**Zeitschrift:** IABSE reports = Rapports AIPC = IVBH Berichte
**Band:** 49 (1986)

**Artikel:** New concept of economic and fire-resistant profiled steel sheet floors

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**DOI:** https://doi.org/10.5169/seals-38330

# New Concept for Economic and Fire-Resistant Profiled Steel Sheet Floors

## Nouvelle conception de planchers mixtes économiques résistant au feu

## Neues Konzept für wirtschaftliche und feuersichere Stahltrapezprofildecken

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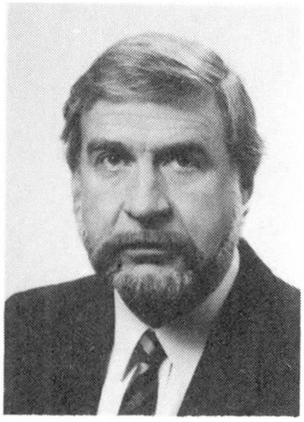

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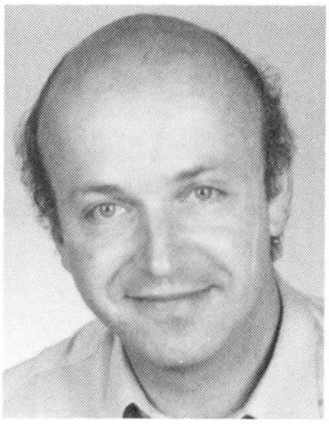

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**SUMMARY**

Floor systems consisting of a profiled steel sheet and concrete with additional reinforcement bars may be economically designed as an additively carrying «sheet-supported reinforced concrete slab». From a recent fire test series this design concept also turned out to be economic for fire resistance without additional protection. A modified fire resistance design procedure is proposed. The concept has been applied in a «demo-building» in Stuttgart.

**RÉSUMÉ**

Un plancher mixte béton-tôle d'acier profilée comportant une armature supplémentaire peut être conçu comme «une dalle nervurée en béton armé supportée par une tôle d'acier profilée» avec une capacité portante plus élevée. A partir de récents essais au feu, cette conception s'est révélée également économique vis-à-vis de la résistance au feu sans protection supplémentaire. Une méthode modifiée de calcul de la résistance au feu est proposée. Cette conception a été mise en pratique dans un bâtiment-prototype à Stuttgart.

**ZUSAMMENFASSUNG**

Decken aus einem Stahltrapezprofil und profilfüllendem Aufbeton mit Zusatzbewehrung können wirtschaftlich als additiv tragende «trapezprofilunterstützte Stahlbetonrippenplatte» bemessen werden. Dieses Bemessungskonzept erwies sich aufgrund einer neuen Brandversuchsserie auch für den Feuerwiderstand ohne zusätzliche Brandschutzmassnahmen als wirtschaftlich. Ein modifiziertes Brandschutz-Bemessungsverfahren wird vorgeschlagen. Das Konzept wurde beispielhaft in einem «Demo-Geschossbau» in Stuttgart angewendet.

## 1. INTRODUCTION

It is well known that the fire resistance of an unprotected profiled steel sheet floor can be increased by filling it up with concrete of at least 5o mm thickness above the upper sheet flange. This is due to the heat-absorbing capacity of the concrete. The fire resistance time of such floors amounts to
- at least 2o min for any sheet cross section /1/,
- more than 3o min if using a special sheet cross section /2/,
- more than 3o min for any sheet cross section if providing appropriate interlocking between sheet and concrete to make the system a composite slab /3/.

Further increases of fire resistance can - aside from using insulating coatings or suspended ceilings - only be acchieved by adding reinforcement bars within the concrete ribs. The resulting type of cross section (fig. 1), used as a simply supported floor system, has recently been investigated in a series of fire tests /2/.

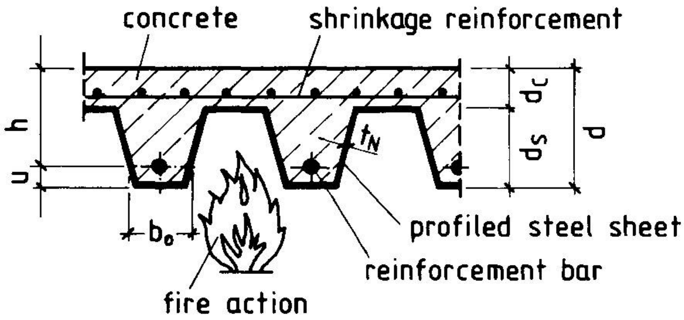


Fig. 1
Unprotected profiled steel sheet floor with fire action from below

## 2. STANDARD FIRE TESTS

### 2.1 Test Programm

The test specimens had o,67 m width (containing two ribs) and 4,oo m span. Their cross section was built up as follows (fig. 1): d = 2oo mm, $d_c$ = 6o mm, $d_s$ = 14o mm, hot rolled reinforcement bars with 42o $N/mm^2$ nominal yield stress. The profiled steel sheet had been specificly folded from hot galvanized 1 mm sheet material with 28o $N/mm^2$ nominal yield stress. Secondary corrugations of 1o mm depth along the web and upper flange center lines were to stiffen the profiled sheet and to provide a certain amount of clamping between sheet and concrete ribs. The shape was virtually identical with the one used for a demo-building in Stuttgart (fig. 8).

Table 1 gives the basic data of 14 fire tests, including one comparison test without sheet. The following parameters were varied:
- concrete covers u and $b_o$;
- diameter of reinforcement bars (column RB);
- type of reinforcement against shrinkage (column RS): 1 = net with o,94 $cm^2/m$, 2 = net with o,85/1,7o $cm^2/m$, 3 = steel fibers 96 $kg/m^3$;
- shear reinforcement in the concrete ribs no/yes (column SR);
- shear connectors between sheet and concrete no/yes (column SC). They were verified by means of flat-bar steel dowels screwed to the bottom flanges of the profiled sheet at the ends of specimen II.5B and along the whole length of specimen II.6B respectively (fig. 2);
- load level q during fire test (from allowable load $q_2$= 5,3 $kN/m^2$ of the profiled sheet alone up to allowable load q = 22,9 $kN/m^2$ of the fully composite slab).

| test No. | cross section of specimens | | | | | | test results | | prediction /3/ | prediction own | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | u mm | $b_o$ mm | RB mm | RS | SR | SC | q $kN/m^2$ | $t_F$ min | $t_F$ min | $\varkappa$ | $\rho$ | $t_F$ min |
| I. 3B | 35 | 12o | 14 | 1 | no | no | 5,3 | 116 | (17o) | o,37 | o,62 | 117 |
| II. 3B | 35 | 12o | 14 | 1 | no | no | 9,8 | 1o5 | 1o3 | o,69 | o,62 | 1o5 |
| I. 4B | 35 | 12o | 14 | 1 | no | no | 13,8 | 99 | 57 | o,96 | o,62 | 86 |
| II. 4B | 35 | 12o | 14 | 1 | no | no | 22,9 | 69 | o | 1,59 | o,62 | 51 |
| III.2B | 35 | 12o | 8 | 1 | no | no | 5,3 | > 74 | 5o | o,64 | o,35 | 73 |
| III.3B | 35 | 12o | 1o | 1 | no | no | 1o,5 | 78 | o | o,97 | o,5o | 7o |
| III.4B | 35 | 12o | 1o | 1 | no | no | 14,o | > 5o | o | 1,3o | o,5o | 52 |
| III.5B | 7o | 14o | 14 | 1 | no | no | 14,o | > 92 | o | 1,11 | o,57 | (1o4) |
| SF3B | 35 | 12o | 14 | 3 | no | no | 14,4 | > 84 | 56 | 1,oo | o,62 | 83 |
| SF4B | 35 | 12o | 1o | 3 | no | no | 11,1 | > 82 | o | 1,o5 | o,48 | 61 |
| II. 2B | 35 | 12o | 14 | 2 | yes | no | 9,8 | 116 | 1o3 | o,69 | o,62 | 1o5 |
| II. 5B | 35 | 12o | 14 | 1 | no | yes | 22,9 | 64 | o | 1,59 | o,62 | 51 |
| II. 6B | 35 | 12o | 14 | 1 | no | yes | 22,9 | > 69 | o | 1,59 | o,62 | 51 |
| II. 1B * | 35 | 12o | 14 | 2 | yes | ./. | 9,8 | 93 | ./. | | | |

* Comparison test with sheet removed before fire test

Table 1 Extract from fire test programm /2/

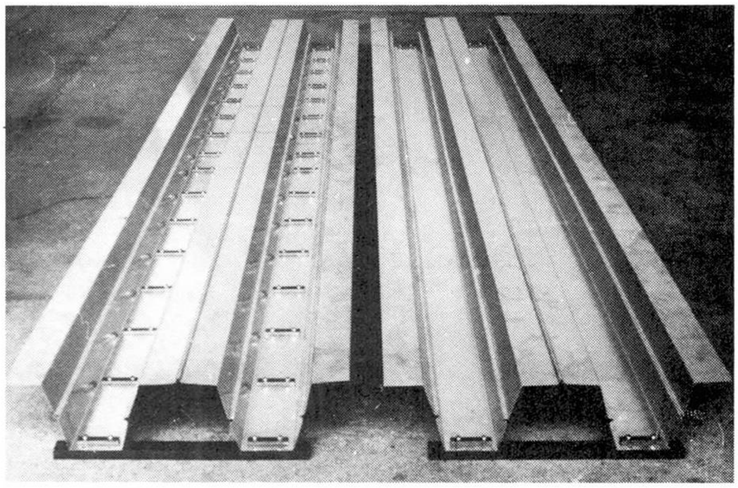

Fig. 2
Profiled sheets of test specimens II.5B (right) and II.6B (left) before fixing of reinforcement and concrete form

## 2.2 Heating Behavior

The heating behavior under standard fire exposure (fig. 3) is characterized by rapid temperature increase in the sheet, medium temperature increase in the reinforcement bars and slow temperature increase at the unexposed side of the concrete. Considering only the load bearing capacity criterion for fire resistance, the concrete temperatures my be neglected. The sheet becomes after about 6o min in all its parts so hot ($\geq 8oo\,^oC$) that, because of the yield limit having decreased to less than 1o %, it cannot bear furthermore a significant part of the load. Nevertheless it remains positively effective in two ways: firstly by preventing the concrete from chipping off and secondly by screening it thermally.

The thermal screening effect of the sheet causes the reinforcement bar to heat up by about 15 min slowlier than it would have done without sheet. After about 8o to 1oo min it reaches the critical temperature crit T of about 5oo to 6oo °C (fig. 3); a specimen with allowable stress in its reinforcement bars would be expected to fail around this time. In fact, if one looks at the deflection-time-curve of test specimen II.3B (fig. 4) being loaded by the approximate allowable load $q = 9{,}8\ kN/m^2$ of the present reinforced concrete slab, the observed rapid deflection increase beyond 1oo min fits well to the measured temperatures. Moreover, the deflection-time-curve of testII.1B (without sheet) confirms the thermal screening effect of the sheet of about $\Delta t$ = 15 min (fig. 4).

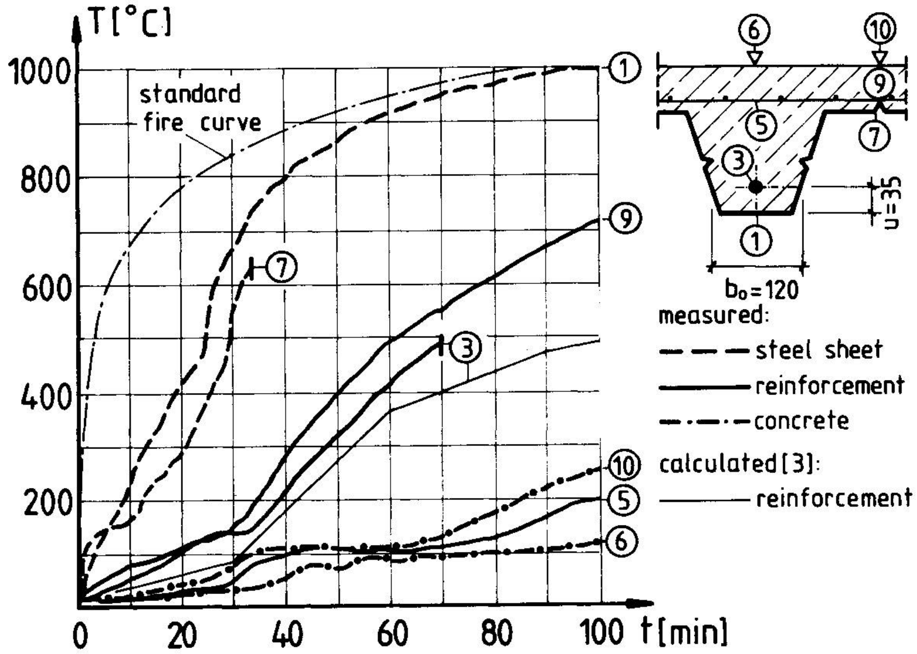


Fig. 3
Typical temperature-time-curves under standard fire exposure (test I.3B)

## 2.3 Fire Resistance

Table 1 contains the experimental fire resistance times $t_F$ (deflection speed criterion of DIN 41o2/2). They show, additionally illustrated by fig. 4, three important facts:

(a) Compare test II.1B with test I.4B: The latter yielded about the same fire resistance, in spite of being loaded higher and having no shear reinforcement in the concrete ribs. Obviously the profiled sheet adds to the "naked" reinforced concrete slab enough positive effects (thermally and mechanically) to compensate for the omitted shear reinforcement and to bear additionally nearly its own allowable load without loss of fire resistance.

(b) Compare tests II.4B, II.5B and II.6B: All of them had identical cross sections and were loaded identically by the allowable load if assuming full composite action. But only specimens II.5B and II.6B actually had shear connectors between sheet and concrete. As can be seen, test II.4B yielded about the same fire resistance. Obviously the composite action - well known to be highly beneficial for the ultimate load under ambient temperature - has no significant improving effect for the load bearing under fire conditions. Thinking of the heating behavior explained before, this result does not surprise:

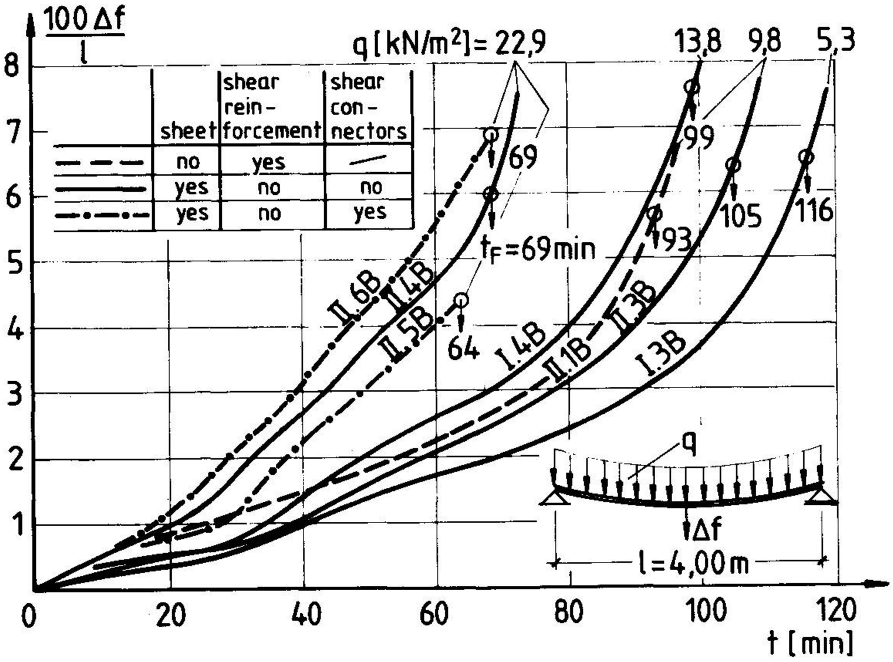


Fig. 4
Deflection-time-curves under standard fire exposure

After more than 6o min fire time, there cannot be a significant difference between a "not carrying shear-connected sheet" and a "not carrying independant sheet".

(b) Compare tests I.3B, II.3B, I.4B and II.4B: All of them had identical cross sections, but were loaded differently. The load level clearly influences the achieved fire resistance.

## 3. DESIGN CONCEPT

### 3.1 General

From the foregoing brief description of selected test results (for detailed information see /2/)the following conclusious concerning an economic concept for fire-resistant unprotected profiled steel sheet floors may be drawn:

(a) Reinforcement in the concrete ribs is necessary to achieve $t_F \geq$ 6o min.

(b) The floor may be designed for the working load case under ambient temperature as "sheet-supported reinforced concrete slab" (i.e. profiled sheet and reinforced concrete slab bearing additively) without giving away the chance of achieving $t_F \geq$ 9o min.

(c) No shear reinforcement in the concrete ribs is necessary if adequate allowable shear stresses are not exceeded.

(d) No composite action between sheet and concrete is necessary. If nevertheless provided, it cannot be utilized for the fire load case.

### 3.2 Design for Construction Load Case

The profiled steel sheet has to be designed for its own and the concrete's dead load ($g_1$= 3 to 4 kN/m$^2$) plus a "construction live load" (e.g. $p_1$= 1,5o kN/m$^2$). The authors recommend to choose a sheet cross section that does not need being intermediately supported during concreting. This implies a cross section depth of at least $d_S$= 12o mm for spans of about 4 m. The advantage of such a design philosophy - besides resulting in smaller concrete dead loads because of the high ribs - is that during floor construction nothing needs to be done from below. For instance, in a multistory building higher floors could, if for any construction processing reason desirable, be concreted earlier than lower ones.

### 3.3 Design for Working Load Case

The sheet-supported reinforced concrete slab has to be designed for the total load q = g + p. Fig. 5a shows as an example the statical system of a two span floor with simply supported sheets and continuously concreted slab. The total load is split into the partial loads of the reinforced concrete slab and the steel sheet:

$$q_{RC} = \varrho\, q, \qquad q_{SS} = (1-\varrho)q \qquad (1)$$

with the load sharing factor $\varrho$.

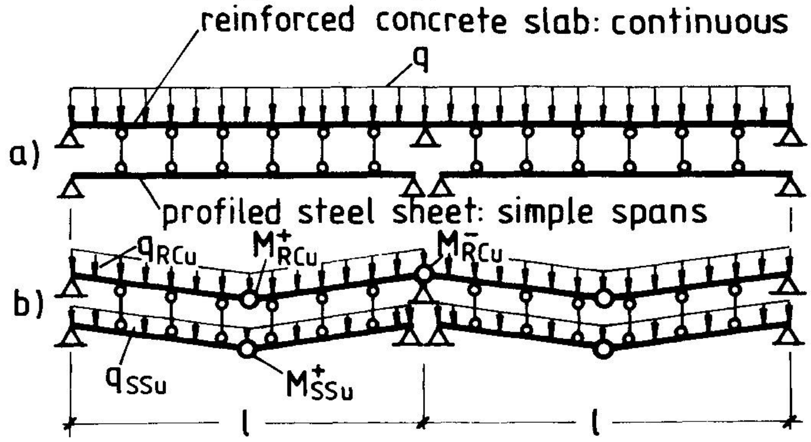


Fig. 5
Example for a sheet-supported reinforced concrete slab
a) statical system
b) limit state mechanism

The factor $\varrho$ may be calculated from elemtary plastic theory (fig. 5b):

$$\varrho = \frac{q_{RCu}}{q_{RCu} + q_{SSu}} = \frac{M^{+}_{RCu} + o{,}5\, M^{-}_{RCu}}{M^{+}_{RCu} + o{,}5\, M^{-}_{RCu} + M_{SSu}} \qquad (2a)$$

or from the relevant allowable loads:

$$\varrho = \frac{\text{all } q_{RC}}{\text{all } q_{RC} + \text{all } q_{SS}} \;. \qquad (2b)$$

The slab and the sheet have to be designed for their partial loads respectively. Particular attention should be paid to the critical shear stress in the comb-like concrete cross section

$$\tau_o = Q_{RC}/(b_o z) \leq \text{all } \tau_o \;. \qquad (3)$$

According to DIN 1o45, the allowable shear stress all $\tau_o$ may be taken as o,5 $N/mm^2$ for concrete with $\geq 25$ $N/mm^2$ nominal strength.

### 3.4 Design for Fire Load Case

Since the sheet - as stated before - does not bear a significant part of the load after medium fire times, its load bearing capacity may be neglected for the fire load case. This assumption leads to the design model of a "thermally screened RC-slab" which has to carry alone the total load, but of which the concrete and reinforcement are heated up slowlier because of the presence of the hot sheet. This design model has been developed in /3/; simple formulae are given for the temperature-time and strength-temperature relations of the concrete (negative moments) and the reinforcement in the ribs (positive moments) respectively. With increasing fire time, the decreasing limit load (using elementary plastic theory) has to be calculated; once the decreasing limit load equals the present load q, the fire resistance time is assumed to be reached.

The temperature-time formulae of /3/ for the reinforcement bar in the rib have been checked against own and published temperature measurements. They give good agreement for relatively large concrete covers u and $b_o$, but seemingly tend to underestimate the heating speed for medium and small concrete covers, especially for longer fire times (> 8o min) and higher temperatures (> 5oo °C). The comparison curve 3 in fig. 3 indicates this lack. An effort to evaluate improved temperature formulae from systematic numerical simulation of the heating behavior is currently on the way /4/.

For the 13 sheet-supported test specimens in table 1 the predicted $t_F$-values, using the design procedure of /3/ with actual material properties, have been calculated (table 1). The agreement is excellent if the load approximately corresponds to all $q_{RC}$ (II.3B, II.2B). This is evident, since the procedure has been calibrated to this case. For lower loads the prediction - received by linear extrapolation of the design formulae in /3/ beyond 12o min - would be very unconservative (I.3B). This is probably due to the mentioned underestimate of temperatures. For higher loads the prediction, though being conservative, is unsatisfyingly poor.The reasons are: firstly the neglecting of the sheet's load bearing contribution and secondly the fact that the true bending capacity of comb-like RC-slabs is much higher than the plastic moment; every standard fire test derives unavoidingly benefit from this "hidden" safety.

In order to overcome the discrepancies, a modification of the design procedure, as illustrated in the schematic chart of fig. 6, is proposed by the authors /2/. The polygonal curves represent, for a given floor cross section

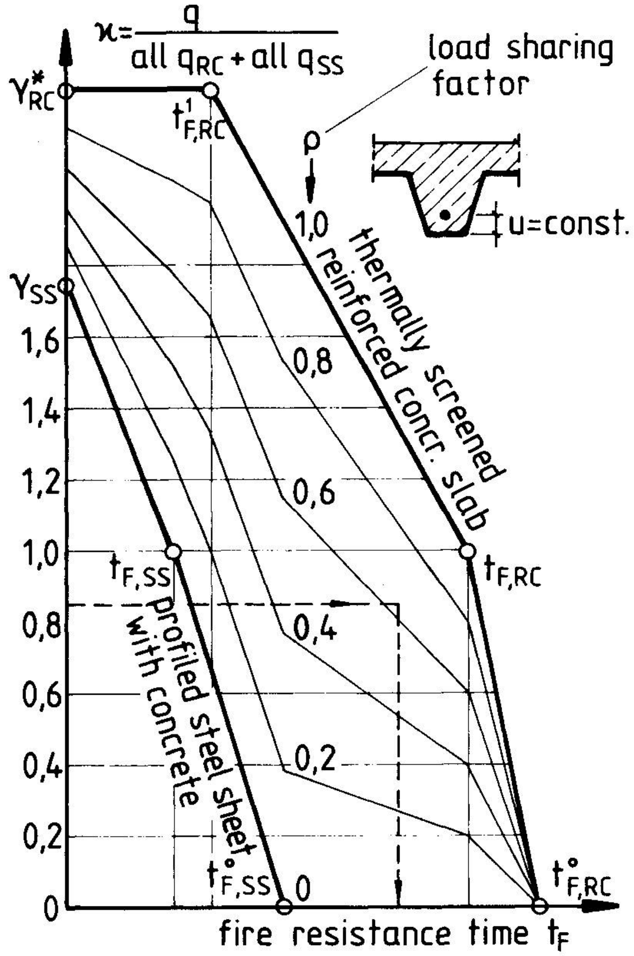


Fig. 6
Fire resistant design chart (schematic) for a profiled steel sheet floor

type, nondimensional load bearing capacities (related to the allowable load all $q_{RC}$ + all $q_{SS}$) versus $t_F$. The curves are, according to their load sharing factor (equ. 2), linearly interpolated between the two limiting cases of the sheet-supported RC-slab:

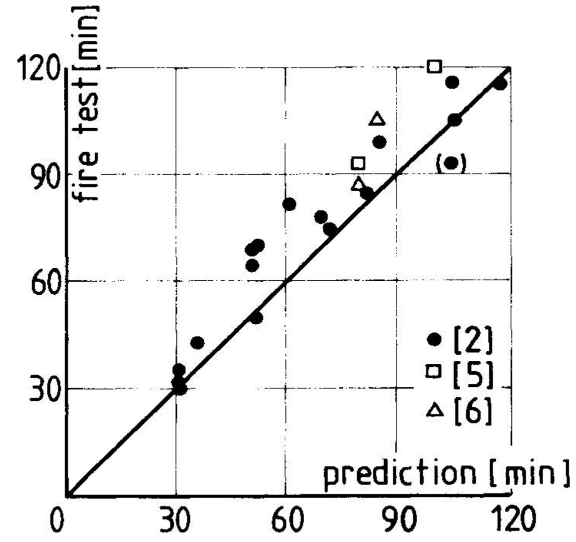


Fig. 7
Comparison of experimental and predicted fire resistance times

(a) Thermally screened RC-slab (upper curve):

- $t^1_{F,RC}$ and $t_{F,RC}$ = time until T = 25o°C and T = crit T in the reinforcement, calculated from the formulae in /3/.
- $t^o_{F,RC}$ = time until T = 8oo°C in the reinforcement; may conservatively be estimated as $t^o_{F,RC} = t_{F,RC}$ + 2oK.
- $\gamma^*_{RC}$ = true safety factor of the RC-slab under ambient temperature; may be assumed as $\gamma^*_{RC}$ = 2,5o.

(b) Profiled sheet with unreinforced concrete (lower curve):

- $t_{F,SS}$ and $t^o_{F,SS}$ = time until T = crit T and T = 8oo°C in the sheet; may conservatively be assumed as 3o and 6o min.
- $\gamma_{SS}$ = safety factor of the sheet = 1,75.

For given values $\varkappa$ (relative working load) and $\rho$ the fire resistance time may be read from the chart. In table 1 the results of this prediction method for all 13 tests are given; the agreement with the test results is reasonable. Fig.7 illustrates the comparison graphically, including 4 tests without reinforcement from /2/ and 2 tests from /5/ and /6/ respectively.

## 4. PRACTICAL APPLICATION

In a 4-story laboratory "demo-building" of the Otto-Graf-Institut in Stuttgart, in which many prototypes of newly developed fire-resistant steel-concrete components (floors, beams, columns, connections) are demonstratively used, the present dedesign concept has been applied to one of the floors (fig.8). It is a 3-span floor with $p = 5 kN/m^2$ live load and F 9o fire resistance. The slab has been connected to the prefabricated composite HEA-3oo beams by studs in order to make it the compression flange of a 5oo mm deep composite floor girder with 9,2o m span.

Fig. 9 shows impressively the construction advantages of self-carrying profiled sheets.

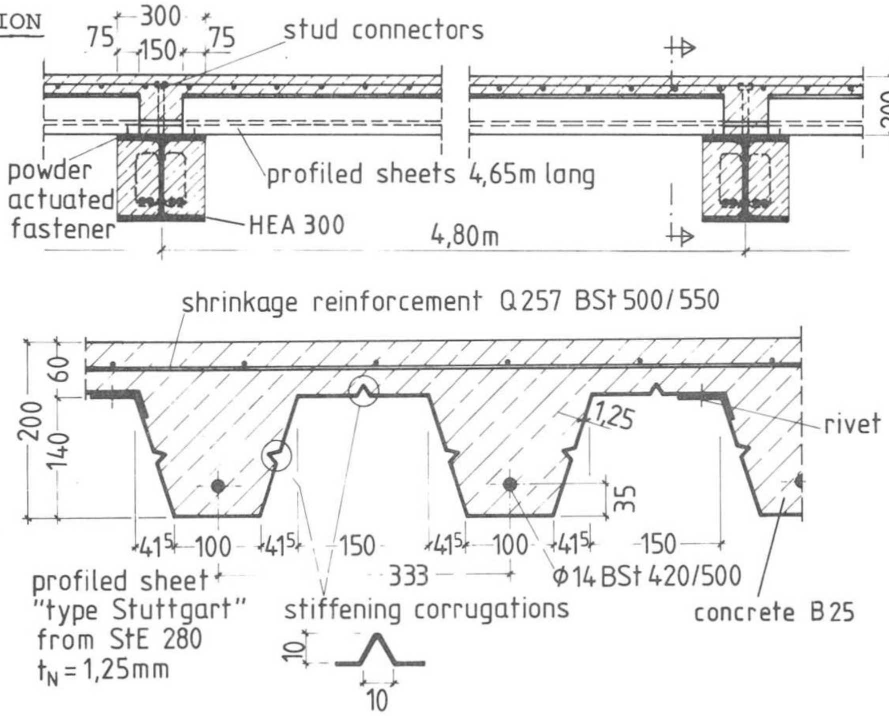


Fig. 8 Sheet-supported reinforced concrete slab in demo-building

Fig. 9 Demo-building under construction

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