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Nonlinear behaviour of unprotected composite slim floor steel beams exposed to different fire conditions

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A B S T R A C T

An efficient nonlinear 3D finite element model has been developed to investigate the structural performance of composite slim floor steel beams with deep profiled steel decking under fire conditions. The composite steel beams were unprotected simply supported with different cross-sectional dimensions, structural steel sections, load ratios during fire and were subjected to different fire scenarios. The nonlinear material properties of steel, composite slim concrete floor and reinforcement bars were incorporated in the model at ambient and elevated temperatures. The interface between the structural steel section and composite slim concrete floor was also considered, allowing the bond behaviour to be modelled and the different components to retain its profile during the deformation of the composite beam. Furthermore the thermal properties of the interface were included in the finite element analysis. The finite element model has been validated against published fire tests on unprotected composite slim floor steel beams. The time–temperature relationships, deformed shapes at failure, time–vertical displacement relationships, failure modes and fire resistances of the composite steel beams were evaluated by the finite element model. Comparisons between predicted behaviour and that recorded in fire tests have shown that the finite element model can accurately predict the behaviour of the composite steel beams under fire conditions. Furthermore, the variables that influence the fire resistance and behaviour of the unprotected composite slim floor steel beams, comprising different load ratios during fire, cross-section geometries, beam length and fire scenarios, were investigated in parametric studies. It is shown that the failure of the composite beams under fire conditions occurred for the standard fire curve, but did not occur for the natural fires. The use of high strength structural steel considerably limited the vertical displacements after fire exposure. It is also shown that presence of additional top reinforcement mesh is necessary for composite beams exposed to short hot natural fires. The fire resistances of the composite beams obtained from the finite element analyses were compared with the design values obtained from the Eurocode 4 for composite beams at elevated temperatures. It is shown that the EC4 predictions are generally conservative for the design of composite slim floor steel beams heated using different fire scenarios.

1. Introduction

Composite "Slim Floor" steel beam structural system offers a fast, innovative, economical, easy serviced, reduced weight and minimum depth construction system. In this system, the steel beam is almost encased within the depth of the concrete floor slab, with the lower flange of the steel beam wider than the upper flange, as shown in Fig. 1. The floor slab may be precast concrete floor slab or composite concrete slab with profiled steel decks. This construction system makes it easy to fit the floor slabs directly onto the lower flange plate of the steel beam, so that the two components form the composite slim floor. This arrangement eliminates steel beam downstands at the level of the floor slabs and ensures that the steel beam and concrete floor slab are working together because of the bonding force between them. In addition to these advantages, the incorporation of the upper flange plate and web of the steel beam in the thickness of the concrete slabs provides better fire resistance.

The behaviour of composite slim floor steel beams under fire conditions has been the subject of limited experimental investigations. These were mainly detailed in Mullett and Lawson [1], Newman [2], Both et al. [3] and Ma and Mäkeläinen [4]. The tests [1] comprised two fire tests on unprotected composite slim floor steel beam with profiled steel deck carried out by the Warrington Fire Research Center (WFRC). The two composite beams were simply supported spanning 4.5 m and were heated

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Nomenclature

ASB	asymmetric slim floor beam
b_1	composite beam dimension
b_2	composite beam dimension
b_3	composite beam dimension
b_4	composite beam dimension
b_5	composite beam dimension
CSB	composite slim floor steel beam
e	emissivity
FE	finite element
f	equivalent uniaxial stress
f_c	compressive strength of concrete
f_{co}	proportional limit stress of concrete in compression
f_{cu}	compressive cube strength of concrete
f_t	tensile strength of concrete
f_y	yield stress of structural steel
f_u	ultimate stress of structural steel
G_f	fracture energy of concrete
h	crack band width
h_1	composite beam dimension
h_2	composite beam dimension
h_3	composite beam dimension
h_4	composite beam dimension
L	length of column
LFY	lower flange yielding failure mode
t_1	composite beam dimension
t_2	composite beam dimension
t_3	composite beam dimension
ε	strain
ε_{cu}	ultimate compressive strain of concrete
ε_{tu}	ultimate tensile strain of concrete
α_c	convective coefficient

according to the ISO standard fire curve under static loads with load ratios of 0.36 and 0.43. The tests reported in [2] comprised six fire tests on unprotected composite slim floor steel beam with precast concrete floor conducted by the Steel Construction Institute (SCI). The fire tests had different cross-section geometries and were heated using the ISO standard fire curve under static loads, with load ratios varied from 0.17 to 0.55. The experimental investigation reported in [3] was international research project performed by the SCI (UK) and TNO Building and Construction Research (NL). The investigation comprised three fire tests on composite slim floor steel beam with welded steel plate to the lower flange. The main objective of the fire tests was to investigate the influence of an air gap between the lower flange and the plate. The fire tests [3] have shown that the presence of the air gap causes significant reduction in the lower flange temperature, however the air gap thickness hardly affect the fire resistance of the composite steel beam. Finally the fire test reported in [4] was on unprotected composite slim floor steel beam with profiled steel deck carried out by Laboratory of Steel Structures at Helsinki University of Technology, Finland. The test [4] was for 9-m-span simply supported steel beam heated using the ISO standard fire curve under static load with a load ratio of 0.53. The fire tests [1–4] have provided a valuable insight regarding the behaviour of composite slim floor steel beam system under fire conditions. The time–temperature relationships, the time–vertical displacements, failure modes and fire resistances were observed in the tests. However, to date, there is no other tests found in the literature on composite slim floor steel beam system, leading to the current investigation.

Numerical modelling can compensate the lack of test data and provide a good insight into the behaviour of composite slim floor steel beams. Newman [2] used a 2D finite difference heat transfer programme developed by the SCI called TFIRE. The load resistance of the slim floor steel beams at elevated temperature was analysed using the moment capacity method. No structural–thermal analysis was carried out, hence the load–vertical displacement relationships of the composite slim floor beams were not verified. Bailey [5] has presented the composite slim floor beam as 1D two-noded finite elements. The model assumed that full composite action can be achieved by the bond between the steel section and concrete encasement. The mesh reinforcement within the composite section was modelled by representing it as a single layer of steel (of equivalent area). Ma and Mäkeläinen [6,7] has modelled the thermal behaviour of composite slim floor beam using a 2D explicit finite difference method. The structural behaviour was modelled in [6,7] using ABAQUS software. A combination of shell, beam and rebar elements was used to study the structural behaviour. The concrete was considered as an elastic–plastic material, which has a plastic plateau after reaching the compressive and tensile strength. No descending phase in compression and in tension was taken into account. The aforementioned numerical models were the available in the literature on composite slim floor steel beam systems. To date there is no detailed 3D finite element model, highlighting all the parameters affecting the behaviour of this form of structures under fire conditions. This is attributed to the complexity of nonlinear material behaviour of the composite slim floor components at elevated temperature as well as the interface among these components, which is addressed in this study.

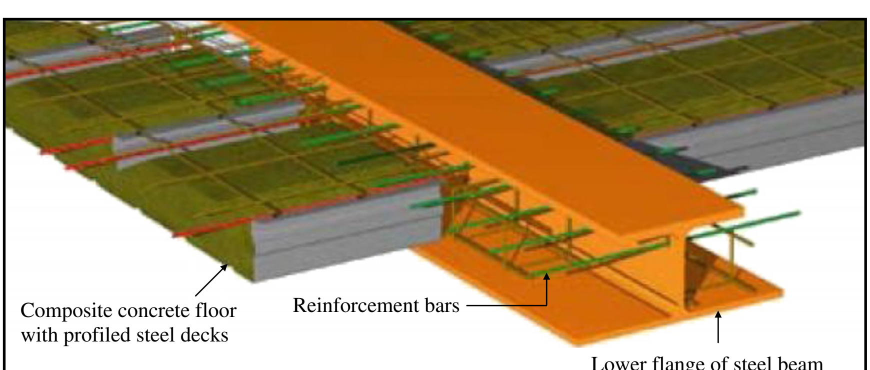

Fig. 1. General layout of unprotected composite slim floor steel beam with profiled steel decks.