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Three-sided heating of I-beams in composite construction exposed to fire

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Abstract

A new and simplified model to analyse the thermal response of steel I-beams in composite construction exposed to the standard fire is presented. The model includes a convection and radiation heat transfer module, a resistance–capacitance formulation for heat conduction in the steel beam and a correlation for estimating heat conduction from the upper flange to the concrete slab. The radiation component accounts for the emission and absorption of radiation by the main combustion products of the standard fire. Heat transfer to the concrete is estimated using computer modelling of a number of case studies. The two dimensional I-beam section is represented by three lumped masses concentrated at nodes located at the centres of the lower flange, web and upper flange and connected by conduction paths. Comparison between measured and computed temperature profiles shows good correlation for most of the case studies investigated.

Keywords: I-beam; Composite structures; Heating; Fire; Heat transfer model; Equivalent emissivity

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1. Introduction

The methods used to predict the temperature response of steel beams and concrete slabs in a composite construction are usually based on tabulated test data [1,2] or finite element and finite difference methods [3]. Both et al. [4] carried out a temperature prediction on partially protected two-span composite slabs exposed to ISO-standard fire using the finite element method. A total of more than 3300 finite elements was used, taking up enormous computing time for a single task. EC4 [1] adopts a simplified approach to steel temperature prediction of a composite beam by using a reduced section factor in terms of the exposed surface area, or part of the area, of the steel beam. This approach, if applied to the whole cross-section as a single element, gives a single average temperature whereas, in reality, a difference of 200 °C could occur between the upper and the lower flanges of the steel beam [5]. This approach ignores the fact that there is heat transfer between the concrete and the upper flange while heat transfer also occurs among the upper flange, the web and the lower flange of the steel beam. Kruppa and Zhao [6] compared the EC4 approach, based on discrete upper flange, web and lower flange elements of the cross-section, with TASEF, a finite element based heat transfer program which is supposedly accurate enough for comparison purposes. The results show that the temperature difference is about 100 °C for a bare steel beam at 25 min and the same for a steel beam protected with 20 mm insulation at 120 min. Given that the maximum temperature is only around 550 °C for the protected steel beam, the difference is quite significant. Wang [7] used the finite element method for heat transfer analysis of a partially protected steel beam in a composite construction.

BS5950 [2] provides tabulated results for the temperature profile of concrete slabs in composite beams according to the fire resistance period required. Lamont et al. [8] used the finite element method to predict the concrete slab's temperature profile; however, the temperature profile of the steel member in the composite beam was not dealt with. Luyckx et al. [9] described a finite element program for heat transfer through steel and concrete materials with detailed theoretical information.

In essence, the models available for the prediction of the temperature profiles of bare steel beams in composite construction range between very simple analytical formulations specified by codes or standards and highly complex simulations requiring finite difference and finite element software packages. The simple analytical formulations usually yield results that deviate significantly from the actual values, whereas finite difference or finite element simulations could be unaffordable, expensive and/or difficult to use for most structural engineers. The present work is an attempt to develop a model that increases the accuracy of existing simple approaches while avoiding the difficulties associated with the use of finite difference or finite element methods. The increased accuracy is due to two major refinements of the simple model. Firstly, the simple model assumes that the fire is separated from the surfaces of the structure by perfectly transparent media, whereas the present model accounts for an important aspect of the combustion environment, namely the effect of the combustion gases on the radiative component of heat transfer to the structural element. Secondly, instead of assuming one lumped mass for the entire steel beam or part of the steel beam without interacting with other parts, the I-beam section is represented by three lumped masses concentrated at nodes located at the centres of the lower flange, web and upper flange and connected by conduction paths. Solution of the model does