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NUMERICAL ANALYSIS OF DELTA COMPOSITE BEAMS IN FIRE

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INTRODUCTION

Various shallow floor systems have been developed recently. The most commonly encountered in the industry are the “slim floor” and the “slim deck” systems. Several companies have developed their own systems, such as the DELTA beam composite deck system [1]. The behavior of such flooring systems when exposed to fire is generally satisfactory, because the encasing concrete acts as thermal insulation, even though the lower flange is unprotected. The results of relevant parametric analyses [2], [3] have shown that the fire resistance of such systems is governed by deflection, because they experience bowing resulting from considerable thermal gradients.

In spite of the fact that the fire behavior of slim floor and slim deck systems has been investigated by various researchers [2], [4] to [9], systems proposed by other manufacturing companies, such as the DELTA beam [1], have not been sufficiently studied at elevated temperatures. Despite this, the manufacturing company certifies (based on experimental testing) that all DELTA beam systems have fire resistances ranging from R.120 to R.180. Due to the absence of vital information for evaluating these tests and the fact that the experimental results are influenced by a number of parameters (e.g. actual strength instead of nominal strength) as well as the arrangement of the beams (moreover, it has been stated [10] that composite beams exhibit better behaviour under fire than anticipated, due to membrane action), the author conducted a numerical simulation of such systems exposed to fire. For this purpose, finite element analyses with the commercial program ABAQUS were carried out. The methodology presented in [2], which was successful in simulating such systems, was followed.

The shape and arrangement of DELTA beams [1] are shown in *Fig.1*. Because according to [3] and the equations proposed by [11], the insulation is less effective for “short” cross-sections, this paper analyzes a beam with a D20-200 [1] cross-section (smallest cross-section). For the dimensions not defined by [1], estimates were made and parametric analyses were carried out.

1 GEOMETRY AND MATERIAL PROPERTIES

1.1 Geometry

The cross-sections shown in *Table 1* (an explanation of the symbols of the dimensions is given in *Fig. 2*) were used in the analyses. These correspond to the geometry of a D20-200 cross-section [1] and estimates were made where there was lack of information. The analysis models included an isolated beam which was simply supported, with a span of 6m (the maximum allowable for these cross-sections [1]) and an effective width (per EN1994-1-1 [12]) of 1,60m.

1.2 Thermal Properties

The thermal properties of the structural steel and the reinforcement used in the analyses were according to EN1993-1-2 [13], while those of concrete followed the specifications of EN1992-1-2 [14]. A more detailed presentation regarding their modelling is given in [2].

1.3 Mechanical Properties and Thermal Expansion

The simulated mechanical properties of steel (S355) followed the EN1993-1-2 [13] specification and those of concrete (C25/30) and reinforcement (S500) were selected according to EN1992-1-2 [14]. Their modeling is described in detail elsewhere [2]. The thermal expansion was modeled according to the same specifications (the modeling procedure is also given in [2]).

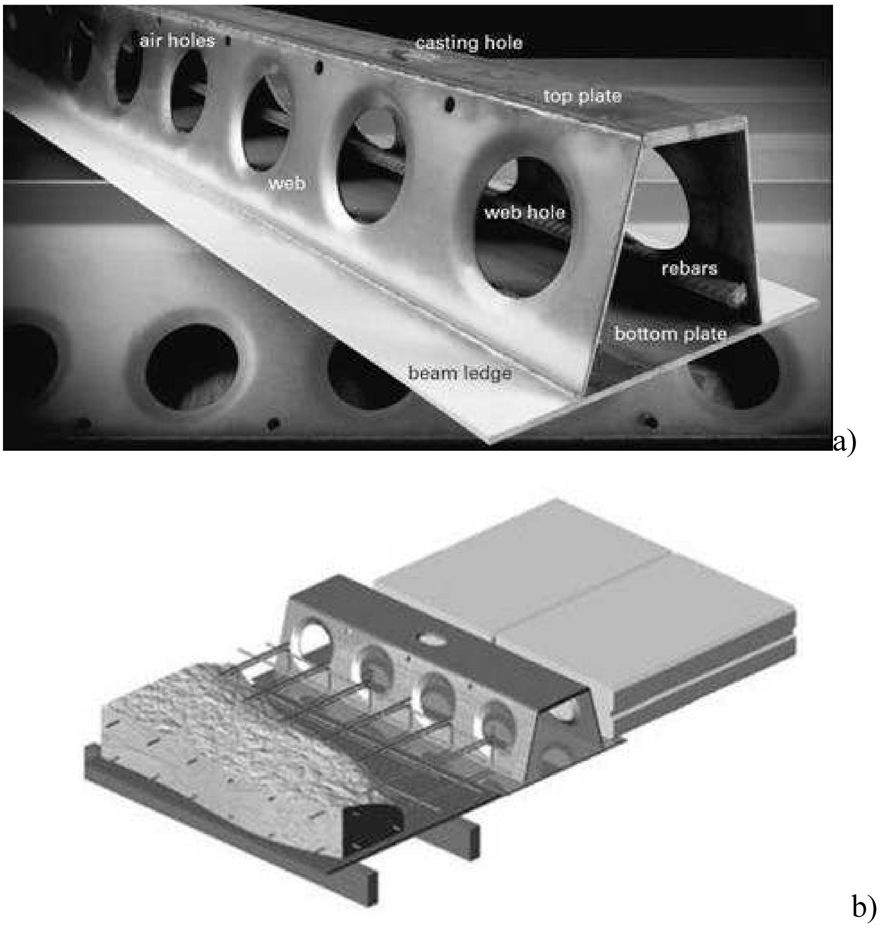

Fig. 1. a) Typical DELTA beam; b) Delta beam with light weight pre-cast concrete element and in-situ casting [1].

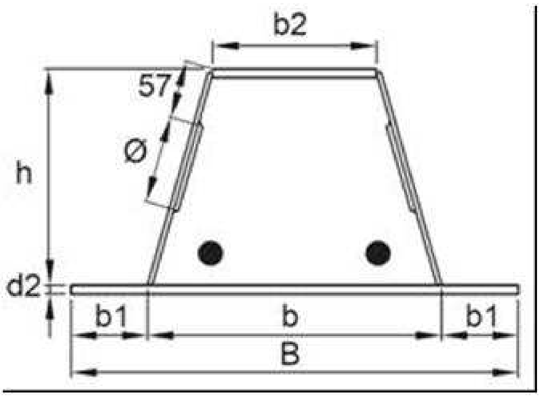

Fig. 2. Dimensions of DELTA beam cross sections [1].

Table 1. Dimensions of DELTA beam cross sections modelled (D20-200) [1].

Cross Section	b (mm)	B (mm)	b1 (mm)	b2 (mm)	d2 (mm)	h (mm)	Ø (mm)	Upper flange thickness (mm)	Web thickness (mm)
1	200	395	97.5	100	5	200	80	5	5
2	200	395	97.5	100	5	200	80	5	10
3	200	395	97.5	100	25	200	80	5	5
4	200	395	97.5	100	25	200	80	5	10

2 NUMERICAL MODELLING

2.1 Finite Element Modelling

For the numerical simulation, the commercial program ABAQUS was used. Due to symmetry, half of the beam was modeled and the appropriate boundary conditions were inputted. A representative finite element model is presented in *Fig. 3*. The type of the finite elements used and the simulation details are the same with those given in [2]. The only difference is that in the models presented here, full interaction between the steel beam and the concrete was taken into account.

Fig. 3. 3D finite element model generated for the coupled thermal-structural analysis of DELTA composite beams.

2.2 Thermal Analysis

The simulated beams were exposed to the standard fire curve [15], [16] from below (lower flange), while on the upper surface convection at ambient temperature conditions (20^{o}C) was assumed. The thermal analysis parameters (convection coefficient, radiation emissivity) are those specified in [2] and comply with the regulations of the Eurocodes [12]. A cross-section of the finite element model, together with the boundary conditions, is shown in *Fig. 4*.

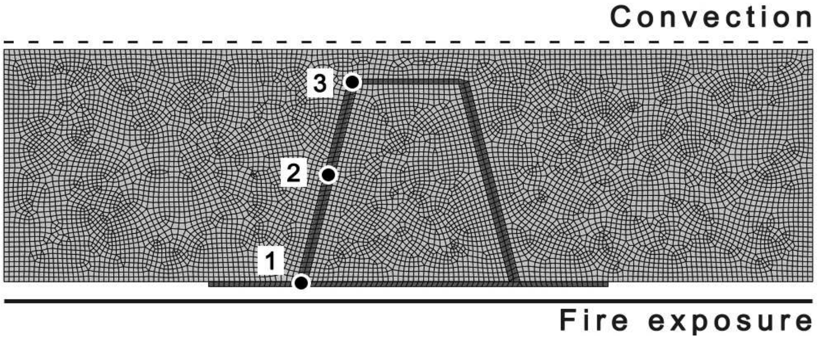

Fig. 4. Finite element model generated for the thermal analysis of DELTA composite beams, including boundary conditions. Temperature evolution is shown for nodes 1 (lower flange) 2 (web mid-height) and 3 (lower flange).

2.3 Structural Analysis

For the structural analysis, a uniform load of 15 kN/m, which corresponds to the maximum load of 30 kN/m for D2-200 beams [1] (half of the cross-section was simulated), was applied at time t=0. The remaining parameters for the static analyses are listed elsewhere [2]. A total of eight analyses (two for each beam) were performed. In four of them, the thermal expansion was neglected for the purpose of investigating its effect on the simulation results.

3 NUMERICAL RESULTS

3.1 Thermal Response

The thermal analysis results showed that the temperature increase at the lower (unprotected) flange is considerable (e.g. temperatures as high as 700^{o}C and 850^{o}C were calculated for 60 min and 90 min of ISO standard fire [15] exposure, respectively). On the contrary, the upper flange, which was well protected, experienced temperatures around 70°C and 120°C for 60 min and 90 min exposure to fire, respectively. Minor variations in the thermal profile, depending on the dimensions of the cross-section (*Table 1*), were observed. The temperature evolution with time is presented in *Fig. 5*. The results show that the beams experience a severe temperature gradient, with temperature differences between the upper and lower flange ranging from 630°C to 800°C (for fire exposures ranging from 60min to 120min respectively).

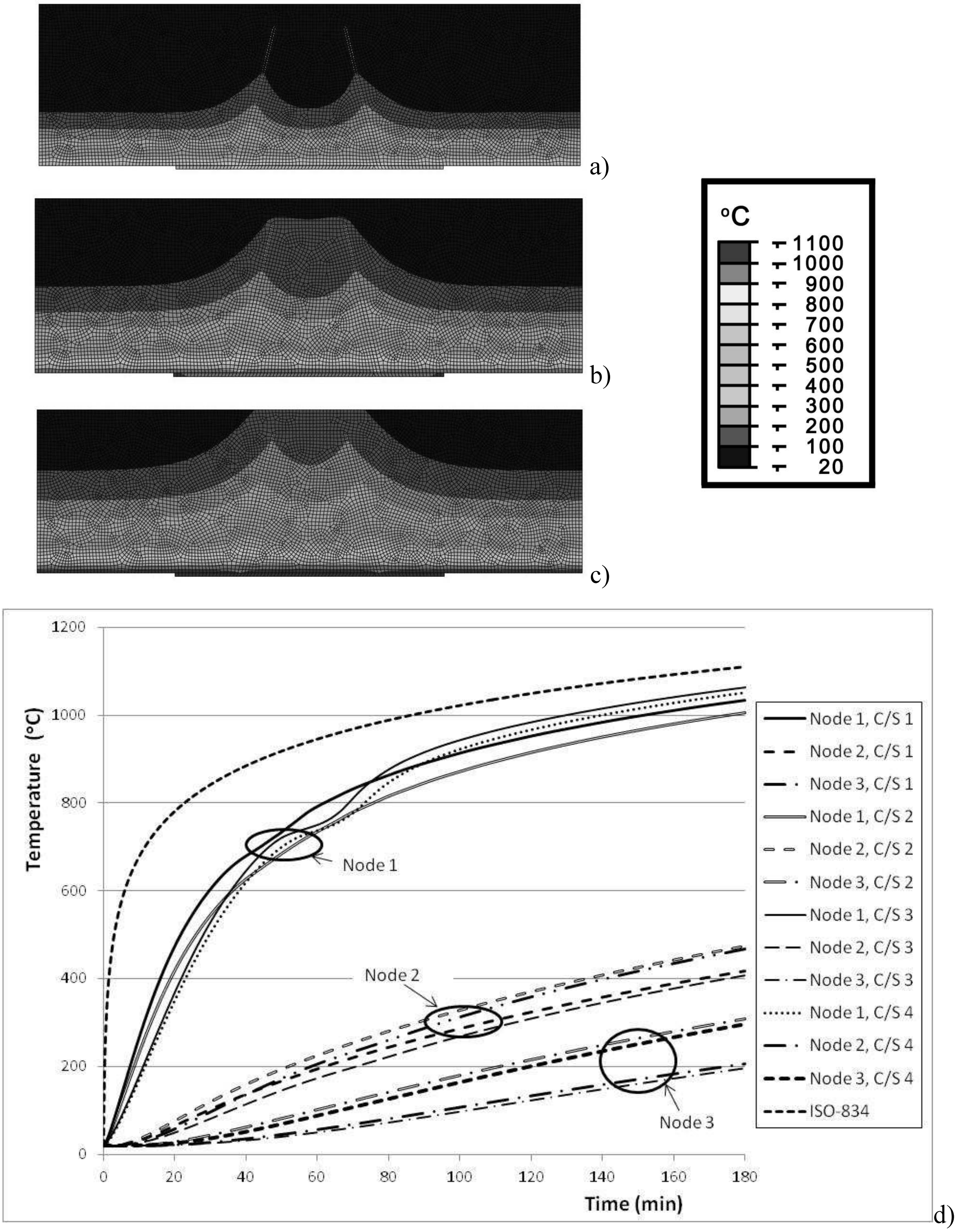

Fig. 5. Thermal response of Cross Section 1 (*Table 1*) exposed to ISO 834 fire [15] for a) 60min, b) 120min and c) 180min and d) temperatures at nodes of *Fig. 3* for the cross sections of *Table 1*.

3.2 Structural Response

The results of the static analyses are presented in *Fig. 6*. From these it is clear that the beams experience severe bowing and their response is controlled by deflections. This is anticipated, because the lower flange expands in a major way due to the significant temperature rise, in contrast to the remainder of the cross-section which experiences low temperatures. Based on the calculated deflections, the fire resistance appears to be approximately 60 min (R60), assuming a deflection limit (which is typical for fire tests according to conventional wisdom) of L/30, where L is the span of the beam. On the contrary, when the thermal expansion is neglected, failure occurs after 150 min of exposure. It is also notable that when thermal expansion is taken into account, beams with thinner flanges fail first. This is to be expected, as increased thickness improves the resistance of the exposed lower flange. However, when thermal expansion is neglected, beams with thicker webs (10mm thickness) exhibit greater fire resistances.

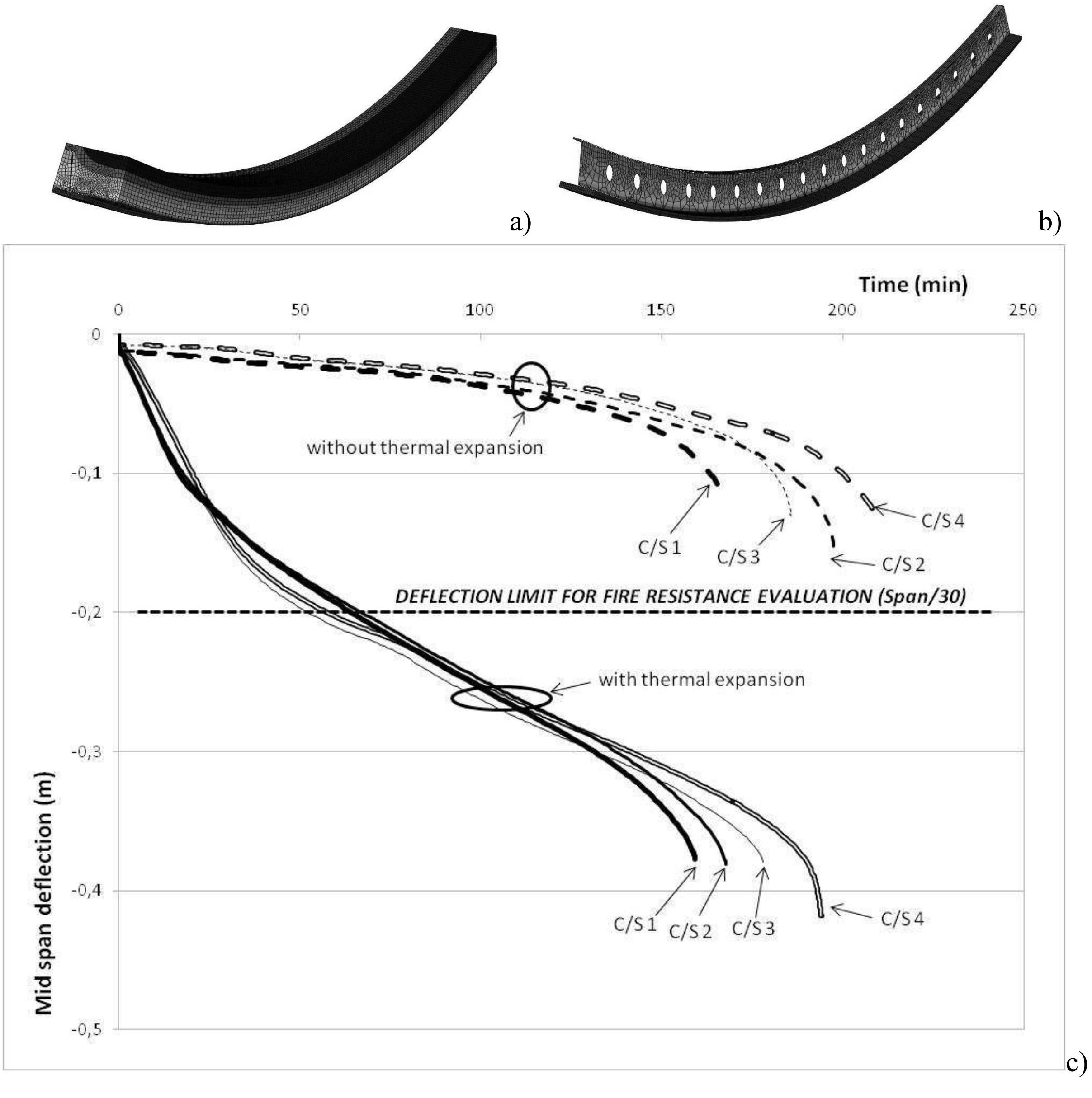

Fig. 6. Structural response of DELTA composite beams exposed to ISO 834 fire [15]. a) Deformed FE model for 120min exposure with temperature contours, b) Deformed shape of the steel part only (FE model) with temperature contours after 120min exposure c) mid-span deflection as a function of the duration of exposure.

4. CONCLUTIONS

Based on an overall evaluation of the analysis results, the following conclusions can be drawn:

- Composite DELTA beams exhibit severe thermal gradients and are subjected to intense bowing when exposed to fire from below.

- The fire resistance of these beams is governed by deflections resulting from thermal gradients and bowing.
- Despite the limited knowledge regarding the conducted fire tests by the manufacturing company, their results seem to overpredict the fire resistance of such beams. However, more information on these tests is necessary to further evaluate the results.
- The fire resistance of these beams is satisfactory and is conservatively estimated to be approximately 60min for standard fire exposure.

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KEYWORDS: DELTA composite beams, fire resistance, thermal bowing, temperature gradient.

ABSTRACT

Composite state-of- the-art decks include shallow floor systems such as the "slim floor" and the "slim deck". One such type of floor, which has been manufactured recently and is of particular interest to the industry, consists of DELTA steel beams partially encased in concrete. Investigating the behaviour of DELTA composite beams under elevated temperatures is crucial in determining their fire resistance and evaluating their overall performance in contemporary construction. Even though the manufacturing company provides fire resistances for DELTA composite beams based on experimental testing, their response to elevated temperature effects remains up to date neither well documented nor clearly understood. This paper presents a detailed numerical simulation of such beams exposed to fire, via the finite element method. Material modelling followed the specifications of the Eurocodes. Eight coupled thermal-structural analyses were carried out in total. The parametric analyses involved four different variations of the "shortest" cross-section specified by the manufacturer. Analysis results showed that such beams experience severe temperature gradients when exposed to fire, because the lower flange remains unprotected, in contrast to the concrete encased part of the cross-section. Deflection governed the failure of the beams in all cases. Results also suggest that simulated beams sustained the applied load for approximately 60min of exposure to the standard fire.

CONCLUSIONS

The behavior of DELTA composite beams [1] exposed to fire was investigated in this paper. Numerical simulations via the finite element method were carried out for variations of a typical cross-section. Modeling followed the methodology for slim floor beams at elevated temperatures described elsewhere [2]. Material properties (thermal and mechanical) were modeled according to regulations of the Eurocodes. Results showed great differences (exceeding 600^oC) in temperatures between the unprotected lower flange and the encased part of the steel beam, which result in a severe temperature gradient. The evolution of midspan deflection for the simulated beams is presented in *Fig. 1.* Based on a deflection limit of span/30, beams failed after approximately 60min of standard fire exposure [3]. Neglecting thermal expansion prolongs (erroneously) the failure time up to 150min. This observation shows that the latter plays an important role in the failure mechanism of such beams.

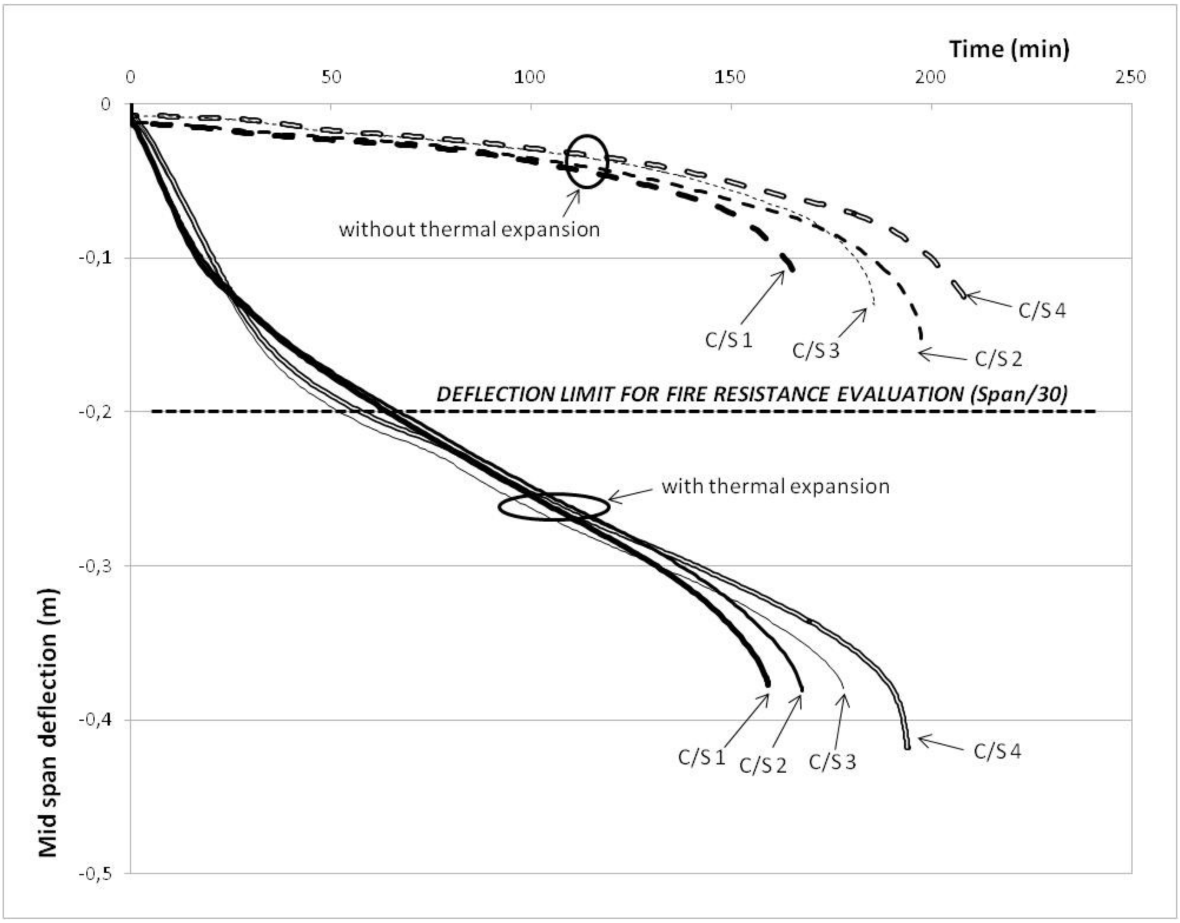

Fig. 1. Mid-span deflection as a function of time for DELTA composite beams exposed to ISO 834 fire [3]

Based on an overall evaluation of the analysis results, the following conclusions can be drawn:

- Composite DELTA beams exhibit severe thermal gradients and are subjected to intense bowing when exposed to fire from below.
- The fire resistance of these beams is governed by deflections resulting from thermal gradients and bowing.
- Despite the limited knowledge regarding the conducted fire tests by the manufacturing company, their results seem to overpredict the fire resistance of such beams. However, more information on these tests is necessary to further evaluate the results.
- The fire resistance of these beams is satisfactory and is conservatively estimated to be approximately 60min for standard fire exposure.

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