Fire-exposed continuous span composite steel-concrete slabs

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From experimental evidence, it was concluded that existing rules for the calculation of the behaviour of fire-exposed composite beams and slabs often lead to conservative solutions. Furthermore, the range of common applications had grown beyond the limits of existing calculation rules. It was felt that existing rules lacked a fundamental basis, in order to optimally design and evaluate fire-exposed composite beams and slabs.

Therefore, a research project was started in 1989, in which CTICM (F), TNO (NL) and ARBED (L), together with both Delft and Eindhoven Universities of Technology, shared numerical and experimental research activities with respect to the behaviour of fire-exposed composite beams and slabs. The project aimed at gaining more insight into the behaviour -failure mechanisms in particular- of fire-exposed composite beams and slabs by means of the development of numerical models and their validation based upon a limited number of full-scale well-instrumented fire tests. The final goal of this research project was to establish simple calculation rules, which would allow for easy and fast assessment of the fire-behaviour of composite beams and slabs. The project was co-sponsored by the ECSC; the part on composite slabs was conducted in the Netherlands, the part on composite beams in France.

In the paper, the results of the Dutch part of the research project are described. After a brief introduction, the experimental programme is outlined. A total of 21 full-scale fire tests was performed on unloaded as well as loaded test specimens. These experiments have successfully been modelled using a general purpose finite element programme, with some pilot extensions. With the numerical model, a parameter study was performed. The results of this study were translated into a proposal for new simple calculation rules.

Key words: **finite element analyses, fire-exposure, composite steel/concrete slabs, continuous span, calculation rules.**

1 Introduction

Composite steel / concrete slabs are a popular flooring system in modern steel framed buildings. They consist of a cold-formed profiled steel decking, and concrete, which is cast on top of the steel decking. Normally, the concrete will be reinforced. The steel decking has three functions. Before casting of the concrete, it serves as a work platform and a safety screen for floors below. During casting, the decking acts as permanent shuttering. After hardening of the concrete, indentations or

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embossments in the steel decking provide the composite action between steel and concrete; thus, in the final stage, the steel decking serves as reinforcement.
Typical cross sections and dimensions of composite steel / concrete slabs are plotted in Fig. 1.

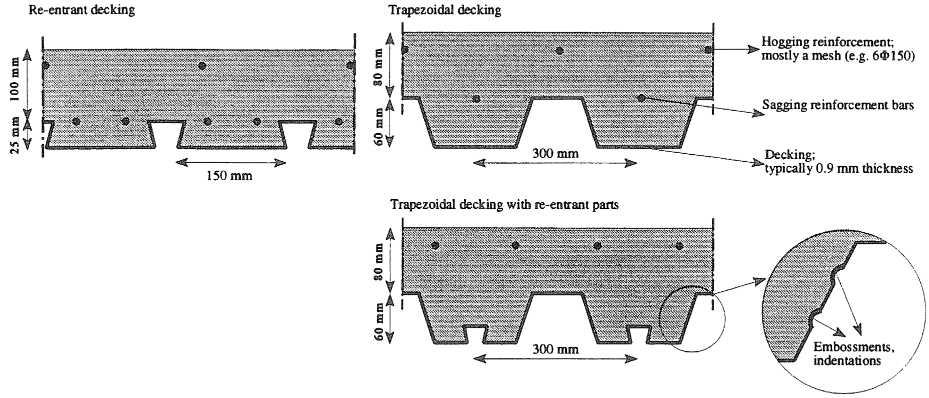


Fig. 1. Typical cross sections of composite slabs; indentations provide composite action.

For composite slabs under service conditions, the fire resistance is an important criterion. In order to determine the fire resistance, calculation rules are available [1]. These calculation rules however are based on limited experimental evidence only. This is because experiments are time-consuming and expensive, whilst the possibility to vary important parameters is limited; e.g. the maximum span of test specimens is restricted due to the sizes of the test furnaces used.
Consequently, the calculation rules are based on hypotheses and rather rough approximations:

- The influence of the profiled shape of the composite slabs is approximated in a rough manner. This holds for the design rules for thermal insulation, as well as for the design rules for the load-bearing capacity.
- The load bearing capacity is determined on the basis of the assumption that elementary plastic theory may be applied. It is assumed, without further proof, that sufficient deformation capacity is available, especially at intermediate supports of continuous span slabs, if the relevant rules at ambient conditions are met.
- The contribution of the steel decking to the load-bearing capacity is neglected.

In order to address the above problems, a research project was started in 1989, in which CTICM (F), TNO (NL) and ARBED (L), together with both Delft and Eindhoven Universities of Technology, jointly shared numerical and experimental research activities with respect to the behaviour of fire-exposed composite beams and slabs. The project aimed at gaining more insight into the behaviour of fire-exposed composite beams and slabs by means of the development of numerical models and their validation based upon a limited number of full-scale well-instrumented fire tests. The validated numerical models could then be used to perform a parameter study, in which the relevant parameters (slab geometry, position of hogging and / or sagging reinforcement, etc.) are varied. The final goal of this research project was the establishment of simple calculation rules. The project was co-sponsored by the ECSC; the part on composite slabs was conducted in the Netherlands, the part on composite beams in France.

In this paper, the results of the Dutch part of the research project are summarized. Firstly, a quantitative description of the behaviour under fire conditions is given. Secondly, the verification of the numerical models on the basis of full-scale fire tests is illustrated. Finally, typical results are presented of the proposed new calculation rules.

2 Fire exposed composite slabs

2.1 *Fire conditions*

Traditionally, the fire resistance is assessed on the basis of tests on single structural elements, like beams and columns. In such fire tests, the specimens are placed in or on furnaces, in which the gas temperature follows a standard specified curve, see Fig. 2 [2].

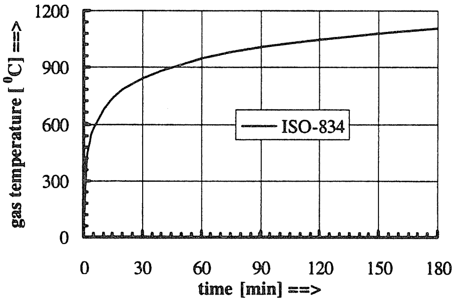


Fig. 2. Determination of the fire resistance: ISO standard fire curve.

The fire resistance is usually expressed in classes, ranging from 30 to 120 minutes (and beyond) in 30 minutes intervals. In general, it is distinguished between the fire resistance with respect to:

- *load-bearing capacity*: resistance to collapse or excessive deformations;
- *thermal insulation*: limited temperature increase at unexposed side (maximum average increase 140 °C and maximum increase 180 °C);
- *integrity*: the ability to resist penetration of flames and hot gases.

In the case of composite slabs, the steel decking ensures integrity, thus only the first two criteria are relevant. Furthermore, only exposure from below is considered, which, in practical cases, will always be decisive.

2.2 *Thermal behaviour*

Due to the profiled shape of the decking, the heat transfer to and in the composite slab is essentially two-dimensional. The heat transfer to the upper flange and web is more or less obstructed, depending on the shape of the decking. Temperatures of these parts are therefore lower than in the lower flange of the steel decking. This is illustrated in Fig. 3, on the basis of a typical test result (Prins PSV 73 steel decking; normal weight concrete).

Notice the plateaus in the temperature developments at the levels of 100 °C. This is caused by the evaporation of (free) moisture, which consumes energy and slows down the heating up of the concrete.

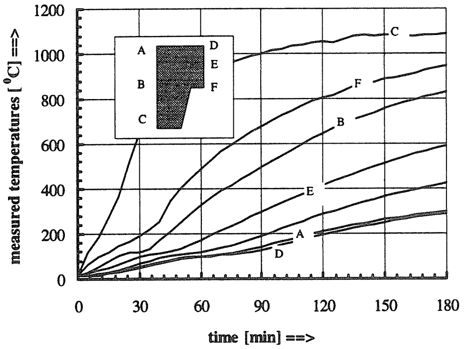


Fig. 3. Typical temperature development in the cross-section of a fire-exposed composite slab.

Furthermore, the thermal properties of concrete are important. These properties are functions of the concrete temperature and the type of concrete (normal weight / light weight). Due to the smaller thermal conductivity, in general, the thermal diffusivity for lightweight concrete aggregates is less than for normal weight concrete. Therefore slabs of lightweight concrete have higher temperatures at the exposed side (steel decking) and lower temperatures at the unexposed side (top of slab and negative reinforcement) than slabs of normal-weight concrete.

In many cases the heat transfer in longitudinal direction of the slab can be neglected. This is not the case near internal supports of continuous span slabs. The cross-sections above these supports are thermally shielded by the supporting structure, yielding lower temperatures. See also further on in this paper.

It may be clear that the simulation of the temperature development in fire-exposed composite slabs is rather complex, due to the time-dependency and the non-linear material behaviour. In the underlying study, the general purpose finite element program DIANA has been used.

2.3 *Mechanical behaviour*

2.3.1 Material properties

The mechanical material properties of the steel and concrete change at elevated temperatures. Firstly, temperature increase causes thermal expansion. The thermal expansion coefficients of concrete and steel at elevated temperatures are plotted in Fig. 4 [1]. Furthermore, strength and stiffness of steel and concrete decrease at increasing temperature. See also Fig. 4.

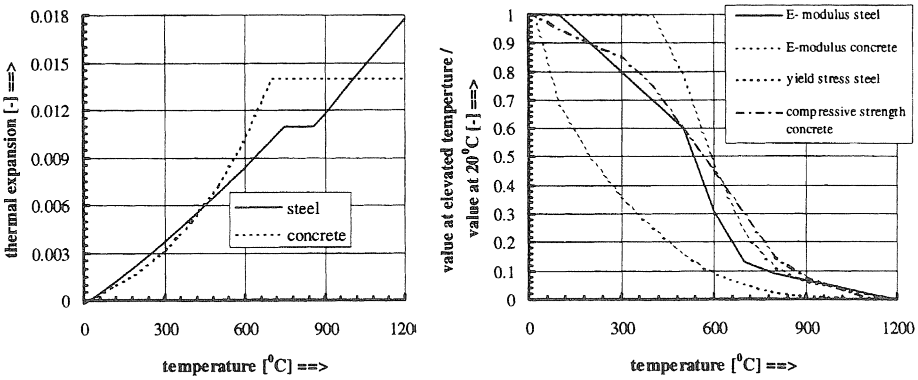


Fig. 4. Temperature dependency mechanical material properties.

The thermal gradient over the height of the specimen (see Fig. 3) causes a thermal curvature, which results in a redistribution of bending moments in the case of continuous span slabs. This is illustrated in Fig. 5, for a continuous span slab with positive reinforcement at midspan and negative reinforcement at the supports. The sum of moments (midspan moment M_A and support moment M_B) remains constant, i.c. $1/8qL^2$. The linear elastic moment distribution at room temperature is given in Fig. 5b. Due to the temperature increase during fire, the thermal curvature increases and the flexural stiffness at midspan decreases faster than at the support sections. Because of the first effect in particular, the support moment M_B increases in the early stage of the fire. Both positive and negative plastic moment ($M_p^+$and M_p^-) decrease as a function of time. After reaching the negative plastic moment at a certain time the support moment M_B begins to decrease in accordance with the decrease of M_p^-. Since M_B decreases as a function of time, midspan moments M_A increase accordingly. These midspan moments may increase up to the sagging plastic moment capacity (plastic hinge failure in Fig. 5e) provided that the rotational capacity is sufficient.

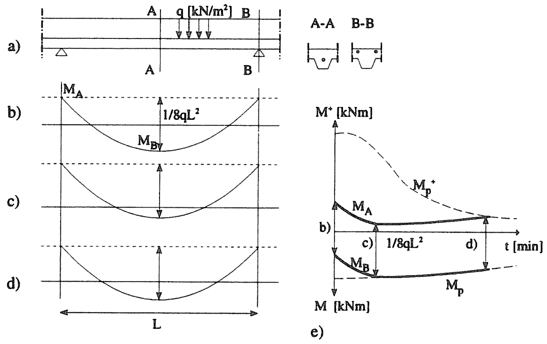


Fig. 5. Redistribution of bending moments in continuous fire exposed composite slabs:
a) static system and cross sections;
b) moment distribution at room temperature (linear elastic);
c) moment distribution at an initial stage of fire;
d) moment distribution at failure;
e) moment capacity as a function of time.

The above qualitative description illustrates the complexity of the mechanical behaviour of fire-exposed composite slabs. The inherent physical and geometrical non-linearities call for numerical modelling. In the underlying study, the general purpose finite element program DIANA has been used as well.

3 Numerical simulation of experiments

3.1 Brief description of numerical models

3.1.1 Thermal response

Besides conventional boundary (i.e. prescribed surface or environment temperatures and fluxes) conditions, a recent development in the general purpose model allows to account for heat transfer by means of radiation and convection in (convex-shaped) voids in structural elements. Originally, this option was developed in order to study fire-exposed hollow core slabs and box-protected steel sections [3].

This option has also been used to model the effect of heat exchange by means of radiation between the upper flanges and the webs of composite slabs and the fire environment. The principle is illustrated in Fig. 6. An artificial void is defined, bounded by the upper flanges, webs and an artificial surface, spanning between two lower flanges. At the latter surface, the temperature-time history is specified, according to the ISO standard fire curve (see also Fig. 2).

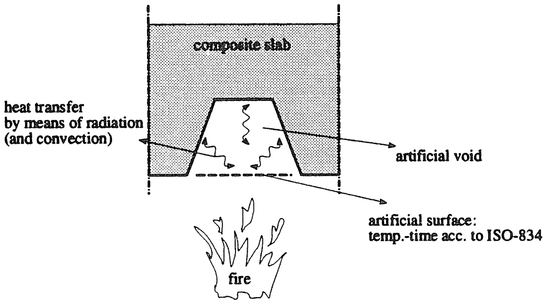


Fig. 6. Modelling of heat transfer by means of radiation: introduction of an artificial void.

Furthermore, the effect of melting of the sinc-layer on the steel decking has been modelled by means of a temperature dependent emissivity. The effect of evaporation of free moisture, has been modelled by means of a modified relationship for the temperature dependency of the specific heat.

Use was made of linear 8-noded solid elements, with 1-point Gauss integration. Full implicit time integration was adopted, in combination with a standard Newton Raphson iteration scheme. Time steps typically range between 1 sec. to 5 min.

3.1.2 Mechanical response

Both Mindlin 3-noded beam elements as well as 8-noded solid elements have been used. The latter approach allows for the introduction of the discrete crack concept, which is relevant when studying the rotational capacity.

Experiments on canti-lever slabs and continuous slabs, with relatively low reinforcement ratio's, showed that rotations may concentrate in one or two major cracks above the internal support. This holds under ambient as well as at elevated temperatures. Hence, in order to describe the behaviour near these localised cracks, a discrete crack approach is more applicable than a smeared crack approach.

The governing factor for the rotational capacity at internal supports is the behaviour of the reinforcement [4]. As mentioned above, in an early stage of fire-exposure, the hogging moment capacity is reached, and the reinforcement yields. It appeared from recent studies at Delft University of Technology, that the currently widely adopted bond stress-slip relationships [5] significantly overestimate the bond stress resistance, due to the fact that these relationships do not cover the effect of yielding of the reinforcement [6].

By means of special interface elements, both the discrete cracks as well as bond stress-slip has been modelled. With respect to the latter point, it is noted that results of recently performed detailed experiments have been adopted.

In the simulations, an iteration scheme on the basis of a secant-stiffness, appeared to be most successful. Due to complex cracking behaviour, influenced by thermal stresses and redistribution of bending moments, a standard Newton Raphson iteration scheme may easily fail.

Further relevant options are:

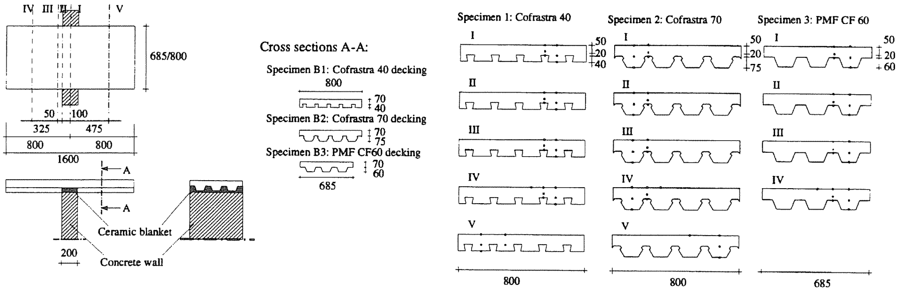
- Drucker-Prager yield criterion for concrete in compression;
- Von Mises yield criterion for steel;
- geometrical non-linearities on the basis of the Total Lagrange approach;
- temperature dependent thermal expansion and Young's moduli, according to [1];
- high temperature creep implicitly accounted for by means of a cohesion coefficient (compressive strength c.q. yield strength) depending not only on the equivalent plastic strain, but also on the temperature.

3.2 *Comparison models and tests*

3.2.1 Thermal

In order to study the influence of the steel decking and the concrete depth on the thermal response, fire tests were performed on a total of 12 different specimens [7]. The three-dimensional heat flow near internal supports was separately investigated by means of 3 fire tests on unloaded specimens, each with a different steel decking [8].

The main objective of the fire tests was verification of the numerical model. To that extent, a large number of thermocouples was applied. This is illustrated in Fig. 7. In this figure, a schematical presentation is given of the test arrangement for the experiments in which the three-dimensional heat flow was investigated.

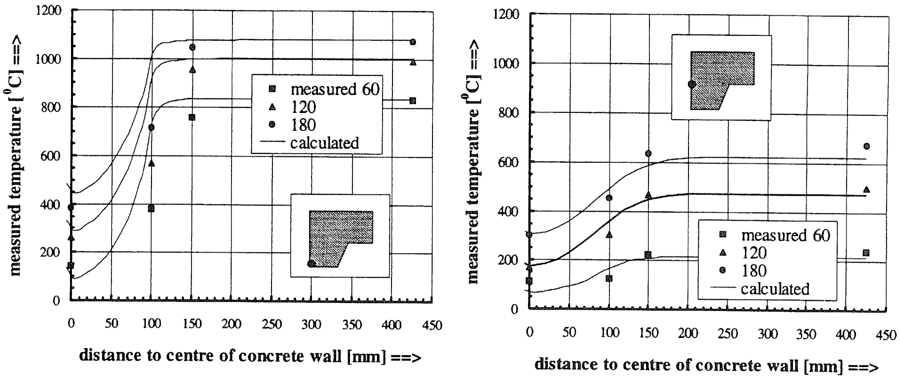


(a) test set-up. *(b) distribution of thermocouples.*

Fig. 7. Test arrangement heat flow near (insulated) internal supports.

The results of the numerical simulation are compared to the experimental results in Fig. 8. It can be seen that:

- the agreement between model and test is satisfactory;
- the length of the area in which the temperatures are influenced by the (insulated) support is rather small (approximately equal to the height of the slab plus the width of the support).



(a) lower flange *(b) sagging reinforcement level .*

Fig. 8. Measured temperatures in composite slab on insulated support, as a function of the distance from the centre of the internal support (PMF CF60 decking).

3.2.2 Mechanical

Ten full-scale fire tests were performed on loaded test specimens. The behaviour under positive bending was investigated by two tests on simply supported slabs; the behaviour under negative bending was investigated by means of three tests on cantilever slabs [7]. Furthermore, five tests were performed on continuous two-span slabs in order to study the effect of the redistribution of bending moments [9].

The parameters investigated were:

- type of steel decking: Prins PSV73 and Ribdeck 60 steel decking (both trapezoidal);
- reinforcement ratio: the sagging reinforcement ratio between 0 and 0.31%; the hogging reinforcement ratio between 0.18 and 0.52%;
- hot rolled vs. cold-worked reinforcement.

In the specimen with the Ribdeck 60 steel decking, a draped mesh was applied. The test arrangement is schematically presented in Fig. 9. In one of the spans, the mesh was fastened to the upper flanges of the decking; in the other span, the position of the mesh was such that an optimal sagging moment capacity was reached. The internal support consisted of a box-protected steel beam. In the simulation, relationships for temperature dependent material properties were adopted from [1].

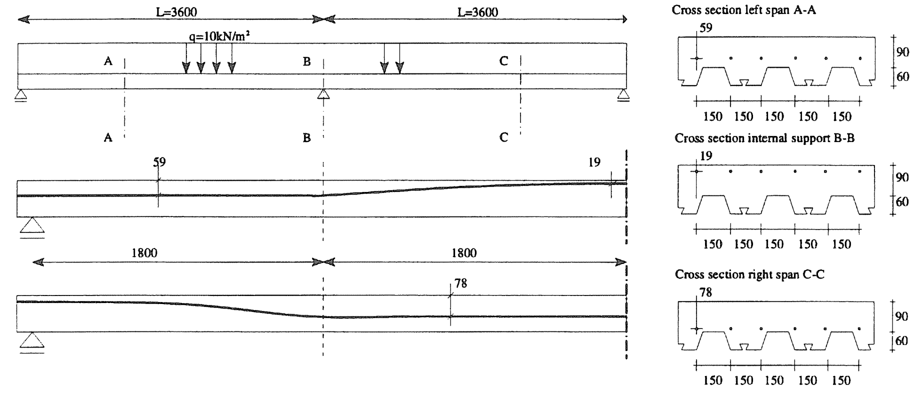


Fig. 9. Test arrangement continuous span slab; draped mesh.

The numerical results are compared to experimental results in terms of mid span deflections in Fig. 10. It can be seen that the overall behaviour is simulated quite well. More in particular, failure is predicted in good agreement with test results.

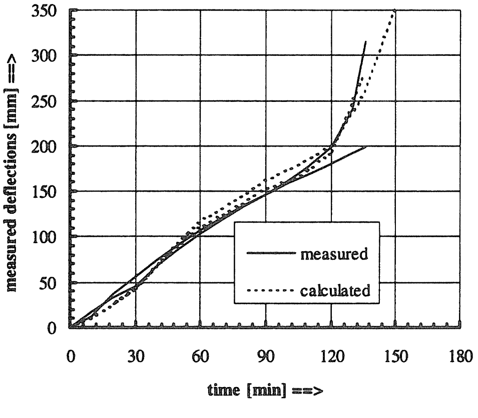


Fig. 10. Comparison of numerical and experimental results of the continuous slab test.

4 Proposal new calculation rules

4.1 *Parameter study*

An inventory was made of existing deckings, both re-entrant and trapezoidal, in Europe. It appears that there are only 7 different re-entrant deckings, as opposed to 48 different trapezoidal deckings. It is noted that trapezoidal deckings include so-called "mixed" deckings, i.e. deckings with a small

re-entrant part in lower or upper flange. See also Fig. 1. For all these deckings, thermal calculations were made for both normal and light weight concrete, up to four hours of fire exposure, varying the concrete depth between 50 to 120 mm. Thus a data set has become available with temperature distributions in all known slabs up to 4 hours. The advantage of such a data set is that with a simple program, data (in terms of temperatures at specific points or averages at certain points) can be filtered and plotted against a range of parameters. It is also relatively easy to change the underlying modelling assumptions – for instance material properties – and thus create a new data set.
By means of simple model based on a block-stress approach, the sagging and hogging plastic moment capacities can be calculated, using the above data set as input.
Below, the relevant assumptions in the calculations are listed:

- convective and radiative heat transfer based on relationships as put forward in [7];
- the decking (1 mm) was accounted for;
- thermal and mechanical material properties according to [1].

The results of the numerical simulations have been used to set up new calculations rules. These rules will be proposed for adoption in a renewed version of Eurocode 4 [1]. By means of illustration, the proposal for the calculation of the *hogging moment capacity* is briefly described in the next section.

4.2 *Hogging moment capacity*

For the hogging moment capacity, a method is proposed, based on a reduced cross section. The proposed method is similar the simplified method for reinforced concrete adopted in [10]. The parts of the cross section with temperatures beyond a certain limiting temperature are neglected. The limiting temperature depends on the area of the hogging reinforcement and the fire resistance [9].
The hogging moment is determined by means of a block stress method, by considering the reduced cross section as if under room temperature conditions. It is proposed to schematise the isotherm for the limiting temperature, by means of 4 characteristic points, as shown in Fig. 11.

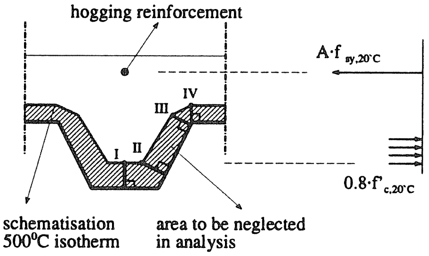


Fig. 11. Principle proposed new rule for hogging moment capacity.

For composite slabs, with 70 mm normal weight concrete, and trapezoidal deckings, the results obtained with the simple rule are compared to numerical results, for different levels of hogging reinforcement, in Fig. 12. The agreement is good; i.e. the regression coefficient is close to unity, as well as the correlation coefficient (R^2) value. For re-entrant deckings and / or light weight concrete similar conclusions hold [9].

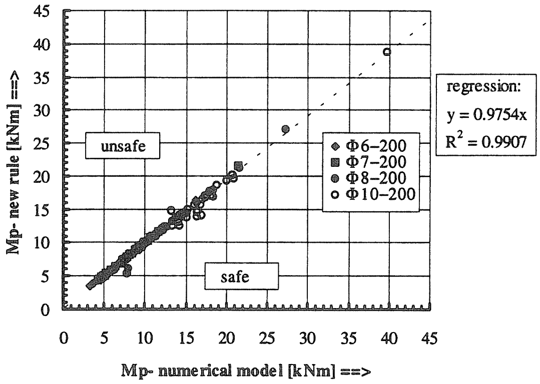


Fig. 12. Hogging moment capacity: proposed rule versus model predictions.

5 Summary and conclusions

Recently, a research project was completed, which aimed at the improvement of existing simple calculation rules for the assessment of the fire behaviour of composite steel / concrete slabs and beams. The project started in 1989. The part of the project on composite slabs was carried out in the Netherlands, by TNO Building and Construction Research together with both Eindhoven and Delft University of Technology. In the scope of the project, co-sponsored by the ECSC, a total of 21 fire tests was performed. The parameters investigated comprise: reinforcement ratio, deformation capacity of hogging reinforcement, load level, insulation of internal support and type of steel decking. Numerical models have been established, both for the simulation of the thermal and structural response of composite concrete slabs with profiled steel decking to fire. It is concluded that the numerical models are able to describe the two- and three-dimensional heat flow in fire-exposed composite slabs in good agreement with test results. In practical cases, the structural response to fire can also be simulated well. By means of the numerical models, a parameter study was performed, which comprised all available steel deckings on the European market. In this study, the simple calculation rules of Eurocode 4, part 1.2, were critically reviewed and modified were appropriate.

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