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Nonlinear analysis of composite castellated beams with profiled steel sheeting exposed to different fire conditions

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ABSTRACT

This paper discusses the nonlinear analysis and design of unprotected composite castellated and noncastellated steel beams with profiled steel sheeting at elevated temperatures. The nonlinear material properties of steel, concrete, profiled steel sheeting, longitudinal and lateral reinforcement bars as well as shear connection behaviour at ambient and elevated temperatures were considered in the finite element models. The thermal properties at the steel section/profiled steel sheeting and profiled steel sheeting/concrete element interfaces were considered in the thermal heat transfer analysis that allowed the temperatures to be accurately predicted in the composite slab during fire exposure. It has been shown that the finite element models can efficiently predict the thermal and thermal–structural behaviour of the composite beams at elevated temperatures during the heating and cooling phases of fire. Furthermore, the variables that influence the fire resistance and behaviour of the composite beams comprising different load ratios during fire, different fire curves, presence of web openings and different steel grades were investigated in parametric studies. It is shown that the fire resistances of the unprotected simply supported composite castellated and noncastellated steel beams could be below 30 min when heated using the standard fire curve. It is also shown that the strength of steel beam has a considerable effect on the behaviour and failure modes of the composite beams, which could change the failure mode of the composite beams in fire. The fire resistances of the castellated and noncastellated 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 is conservative for most of the unprotected composite castellated and noncastellated steel beams, except for some composite beams heated using the standard fire curve under load ratios of 0.4 and 0.5.

1. Introduction

Extensive experimental and numerical investigations were reported in the literature on structural performance of steel-framed structures with composite slabs under fire conditions. The earlier and pioneer investigations were detailed by Bentley et al. [1,2], Najjar and Burgess [3], Lennon [4], Zhao and Kruppa [5], O'Connor and Martin [6], Bailey et al. [7], Bailey and Moore [8,9], Huang et al. [10], Elghazouli et al. [11], Elghazouli and Izzuddin [12], Huang et al. [13–15], Lamont et al. [16], Wald et al. [17] and by other researchers. The investigations have described the whole building behaviour and structural fire design of steel-framed structures based on real fire conditions as well as full-scale fire tests. Extensive review on fire tests has recently presented by Bisby et al. [18]. The investigations [1–17] have outlined the performance of framed at elevated temperatures and provided useful and detailed experimental and numerical data on how a steel-framed structure behaves in the event of sever fires. However, to date, there is no detailed nonlinear 3-D finite element models reported in the literature simulating the behaviour of unprotected composite castellated steel beams with profiled steel sheeting including shear stud exposed to different fire conditions, leading to the current investigation.

Finite element modelling of isolated fire tests on composite structural members can provide detailed information regarding the failure modes, fire resistances, time–displacement relationships and time–temperature relationships in the composite members, which can compensate the lack of information and fire tests on composite structures at elevated temperatures. Finite element modelling of isolated fire tests can also be used as an introduction to whole building behaviour of steel-framed structures with profiled steel sheeting exposed to fires. However, detailed finite element modelling of composite beams with web openings and profiled steel sheeting under fire conditions was rarely found in the literature owing to the lack of information on how to accurately consider the shear connection behaviour, the contribution of the concrete slab to the local bending caused by the shear forces in the sections above and below the openings, the so-called Vierendeel action, partial shear connection, web buckling and web yielding at the opening regions, nonlinear material behaviour of the

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Table 1
Comparison of test/numerical and finite element analysis results.

Specimen [reference]	Fire curve	Load ratio	Test/numerical[a]		Finite element analysis		$\frac{(Test/numerical)^a}{FE}$
			Fire resistance	Failure mode	Fire resistance	Failure mode	
CSB1 [35,36]	ST	0.36	108.0	BFY	107.8	BFY	1.00
CSB2 [35,36]	ST	0.43	76.0	BFY	79.0	BFY	0.96
CSB1 [35,36]	ST	0.53	68.0	BFY	72.0	BFY	0.94
CB1 [48]	ST	0.39	21.5[a]	TFB + WB + PO	22.3	TFB + WB + PO	0.96
CB2 [48]	ST	0.39	20.0[a]	TFB + WB + PO	18.9	TFB + WB + PO	1.06
AS2 [22]	Exp.	0.26	57.5[b]	BFB + WB + PO	48.8	BFB + WB + PO	1.18
Mean	–	–	–	–	–	–	1.02
COV	–	–	–	–	–	–	0.089

[a] Numerical (SAFIR software) [49].
[b] At the start of overall collapse [22].

composite beam components as well as interaction of moment and shear at the openings at ambient and elevated temperatures. This complicated structural behaviour is addressed by nonlinear finite element analyses presented in the current study.

Limited numerical investigations on the behaviour of composite beams with web openings are found in the literature [1–17]. Benedetti and Mangoni [19] proposed an analytical method to study the behaviour of composite beams with solid reinforced concrete slabs at elevated temperatures based on an extension of the method of Fourier series expansion to the fire analysis of composite beams. Benedetti and Mangoni [19] showed that the behaviour of shear connection under fire conditions at the steel–concrete interface can produce a new type of composite beam collapse, which is 'debonding between steel and concrete'. Abu et al. [20] performed simplified analyses for the whole building behaviour of two full-scale fire tests commonly known as the Fraccof [21] and the Mokrsko [22] fire tests. In modelling the fire test [21], the authors simulated the composite slab as a flat slab with different bending stiffnesses in the two orthogonal directions to account for the contribution of the ribs. The authors noticed the difference between the experimental and numerical results increased after failure. In modelling the fire test [22], the authors simplified the web opening using an effective web thickness approach. The time–temperature curves used in the simulation of the fire test [22] was predicted by choosing an intermediate parametric natural fire curve between a short hot and long cool fire. It was shown that the vertical deflections were relatively accurate up to approximately 44 min. It was also shown that when modelling the end connections of the composite beams as pin-ended connection, failure was predicted at around 43 min. Considerable valuable numerical investigations were reported in the literature on composite beams with cellular steel beams as detailed by Nadjai et al. [23], Vassart [24], Nadjai et al. [25], Naili et al. [26] and Bihina et al. [27]. The studies [23–27] highlighted the performance and design of composite beams with cellular steel beams. The steel beams were modelled using shell elements, the concrete slab was modelled either using beam or solid elements and full shear connection was assumed between the steel beam and concrete slab. Generally, good agreement was achieved between experimental and numerical results in these investigations [23–27]. However, to date, there is no detailed finite element models reported in the literature on composite castellated beams with profiled steel sheeting accounting for the shear connection behaviour at elevated temperatures, which is addressed in this study.

This study uses a consistent 3-D nonlinear approach for analysing different steel–concrete composite structures in fire conditions. The finite element approach modelled the behaviour of post-tensioned concrete slabs in fire [28–31], the behaviour of steel–concrete composite columns in fire [32–34] and the behaviour of unprotected steel–concrete composite beams in fire [35,36]. In these investigations [28–36], uncoupled thermal heat transfer and structural–thermal analyses were performed to determine the temperature distributions within the structural members at elevated temperatures, time–displacement relationships, failure modes and fire resistances. This nonlinear finite element approach was extended in this study to investigate the structural performance of composite castellated and noncastellated steel beams with profiled steel sheeting exposed to different fire conditions. The current study is also augmented with previously reported nonlinear 3-D finite element models investigating the performance of shear connection in composite slabs with profiled steel sheeting [37], behaviour of castellated steel beams [38] and behaviour of cellular steel beams [39] at ambient temperature. Furthermore, the current study followed a recent investigation on composite beams with stiffened and unstiffened web openings together with profiled steel sheeting [40]. In the study [40], the design of composite beams used a robust and efficient design approach for composite beams with profiled steel sheeting. The design approach addressed composite beams having circular/rectangular web

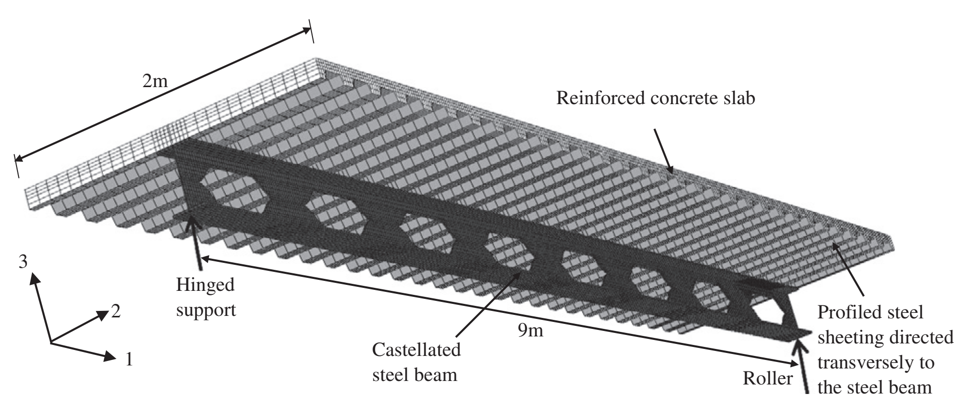

Fig. 1. Finite element mesh and general layout of the composite castellated steel beam used in the fire test and modelled in the study [22].