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THERMAL SHIELDING NEAR INTERMEDIATE SUPPORTS OF CONTINUOUS SPAN COMPOSITE SLABS

Kees Both[1], Jan W.B. Stark[2] and Leen Twilt[3]

SUMMARY

At TNO Building and Construction Research, in close co-operation with the Eindhoven University of Technology, research is carried out on the behaviour of fire-exposed composite steel/concrete slabs, in the framework of a research project co-sponsored by the ECSC (European Community for Steel and Coal). The paper describes the state of the art of the research project.

INTRODUCTION

The increasing popularity in Europe of composite slabs with cold-formed steel decking has underscored the need to improve calculation rules for the fire resistance. Existing rules, based on earlier work carried out by the European Convention of Constructional Steelwork [ECCS^{1983}], have some drawbacks. They especially do not cover the full range of application. Furthermore, the predictions are based on gross approximations [Twilt^{1991}].

Therefore, in 1989, a joint research project was started, in which TNO and the Eindhoven University of Technology carry out experimental and numerical investigations. The aim of the project is to increase insight in the behaviour of fire-exposed composite slabs and the development of numerical models. This will enable to improve and extend the presently available simple calculation rules.

The research project is carried out in the scope of an international research project on fire-exposed composite structures, and is granted by the European Community for Steel and Coal. TNO and the Eindhoven University of Technology are responsible for the (Dutch) part of the project concerning composite slabs; the Centre Technique Industriël de la Construction Métallique (CTICM, France), and ARBED Luxembourg focus on fire-exposed composite steel/concrete beams [Aribert^{1991}].

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The Dutch research is divided in two phases. In the first, recently completed phase, a numerical model was developed and verified on basis of fire tests. The results of the first phase are briefly discussed in the next section. For a more extensive description, reference is made to [Hamerlinck^{1990}, Hamerlinck^{1991}].
The second phase of the project is concerned with further validation of numerical tools (especially with respect to continuous span composite slabs) and the development of simple calculation rules. In the second phase, a start has been made with the investigation of the three-dimensional transient heat flow near intermediate supports of continuous span slabs. In particular the influence of the non-uniform temperature distribution on the mechanical response is discussed.

FOREGOING RESEARCH: RESULTS OF FIRST PHASE

Brief description of numerical model

The strategy used in the research project consists in the development of a numerical model, which is to be verified on basis of a limited number of full-scale fire tests. After verification, the numerical model will be used to systematically vary parameters (slab geometry, material properties, static system, heating conditions and the like) and study their influence.
A pilot version of such a model has been developed at the Eindhoven University of Technology [Hamerlinck^{1990}].

The numerical model comprises three submodels:
1 a computer programme for the analysis of two-dimensional transient heat flow;
2 a computer programme for the calculation of moment-curvature (M-κ) relationships;
3 a computer programme for the calculation of deflections and the distribution of forces.

The submodel for thermal analysis is based on the finite difference method, and accounts for temperature dependent material properties and the effect of evaporation of moisture. Arbitrary fire-exposure conditions can be dealt with.
The computer programme for cross-sectional analysis is based on the assumptions of a uni-axial stress-state and the Bernoulli hypothesis. High-temperature creep of steel and concrete are implicitly accounted for by means of non-linear stress-strain (σ-ϵ) relationships.
The displacement method is used in the submodel for the analysis of the flexural behaviour. The model allows the analysis of both simply supported and continuous composite slabs.

Simulation of test results

In order to verify the two-dimensional thermal model, a total of 12 fire tests were performed, on unloaded specimens. During the tests, the temperature development in several points in the cross-sections were recorded [Brekelmans$^{1990^a}$].

An acceptable agreement between experimental results and model predictions was found, see Fig. 1A and 1B. Considering the uncertainties involved, especially with respect to the heat transfer phenomena in the furnace, the differences between calculated and measured temperatures are relatively slight.

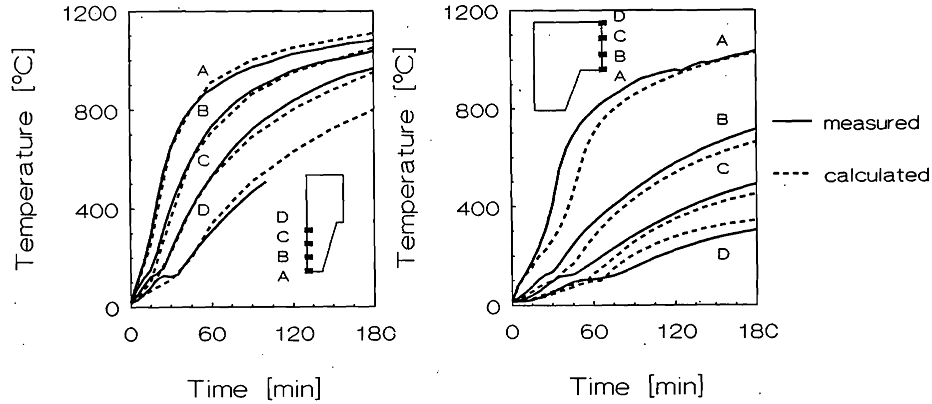


Fig. 1 Comparison of calculated and measured temperatures in simply supported composite slabs. A: Prins73 steel decking; B: PMF-CF60 steel decking.

A total of six fire tests were performed on loaded specimens, in order to verify the numerical models for the mechanical behaviour. The tests mainly concerned simply supported slabs; one test was performed on a continuous two-span slab, see Fig. 2 [Brekelmans^{1990b,c,d}].

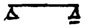
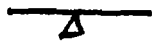
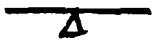
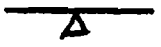
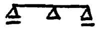
test no.	static system	positive reinforcement	negative reinforcement
1		-	ϕ6-150 cold-formed
2		ϕ10-208 hot-rolled	ϕ6-150 cold-formed
3		-	ϕ6-150 cold-formed
4		-	ϕ10-150 cold-formed
5		-	ϕ10-150 hot-rolled
6		ϕ10-208 HWL hot-rolled	ϕ10-150 hot-rolled

Fig. 2 Review of mechanical tests carried out in the first phase of the ECSC-sponsored research project.

Comparing test results to model predictions, the following conclusions can be drawn, see e.g. [Hamerlinck^{1990}], [Hamerlinck^{1991}] and [Twilt^{1991}].

1 The numerical model reasonably predicts the thermal and mechanical behaviour of simply supported composite slabs, see Fig. 1 and 3.

2 The rotational capacity at intermediate supports may prove to be insufficient, when cold-formed reinforcement with a relatively low deformation capacity is

applied.

3 Thermal shielding of the slab caused by an insulated intermediate support has significant influence on the thermal behaviour, and, possibly, on the mechanical behaviour. Due to the two-dimensional character of the thermal model, these effects could not be studied thoroughly in this phase of the project.

4 The numerical model could not predict the failure-mechanism of the tested continuous beam (which had a relatively high ratio of negative reinforcement of 0.52%), see Fig. 5.

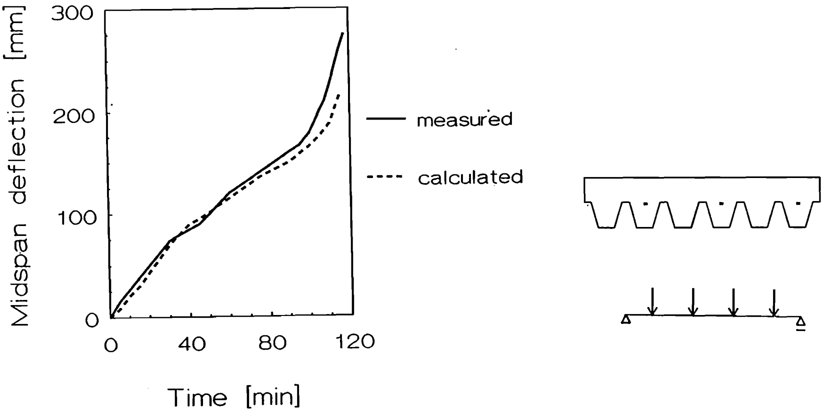


Fig. 3 Comparison of calculated and measured midspan deflections in a simply supported fire-exposed composite slab.

The inadequacy of the numerical model mentioned in point 4, might be due to concrete cracking at the level of the upperflange of the steel decking. This cracking was observed when the specimen was cut after testing, as schematically shown in Fig. 4.

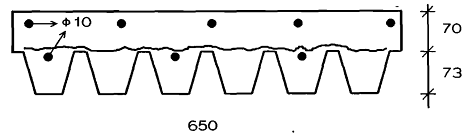


Fig. 4 Cracks observed in a tested continuous span composite slab.

This failure-mode was not expected and is possibly caused by the relatively high ratio of negative reinforcement. A high ratio of negative reinforcement gives rise to a large difference in stiffness between upper and lower part of the slab. As a result shear stresses develop, which may initiate cracking. Such cracking may not occur in composite slabs with more practical ratios of negative reinforcement.

A reasonable prediction of the flexural behaviour of the tested continuous slab could only be obtained by explicitly taking into account horizontal cracks. The results of the calculation in which this was done, is plotted in Fig. 5, in terms of midspan deflections. For comparison, the results of a calculation in which horizontal cracking is neglected are given as well, together with experimental results.

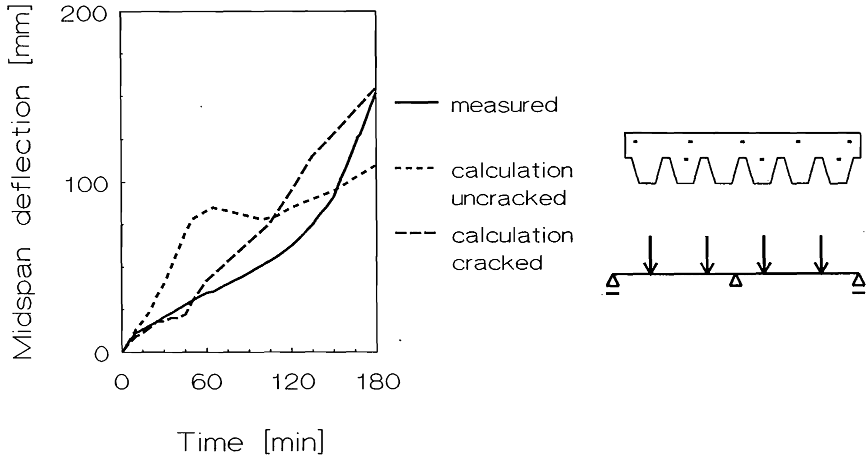


Fig. 5 Comparison of calculated and measured midspan deflections in a continuous span fire-exposed composite slab: calculation 1 neglecting and calculation 2 including horizontal cracks.

Because of its underlying assumptions of a uni-axial stress-state and the Bernoulli-hypothesis, the present numerical model is not suitable for the investigation of the initiation and development of the above concrete cracking [Hamerlinck^{1991}].

CURRENT RESEARCH

Introduction

In the second phase of the project, apart from establishing simple calculation rules, attention is on further development of numerical models. Emphasis is, so far, on the verification of the hypothesis of horizontal cracking, and on the determination of the effect of thermal shielding of intermediate supports of continuous span composite slabs.

To this extent, use is made of the general purpose three-dimensional finite element package DIANA, which is available at TNO, and recently offers special features which allow the analysis of fire-exposed structures.

Horizontal cracking

In order to investigate conditions under which horizontal cracks may initiate at

the level of the upper flange of the steel decking, use has been made of the advanced non-linear finite element package, provided by DIANA.
As a first attempt, a hypothetical case has been chosen, in which the reinforcement ratios have been taken equal to the ones in the continuous span composite slab tested in the first phase of the research project, see Fig. 6.

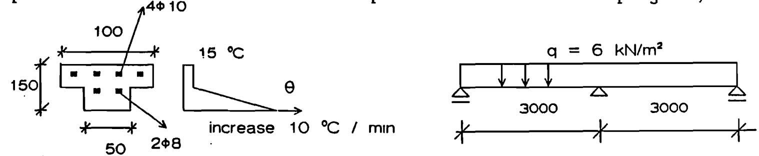
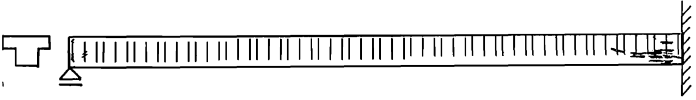


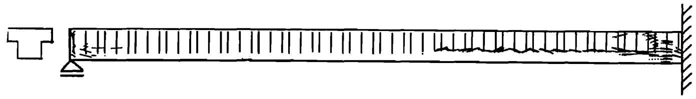
Fig. 6 Hypothetical case, used in the analysis of possible horizontal cracks in fire-exposed slabs with high thermal gradients and high level of negative reinforcement.

Both the high level of the negative reinforcement ratio, and the thermal gradients, induce shear stresses, which may cause horizontal cracking. In order to obtain extreme temperature gradients, the heating range of the bottom flange was chosen 10 °C/min, whereas for the upper flange a constant temperature was taken.

The calculated crack patterns in one span after 30 and 60 minutes of fire exposure in one span of the two-span system are plotted in Fig. 7. After 30 minutes, besides vertically oriented cracks due to the thermal expansion of the concrete, horizontal cracks at the level of the positive reinforcement become apparent, which start to grow from the intermediate support towards the span. After 60 minutes, the horizontal crack has grown almost to midspan.



a) Cracks after 30 minutes



b) Cracks after 60 minutes

Fig. 7 Calculated crack patterns after 30 and 60 minutes of fire exposure.

It is concluded from the calculation that the computer programme may provide a tool for the prediction of the horizontal cracks. The results of further investigations, based on measured temperature distributions in composite slabs, will be of help to optimally configure the test arrangement and the geometry of the loaded test specimen.

Thermal behaviour of insulated intermediate supports

The transient heat flow near intermediate supports has been investigated, by means of fire tests on three unloaded specimens, each with different steel decking, supported by an insulated concrete wall. A schematic presentation of the test set-up is shown in Fig. 8.

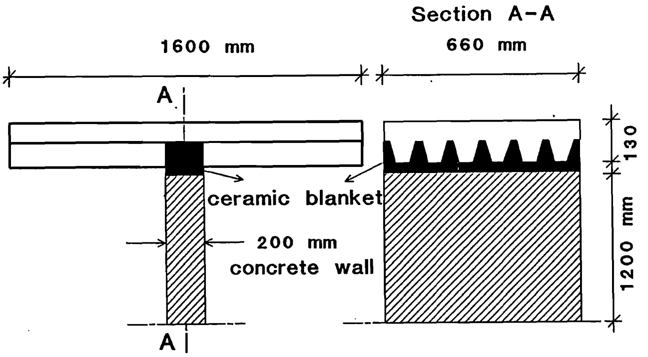


Fig. 8 Test set-up for investigation of thermal shielding near intermediate supports of continuous span composite slabs.

Experimental results are compared to numerical results obtained with DIANA in Fig. 9. It can be seen from Fig. 9, that the agreement between experimental and numerical results is satisfactory. It furthermore appears, that the area in which the temperature development is affected by the insulated support is rather small.

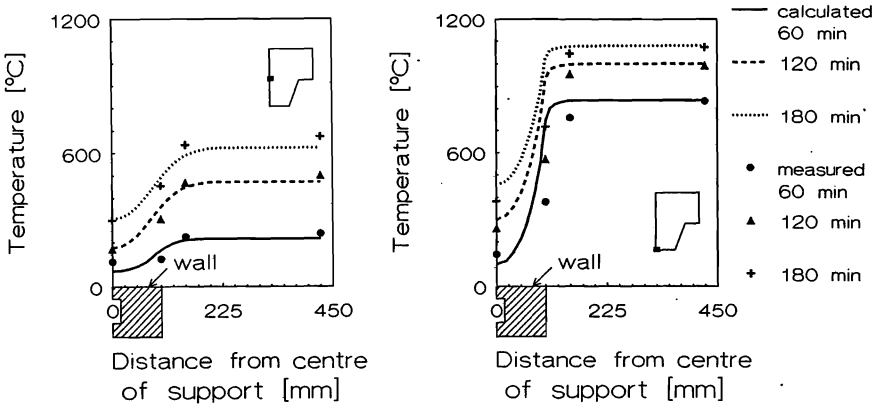


Fig. 9 Comparison of calculated and measured temperatures in a composite slab supported by an insulated wall.

To date, the three-dimensional computer programme is used to study the influence of parameters like: geometry of the slab, moisture contents, etc.

Influence of insulated intermediate supports on mechanical response

At first sight, the influence of insulated intermediate supports on the mechanical response may be regarded as neglectable, bearing in mind the small area in which the temperature development is affected. However, experiments carried out in the first phase of the project on cantilever slabs, supported by an insulated wall, did show significant influence on the mechanical behaviour. Therefore, numerical research is being carried out to further qualify the effect of thermal shielding of composite slabs near intermediate supports.
Starting point for the calculations is the assumption of a temperature-distribution near the intermediate support on basis of the calculation with the 3D-thermal computer programme, as described in the foregoing section. Furthermore, possible influence due to concrete cracking is neglected (on basis of the assumption that the above-mentioned cracking is not likely to occur in case of more practical ratios of negative reinforcement).

Consider a case with a static system with two spans of 3100 mm, and a uniformly distributed load of 7 kN/m². The width of the insulated intermediate support is 200 mm. A composite slab with PMF-CF60 steel decking and a concrete topping of 70 mm, is assumed. The negative reinforcement is ϕ8-200; the positive reinforcement 2ϕ8 (ϕ8-500). See Fig. 10.

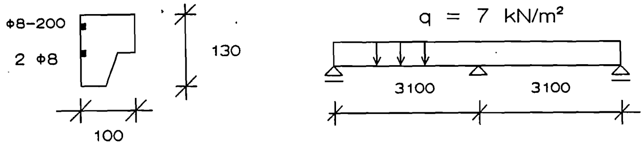


Fig. 10 Hypothetical case, used in the analysis of the influence of thermal shielding near intermediate supports of continuous composite slabs.

First, moment-curvature relationships are calculated, as a function of the fire-exposure time, neglecting any influence due to thermal shielding.
In Fig. 11, both positive and negative plastic moment capacity (M_p^+ and M_p^-) of the composite slab are plotted, as a function of time. Assuming conditions which allow the use of elementary plastic theory, failure will occur at the time that, somewhere near midspan, the positive plastic moment capacity is reached (causing a plastic mechanism with three plastic hinges: see Fig. 11). Approximately, the positive plastic moment will be formed at a distance of 0.6L from the intermediate support.
Thus failure will approximately occur at time t when:

$$M_p^+(t) + 0.4 \cdot M_p^-(t) = 1/8 qL^2 \qquad (1)$$

where:

L	span [m];
$M_p^+(t)$, $M_p^-(t)$	positive resp. negative plastic moment capacity as function of time [Nm];
q	total load [N/m];
t	time [min].

In this case, the calculated fire resistance amounts 88 minutes, see also Fig. 11.

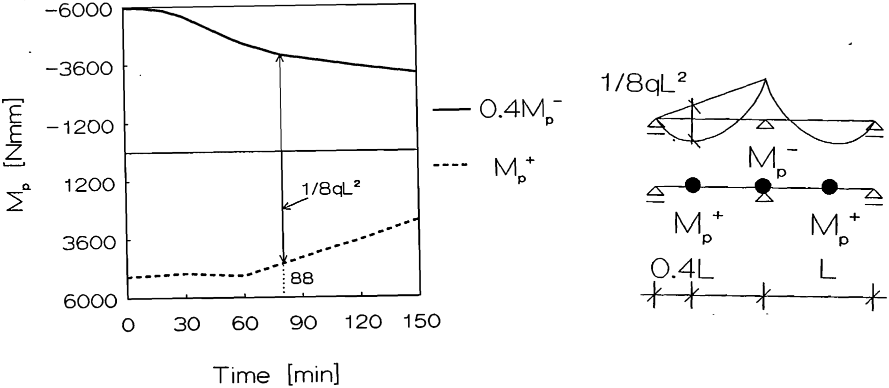


Fig. 11 Development of plastic mechanism in two-span composite slab, neglecting thermal shielding near the intermediate support.

Secondly, the influence of thermal shielding is taken into account. Moment-curvature relationships are now calculated, as a function of both the fire-exposure time and the distance from the centre of the intermediate support. In Fig. 12, the negative plastic moment capacity of the composite slab is plotted. It can be seen that the plastic moment decreases rapidly at increasing distance from the centre of the support. At a distance of 200 mm from the centre of the support, the negative plastic moment capacity has decreased to the level which is found in the area in which temperatures are unaffected by the support.

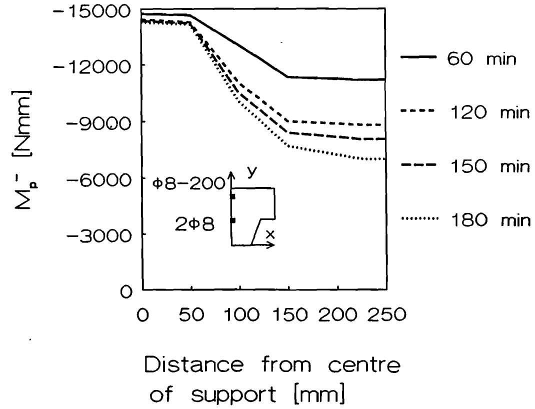


Fig. 12 Calculated negative plastic moment capacity of a composite slab, as a function of the distance from an insulated support, after 60, 120, 150 and 180 minutes fire exposure.

Assuming the development of a plastic moment at the centre of the intermediate support at an early stage of fire exposure, the distribution of bending moments can easily be obtained from equilibrium. In Fig. 13, the moment distribution is plotted in one span of the slab. In the figure, the negative plastic moment capacity after 60 minutes of fire-exposure is given too (see also Fig. 12).

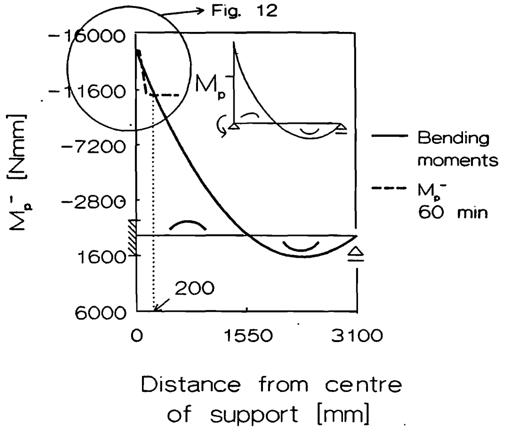
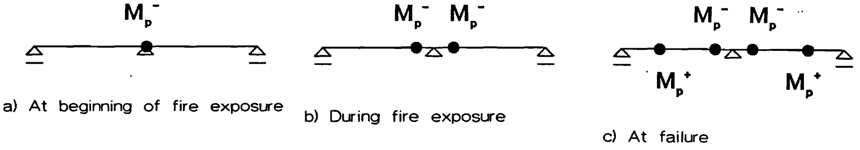


Fig. 13 Distribution of bending moments in a two-span composite slab, in an early stage of fire-exposure.

It can be seen that near the intermediate support, already after 60 minutes fire exposure, the bending moments are larger than the (negative) plastic moment capacity. This indicates a movement of the plastic moment from the centre of the support, towards the span. Failure will not occur at this time, due to the fact that after redistribution of moments, the positive plastic moment capacity is not reached yet.
In fact, the plastic mechanism has changed: see Fig. 14.



a) At beginning of fire exposure
b) During fire exposure
c) At failure

Fig. 14 Schematic presentation of the (trans)formation of the plastic mechanism during fire-exposure in a two-span slab with insulated intermediate support.

Assuming the movement of the plastic hinge to 200 mm (see Fig. 13) from the centre of the support, the fire resistance increases 26% when compared to the outcome of the calculation of the fire resistance in which thermal shielding is neglected. See Fig. 15.

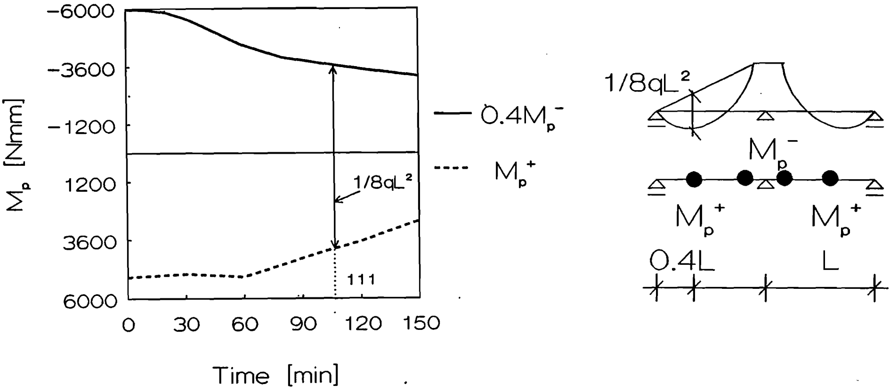


Fig. 15 Development of plastic mechanism in a two-span composite slab, including thermal shielding near the intermediate support.

In order to obtain a fire resistance of 120 minutes, for the investigated case, the thermal shielding due to the insulated support alone is not sufficient.

However, by means of partial protection with e.g. sprayed mortar, the area in which the temperatures are affected can be enlarged. The effect on the mechanical behaviour will be that the plastic hinge will start to move towards the span in a later stage of fire-exposure and over a larger distance.

Let δ be the distance over which the plastic hinge moves from the centre of the support towards the span. Then we can approximate the fire resistance by rewriting Eq. (1) into:

$$M_p^+(t) + 0.4 \cdot M_p^-(t) = 1/8q(L-\delta)^2 \qquad (2)$$

The left-hand side of Eq. (2) can be derived from Fig. 11. From Eq. (2) and Fig. 11, we learn that the plastic hinge should move over a distance of 400 mm, in order to obtain a fire resistance of 120 minutes. A reasonable assumption may be that by means of partial protection near the support over 300 mm (400 minus half of the width of the support), such an increase in fire resistance can be achieved.

Obviously, in the above calculations, several assumptions have been made, which have to be verified. For instance, the reaction force by the intermediate support is assumed to act in one point, whereas in reality the reaction force will be distributed (in some way) over the supporting wall. Taking this effect into account leads to a more smooth curve of the bending moments near the centre of the support. Furthermore, only one case has been investigated, so its difficult to draw general conclusions from the results. Further numerical and experimental investigations will be carried out on short notice.

Further experimental research

Three fire tests on loaded two-span composite slabs are planned, in which the test specimens are to be equipped with measuring devices, to give detailed information about:

- the occurrence of the above mentioned plastic mechanism;
- the thermal gradients near insulated intermediate supports;
- the occurrence of horizontal cracks.

CONCLUSIONS

The thermal and mechanical response of fire-exposed simply supported composite slabs can be determined accurately by means of a numerical model, which is under development at the Eindhoven University of Technology.

The complexity of the behaviour of fire-exposed continuous span composite slabs, requires more detailed investigation.
Tentative numerical calculations with a general purpose three-dimensional finite element programme, support the hypothesis of horizontal cracks at the level of the positive reinforcement in fire-exposed continuous composite span slabs, with a relatively high negative reinforcement ratio.
The development of three dimensional temperature distributions near insulated intermediate supports of continuous span fire-exposed composite slabs, can be predicted in good agreement with experimental results, by means of a three dimensional finite element programme. From both experimental and numerical investigations, it appears that the area in which the temperature development is affected by insulated supports is rather small. However, numerical calculations indicate a significant influence on the mechanical behaviour.

Further experimental and numerical research on the behaviour of fire-exposed continuous span composite slabs will be carried out in the near future, in the scope of an ECSC co-sponsored research project. The results will lead to an extended and improved simple calculation method, to be used in building and engineering practice, allowing easy assessment of the fire resistance.

ACKNOWLEDGEMENT

The financial support of the European Coal and Steel Community, under grant 7210-SA/509, is gratefully acknowledged.

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APPENDIX 2: NOTATION

symbol	**description**	**SI-unit**
L	length of span	[m]
M	bending moment	[Nm]
M_p^-	negative plastic moment of composite cross-section	[Nm]
M_p^+	positive plastic moment of composite cross-section	[Nm]
q	equally distributed load	[N/m]
t	time	[min]
	greek characters:	
δ	arbitrary linear distance	[m]
ϵ	total stress related strain	[-]
κ	curvature	[m^{-1}]
σ	stress	[N/m^2]
ϕ	diameter	[m]