporting beam in comparison to [7].

$$P_{Rd} = 0.58 \cdot f_u \cdot \pi \cdot \frac{d^2}{4} / \gamma_v \tag{4}$$

$$P_{Rd} = \frac{k_{cc} \cdot C_2 \cdot k_u}{\gamma_v} \cdot \left[\frac{f_{ctk,0,05} \cdot W_{sc}}{h_p \cdot n_r} + \frac{n_y \cdot M_{pl,sc}}{\left(0.82 \cdot h_p - \frac{d}{2}\right)}\right] \tag{5}$$

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The calculation formulae for the design shear resistance under elevated temperature of a welded shear stud are given in EN 1994-1-2 [9]. They rely on the illustrated formulae at ambient temperature (1-5). Based on the calculated shear resistance at ambient temperature, EN 1994- 1-2 [9] specifies temperature dependent reduction factors for the concrete and steel materials. It is proposed to assume that the temperature of the shear stud material is 80% and the temperature of the concrete is 40% of the temperature of the upper flange of the steel profile. The partial safety factor γ_v can be taken as $\gamma_{M,i,v} = 1.0$. An additional empirical factor of 0.8 has been introduced for the "shear failure of the bolt" (6) based on the test results of Zhao and Kruppa [10].

$$P_{fi,Rd} = 0{,}8 \cdot k_{u,\theta} \cdot P_{Rd} \qquad (6)$$

$$P_{fi,Rd} = k_{c,\theta} \cdot P_{Rd} \qquad (7)$$

Compared to tests at ambient temperature, experimental results for elevated temperature are scarce because they are generally complex and costly [11]. The normative approaches in [9] are based on the experimental work of Zhao and Kruppa in 1993 [10]. More recent work by Lim [12], Chen [10] and others also investigates the shear resistance of shear studs applied in profiled composite slabs under elevated temperature. However, the method of experimental testing, the type of loading and the specimen geometry differ significantly from each other, mainly due to the existing laboratory boundary conditions. A new series of push-out tests under elevated temperature is therefore being carried out in the fire laboratory of the Technical University of Munich. In the following, the experimental procedure and first results are presented and discussed.

2 Experimental investigations

The overall project includes 19 push-out specimens tested both at room temperature and under ISO standard fire exposure. The purpose of this paper is to present the results of the first four tests carried out. For the tests reported in the following, push-out specimens were fabricated from the trapezoidal sheets Cofraplus60 with a height h_p of 58 mm and Comflor80 with a height h_p of 80 mm, as shown in Figure 1. The trapezoidal sheet Cofraplus80, also 80 mm high, will be investigated in further test.

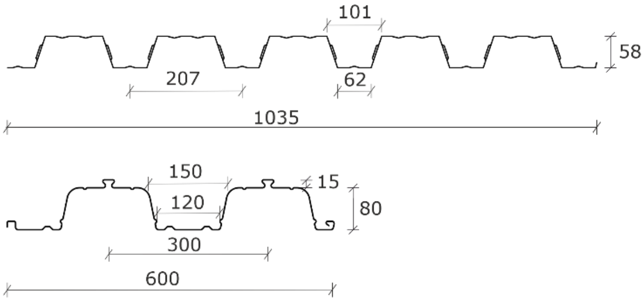

Figure 1 Selected trapezoidal sheet geometry. Top: Cofraplus60, Bottom: Comflor80

2.1 Test specimens

The current Eurocode 4-1-1 Annex B [7] specifies the geometry for a push-out test with a solid concrete slab for ambient temperature. For push-out test specimens with profiled steel sheeting, there is no normative specification of the geometry in [7]. This gap has been filled in prEN 1994-1-1 [8]. For the test at elevated temperatures, there is no specification of standardised test specimens in [9]. Due to the required comparability of the results with the experiments at ambient temperature and the work in [10[10], 12, 13], the specimen geometry from [8] was chosen. Deviating from the normative specifications for the minimum width in prEN 1994-1-1 [8] of 600 mm, the width was reduced to 550 mm for the test specimen. This was done due to the present furnace dimensions with an internal volume of 660x660x700 mm. The height of the concrete chords was also adapted to the existing furnace geometry and chosen to be 605 mm for the Cofraplus60 specimens and 698 mm for the Comflor80 specimens. The thickness of the concrete chords was uniformly set to 150 mm. The shear studs were welded directly to the flange through the pre-punched trapezoidal steel sheets. Exemplary, the geometry of a specimen with the Cofraplus60 profile is shown in Figure 2.

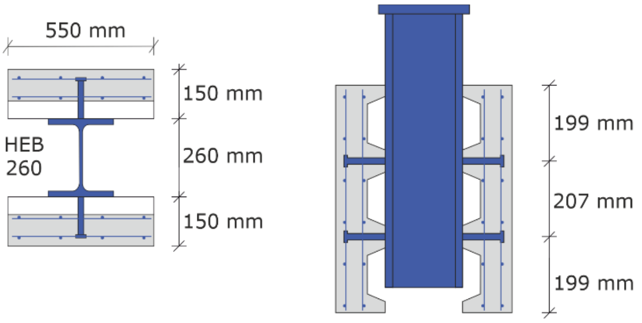

Figure 2 Geometry of Push-Out test specimen CP60 – 1 and 2

The configurations of the four push-out tests are summarised in Table 1. Two of them were tested at ambient temperature, two others under elevated temperature.

Table 1 Overview of the test specimens

Specimen	Profiled steel sheeting	Test condition
CP60 – 1	Cofraplus60 t = 0.88 mm	Ambient
CP60 – 2	Cofraplus60 t = 0.88 mm	Fire
CF80 – 1	Comflor80 t = 1.00 mm	Ambient
CF80 – 2	Comflor80 t = 1.,00 mm	Fire

The specimens were made from C30/37 concrete with a maximum aggregate size of 16 mm. According to EN 1363 [14], the specimens were conditioned for more than 3 months before testing. Concrete cubes and cylinders were made during casting to determine the mechanical properties. These were stored alongside the test specimens. At the start of the experimental tests, 200 days after concreting, the first material tests were carried out on the cylinders and cubes. The results of the material tests gave an average concrete compressive strength $f_{ck,cube}$ of 56.5 N/mm² and $f_{ck,cylinder}$ of 49.8 N/mm². The concrete slab was reinforced with 2 layers of Q188 (Ø6/15) B500B.

The steel section used was a HEB 260 according to EN 1994-1-1 [7]. The steel sections were cut in half at the centre of the web to allow the specimens to be cast horizontally as required by [7]. The shear studs used had a diameter of 19 mm and a height of 125 mm and were of steel grade S235J2+C470 according to the material test certificate. A yield strength of 483 N/mm² and a tensile strength of 521 N/mm² were determined according to the available quality certificate.

2.2 Instrumentations

2.2.1 *Heating Equipment*

An electric oven with an internal volume of 660 x 660 x 700 mm was used to heat the specimens. The furnace has no bottom or top, so that it can be placed around the specimen. The bottom is formed by a concrete support and the top of the furnace is insulated with mineral wool and calcium silicate plates. Only the upper part of the steel beam with the load distribution plate is located outside of the furnace for load application. The furnace heating elements are located on only two sides of the furnace to avoid heating the back of the concrete slab. As the electrical heating capacity was not sufficient to achieve the ISO standard fire curve, the furnace was additionally heated by two gas burners embedded in the concrete support.

2.2.2 *Experimental Setup*

During the test, load, displacement, and slip are measured. The load was applied by a hydraulic cylinder monitored by a load cell. Deformations were recorded using linear potentiometers and a DIC system. As the specimen is surrounded by the furnace for the fire tests, there are only a few locations where the direct attachment of displacement transducers is possible. Furthermore, optical measurements through e. g. DIC are not applicable. Therefore, quartz glass rods were placed inside the furnace at the most relevant locations. Quartz glass has the advantage of very low thermal conductivity combined with a low coefficient of thermal expansion and high temperature resistance. The displacement transducers can therefore be easily attached to the top of the sticks (Figure 3).

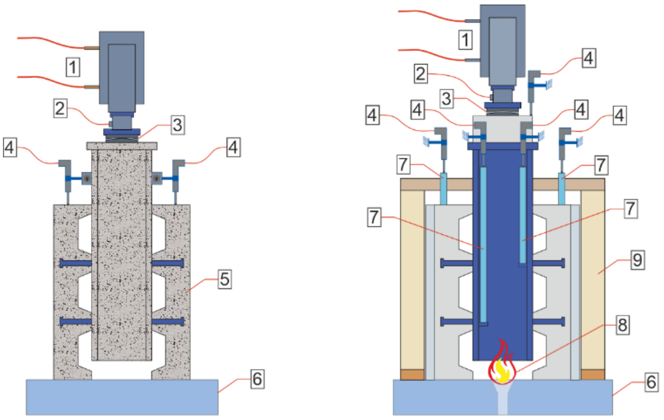

Figure 3 Left side: test setup at ambient temperature, right side: test setup at elevated temperature. 1) Hydraulic cylinder, 2) load cell, 3) calotte, 4) linear potentiometer, 5) pattern for extensometer, 6) concrete abutment, 7) quartz glass stick, 8) gas burner, 9) furnace Insulation

2.2.3 *Temperature Measurements*

In addition to recording the deformation, it is essential to measure the component temperature during the fire tests. For this purpose, type K thermocouples with glass fibre coating providing a temperature resistance of 800°C were used for all measurements on the specimens.

Thermocouples were installed in the concrete prior to concreting. In addition, a thermocouple was inserted 25 mm above the flange of the steel section through a hole drilled in the shaft of the head bolt. For measurements on the steel section, thermocouples were soldered to the surface of the web and flange. In a preliminary test, it was found that it made no difference to the recording of the steel temperature whether the thermocouples were inserted into drilled holes or attached to the surface. The furnace temperature was recorded on both sides of the HEB profile using sheathed thermocouples Type K. Figure 4 shows the temperature measurement concept.

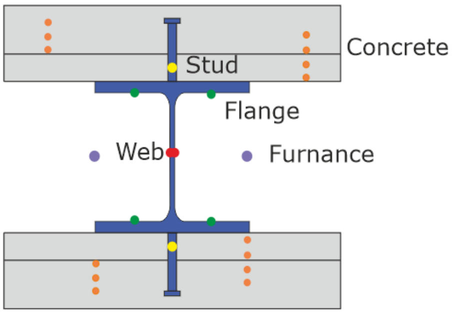

Figure 4 Concept for the temperature measurements

2.3 Testing procedure

The tests at room temperature were carried out according to the normative specifications in Annex B of EN 1994-1-1 or prEN 1994-1-1[7, 8]. According to these specifications, 25 load cycles were applied at the beginning of the tests, with overloads and underloads of 40% and 5%, respectively, of the expected load. The load was then increased in 1 mm increments with dwell times of 30 s to consider the short-term relaxation of the concrete. All tests achieved the required normative test time of > 15 min. Due to the time-dependent continuous heat transfer in the specimens during a fire test, a progressive load increase is not appropriate. Therefore, a constant load level was chosen for the fire tests and the application of the thermal load, the ISO standard fire, was started after a holding time of 5 min. This constant load method was also chosen by Lim [12] as it generally represents a realistic fire scenario. The load was controlled by oil pressure until failure of the specimen. The load level chosen for the initial tests presented in this article was 65%-70% of the shear resistance at room temperature, as this value can also be used in a simplified manner as a reduction factor compared to the action at normal temperature, according to EN 1994-1-2 [9]. The explained testing procedures are illustrated in Figure 5.

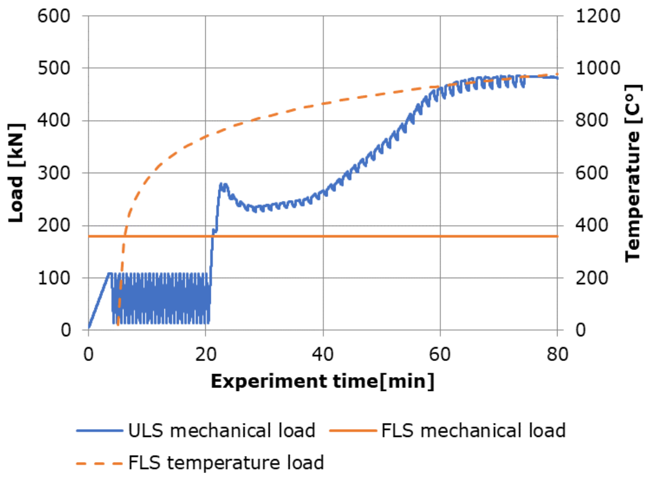

Figure 5 Testing procedure for ambient temperature (ULS) and elevated temperature (FLS)

3 Results

3.1 Temperature Measurements

Figure 6 shows the measured temperature curve for specimen CP60-2. Although the furnace temperature at the beginning of the test is slightly above the ISO standard firing curve, there is a good correlation which is within the tolerances of EN 1363-1 [14]. The values in the diagram should be considered as averages over all the measuring points in each category. The measuring point for the flange was chosen next to the shear stud, as according to the authors opinion that this temperature is also decisive for the failure of the stud. The temperature of the shear stud was measured 25 mm above the weld bead. However, since the reference temperature for the determination of the temperature-dependent reduction factors in EN 1994- 1-2 [9] was measured at a height of 5 mm from the basis of the stud [10]. The measuring point at a height of 25 mm is only used for the subsequent calibration of numerical models. Failure of the shear connectors could be observed in the 47 min of the fire test. The average flange temperature below the shear studs was determined to be approx. 710 C°.

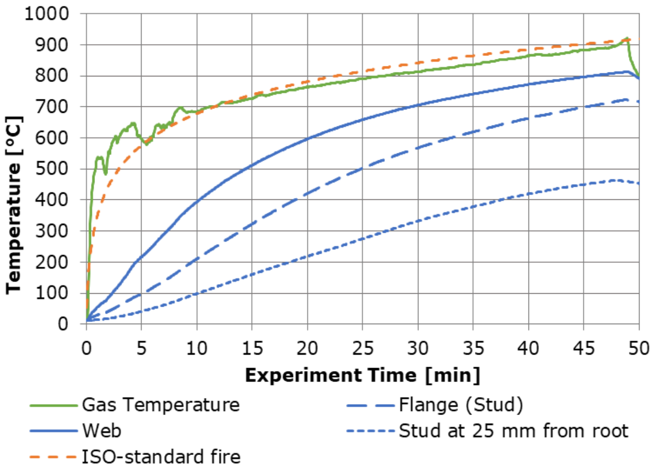

Figure 6 Measured temperatures in the fire test on the specimen CP60 – 2

The CP80-2 push-out specimen withstood the ISO standard fire for 36 minutes. The flange temperature measured beside the shear studs at the time of failure was determined to be approximately 638 C.

According to [9], the reduction factors ku,θ and kc,θ can be derived from the experimentally determined flange temperatures. The reduction factors can be used to determine the shear stud resistance by applying formulae (1)-(3) from [7]. In the author's opinion, these reduction factors can also be applied in combination with formulas (4) and (5) from [8]. They are calculated in the following Table 2.

Table 2 Reduction factors according to [10] based on the experimental flange temperature

Specimen	T-Flange	ku,θ [10]	kc,θ [10]
		(40%T-Flange)	(80%T-Flange)
CP60 – 2	710 °C	0.87 (284 °C)	0.57 (568 °C)
CF80 – 2	638 °C	0.9 (255 °C)	0.75 (510 °C)

3.2 Structural response

The two tests at room temperature showed the expected load-slip curve as reported in [3, 4] and are presented in figure 5. The push-out specimen with the Cofraplus60 trapezoidal sheet exhibited a first load maximum within the first 6 mm of slip. After a slight load drop due to crushing of the concrete at the base of the stud, a second maximum load is formed. This load bearing behavior is only possible with sufficient embedment depth of the shear stud above the profile sheet and has already been described in [15]. The test was terminated at a slip of more than 47 mm. The Comfloor80 slab tests also showed a similar behavior as described in [4]. Despite early cracking in the concrete up to the edges of the push-out specimens, high ductility was also observed in these specimens.

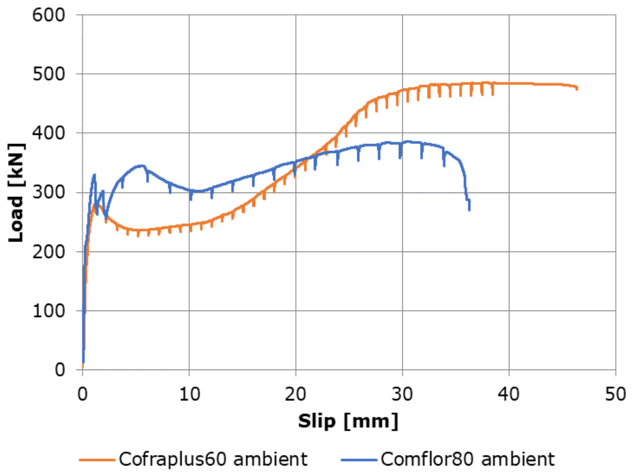

Figure 7 Load–slip curve for experiments at ambient temperature

In Table 3, the experimentally determined shear resistance P_e are compared with the normative calculation approaches according to [7] and [8].

The partial safety factors γ_v were set to 1.0 for the purpose of comparison. Following the procedure in [5] the experimental load bearing capacity P_e was taken as the maximum load within the first 6 mm of slip. According to DIN EN 1994-1-1 [7], composite materials are classified as ductile if they have a characteristic deformation capacity of $\delta_{uk} \geq 6$ mm.It can be seen that the shear resistance of the CP60 - 1 specimen with the Cofraplus60 profile is slightly overestimated by the EN 1994-1-1 [7]. According to the new calculation approach in prEN 1994-1-1 [8], this is no longer the case. In contrast, the test specimen CF80 - 1 showed a higher shear resistance in the test within the first 6 mm slip than calculated according to [7] or [8].

Table 3 Comparison of the shear resistance according to the normative approaches from [8] and [9] with the experimental results at ambient temperature

Specimen	$P_{e,max,6mm}$	$P_{Rk,EN1994\text{-}1\text{-}1\ [8]}$	$P_{Rk,prEN1994\text{-}1\text{-}1\ [9]}$
CP60 – 1	70 kN	76.6 kN	69.2 kN
CF80 – 1	86 kN	67.8 kN	64.8 kN

In the first fire test with the Cofraplus60 sheet (CP60 – 2), the test specimen was loaded with a total load of 180 kN, 45 kN per shear stud. This corresponds to a load level of approx. 65 % of the shear resistance according to prEN 1994-1-1 [8] to be found in Table 3. Figure 8 shows the measured force, temperature and slip for the CP60 – 2 specimen in the fire test. The slip is recorded separately for the upper and lower shear stud. A difference in slip can be observed between the two studs. This difference is probably due to the thermal expansion of the steel beam. The load was kept as constant as possible at 180 kN over the entire test period. Over the duration of the test, a steady increase in slip can be observed. After 47 min of testing, a strong nonlinear increase of the slip up to 30 mm is finally observed. The specimen was then unloaded.

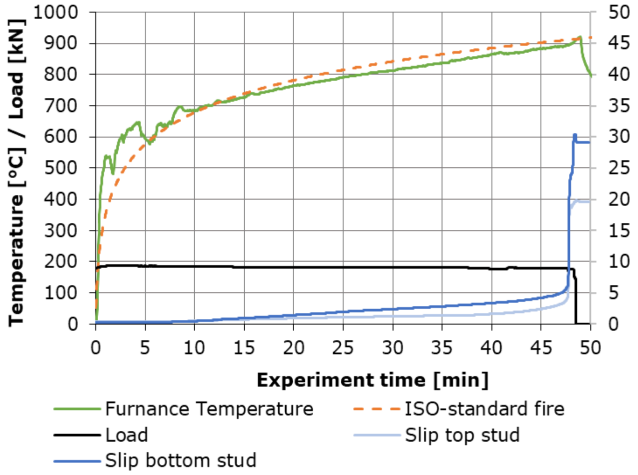

Figure 8 Load, temperature and slip in the fire test for specimen CP60 - 2

Figure 9 shows the measured furnace temperature, the slip and the force for the CF80-2 specimen. For comparison purposes, this specimen was also loaded with a total load of 180 kN, which corresponds to approx. 70 % of the ultimate load of the specimen according to [8]. A good agreement of the furnace temperature with the ISO standard fire could be achieved. The slip curve shows an analogous behavior to the specimen with CP60-2. The failure occurred after a strong increase of the slip in the 36th minute.

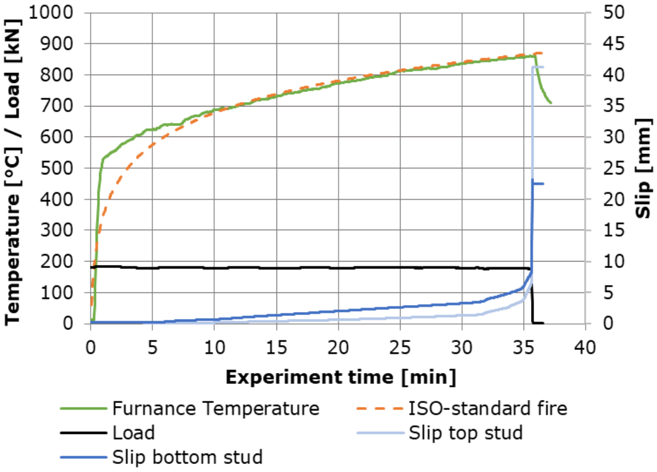

Figure 9 Load, temperature and slip in the fire test for specimen CF80 - 2

Since the shear resistance of the two configurations of specimens can be calculated according to prEN 1994-1-1 [8] using formulae (4) and (5), these shear resistances are taken as the base values for the following diagram in figure 10. The diagram shows the temperature-dependent shear resistance for the two specimens. As illustrated, the results are in good agreement with the normative calculation approaches of [8] and [9].

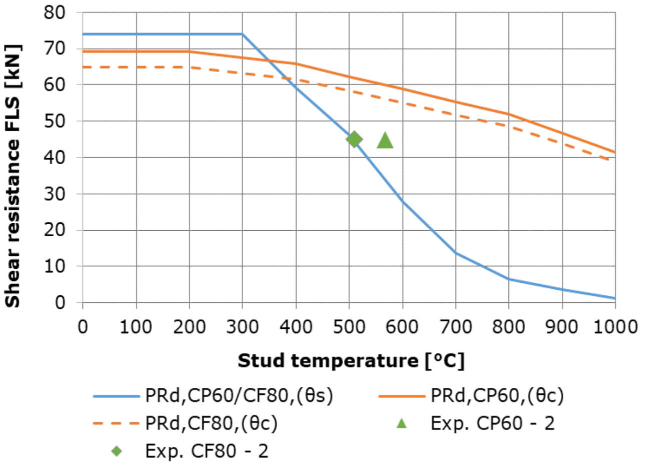

Figure 10 Temperature-dependent reductions according to [10] of the shear resistance according to formulae 4 and 5 from [9] for the given specimen configurations

4 Conclusion

This study investigated the load bearing behavior of shear studs in trapezoidal sheets with high ribs transverse to the supporting beams. Two tests at ambient temperature and two tests under elevated temperature were carried out. The results for the ambient temperature were compared with the calculation approaches according to [7] and [8].

They confirmed the findings of current research studies that the calculation approaches according to EN 1994-1-1 [7] overestimate the shear resistance for studs in transverse profiled sheets with Cofraplus60. This is to be corrected by the new calculation approaches in prEN 1994-1-1 [8].

Two push-out test specimens were tested with the presented test set-up under the ISO standard fire. Temperatures, slip and load were recorded over the test period. Failure of the shear studs was preceded by a large increase in slippage. From the measured flange temperatures, the normative reduction factors were calculated. For both of the push-out tests, this resulted in a higher reduction of the shear resistance than observed in the experiments. The first two conducted tests thus confirmed the compatibility of the new calculation approach from prEN 1994-1-1 Annex G [8] with EN 1994-1-2 [9].

To verify this finding, further tests will be carried out. In addition, the failure mechanism of the specimens will be examined in more detail. For this purpose, a longitudinal cut through the test specimens will be made. Furthermore, validated numerical are developed to investigate other configurations of push-out specimens.

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