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Modeling thermo-mechanical behavior of concrete-filled steel tube columns with solid steel core subjected to fire

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ABSTRACT

Concrete-filled steel tube columns with solid steel core are increasingly used in high-rise building practice due to their high load-bearing capacity and exceptional structural fire behavior. Simulating the structural fire behavior of these innovative composite columns by means of advanced numerical models is a promising tool to achieve an enhanced understanding of the basic thermo-mechanical behavior observed in costly full-scale fire tests, and eventually, to partially replace them. Moreover, the data necessary for the development of a simplified fire design method can be compiled from a parametric study with such models. This paper presents an advanced nonlinear Finite-Element-Method model that incorporates complex experimental calibration data and therefore can robustly simulate various full-scale fire tests of this type of composite columns. Furthermore, tracking in the model the load share redistribution processes between the different components, confirms the innovative design concept of the structural fire behavior of this type of composite column. Finally, a simplified model version that qualifies for partial replacement of full-scale fire tests or use in both a parametric study and advanced structural design is presented and conditionally validated.

1. Introduction

Concrete-filled steel tube columns with solid steel core are innovative composite columns that exhibit a high load-bearing capacity and an exceptional structural fire behavior. In high-rise building practice, these features allow relatively slender design solutions under high load levels and fire resistance requirements. Besides their structural advantages, they are also appealing architecturally and economically: High fire ratings can be achieved without the use of fire protection material, which increases the floor space in high-rise buildings and eliminates an in-situ work step in comparison to conventional fire-protected steel columns or reinforced concrete columns. Their cross-sections consist of an outer steel tube, a concentrically placed round solid steel core and concrete-infill in between (Fig. 1e). Conceptually, their single structural fire behavior stems from the specific design of composite action between the different structural components: With the ongoing temperature-induced degradation of the outer components in the case of fire, the load shares that are initially carried by the steel tube and the concrete are gradually redistributed on the steel core that becomes the crucial structural component and assures eventually the stability and strength of the entire composite column. On the other hand, the thermally robust insulating properties of the concrete infill (reliably prevented from spalling by the steel tube) lag behind the temperature increase of the steel core, which promotes the achievement of high fire resistances. However, as a result of the high load-bearing capacity of these composite columns also during fire, experimental investigation of their structural fire behavior is substantially limited by the capacity of common test facilities and cost. Therefore, advanced numerical models that are capable of simulating their structural fire behavior, are appealing tools to partially replace costly full-scale fire tests or to extend sparse experimental databases and make them usable for the development of simplified fire design models.

The structural fire behavior of ordinary concrete-filled steel tube columns, without core however, has been studied extensively in the past decade using Finite-Element Method (FEM) models of different degree of complexity [1–6]. Thereby, the validation of the suitability of the method and of the particular numerical models was facilitated by a substantial experimental database of full-scale fire tests [7–13] that has been complemented since [14–17]. Further research in this field, lead most recently to the proposition of a simplified fire design method for ordinary concrete-filled steel tube columns [18], which was derived from

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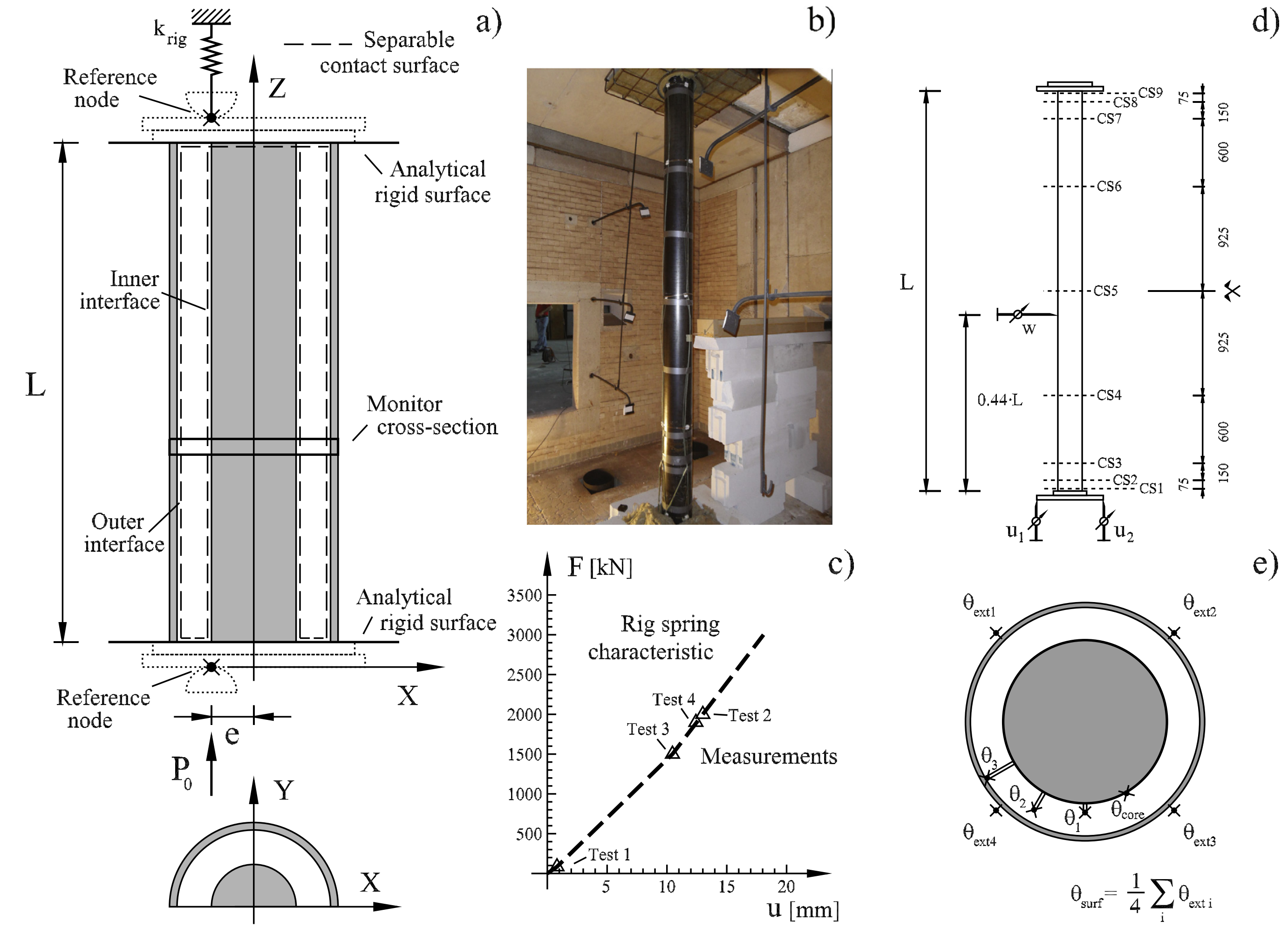

Fig. 1. Overview of model features and illustration of the test setup.

a numerical database that was compiled with a FEM beam fiber-model [19]. This research gives promising prospects of eventually adopting such general numerical investigation methods also in the case of concrete-filled steel tube columns with solid steel core. However, in the first place, the basic characteristics of their single structural fire behavior must be studied apart, because of the higher complexity of their cross-sectional typology that allows more complicated load redistributions, when the stiffness and strength of the materials exhibit temperature-induced degradation. To date, only Hanswille et al. presented a three-dimensional FEM model for the load-carrying behavior at ambient temperature and validated the model against ultimate load tests with different load eccentricities [20]. Beyond that, the structural fire behavior of these innovative composite columns has not been studied numerically with advanced three-dimensional FEM models that consider experiment-based temperature-dependent constitutive relations for the materials or have been validated with full-scale fire tests. Furthermore, there is only one single thermo-mechanical test with a concrete-filled steel tube column with solid steel core available in the literature [21], in which a pre-loaded specimen was exposed to ISO-fire for 108 min and then loaded until failure with the furnace switched off.

Therefore, within the framework of a combined experimental and numerical research project on the basic structural fire behavior of concrete-filled steel tube columns with solid steel core, a series of ISO fire tests was performed [22]. The objective of this test series was to provide a primary experimental database, which could be used furthermore in the numerical part of the research project, to assess the suitability of numerical simulation tools such as advanced three-dimensional FEM models, for predicting the structural fire behavior and therefore eventually replacing (partially) full-scale fire tests of this type of composite column. However, the predictive capacity of such simulation tools is strongly affected by the accuracy of the temperature-dependent constitutive input data for the material models. For this reason, the experimental part of the research project included also an extensive test program to establish the elevated-temperature material properties of the steel tubes, the steel cores and the concrete infill that were used in the full-scale column specimens.

This paper presents the results of the numerical study that was undertaken within this combined experimental and numerical research project on the basic structural fire behavior of concrete-filled steel tube columns with solid steel core. The primary objective of the numerical study was to develop an advanced three-dimensional FEM model that can reasonably reproduce the recorded deformation time-histories of the fire tests until failure, and in which as many potential sources of uncertainty as possible are eliminated by using suitable experimental calibration data. This best-calibrated and validated model allows taking full advantage of the potential of advanced numerical simulations which (1) enhance the understanding of the experimental test data, and (2) validate the design concept of the structural fire behavior of this type of composite column, by studying with the model the load-share time-histories of the different components (steel tube,