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Full-scale fire testing and numerical modelling of the transient thermo-mechanical behaviour of steel-stud gypsum board partition walls

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HIGHLIGHTS

- Full-scale fire testing was performed on 3 m × 3 m steel-studs gypsum-faced partition walls according to the Eurocodes.
- Experimental data related to the transient thermal and mechanical behaviour during exposure to fires were collected.
- The transient thermal gradients and thermal bowing characteristics were recorded throughout the duration of the fire.
- Good numerical prediction of the thermo-mechanical behaviour of the partition walls during fires.
- A new methodology for carrying out the thermo-mechanical simulation and prediction of fire behaviour is proposed.

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ABSTRACT

In this paper, the authors present experimental observations and results of full scale standard fire tests as well as thermo-mechanical sequentially coupled finite element simulations on partition walls. A procedure for carrying out numerical simulation of the coupled-thermo-mechanical behaviour is proposed. The numerical models presented for predicting behaviour during fires were calibrated and verified by full scale fire testing. The test wall was constructed using steel C-section studs with gypsum boards fixed on both sides. The wall cavity was filled with Rockwool insulation. The partition wall was tested during exposure to the standard fire test. The thermo-mechanical behaviour of the wall was found to be heavily coupled and influenced by the physical and chemical changes in all constituents of the wall during exposure to fire.

The sequentially coupled mechanical response simulation included geometric and material non-linearity as a function of temperature. In spite of the complexity of the fire effects and the strongly coupled thermo- mechanical behaviour, the results of the computational model practically agree with the full scale experimental results. The numerical prediction of the maximum thermal bowing of the wall was found to be very similar to the maximum values measured during the fire test. This has practical implications for assessing the integrity such wall assemblies during exposure to elevated temperatures. The proposed procedure can be used by fire structural engineers and fire testing laboratories as a tool to assist technical assessment exercises. In addition, the proposed procedure can be used during the developmental and modification stages of building components to optimise performance during fire.

1. Introduction

During the last two decades, the discipline of structural fire engineering has significantly developed adopting a new philosophy of performance-based and risk-based design. Fire resistance rating of building components is based on standard fire testing to determine the duration of exposure to fire until a failure criterion is reached. The integrity and insulation criteria for fire resistance are indeed as important for safety, if not more so, as the load-bearing criterion. How a structure behaves in a given fire scenario can be investigated using numerical models capable of coupling the thermal behaviour with the mechanical behaviour.

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The numerical thermal model determines the transient thermal profile in the system during exposure to a design fire scenario. The transient thermal profile is then coupled to the mechanical model to predict the transient mechanical behaviour during fire exposure. Such numerical simulations are made complex due to the non-linearity of material properties at elevated temperatures as well as changes in the geometry as a result of the thermal deformations. In addition, the changes in the boundary conditions and the degree of composite action between the constituents of the wall at elevated temperatures significantly influence the thermo-mechanical behaviour and the fire resistance rating of such systems. A number of studies related to the thermal response of such partition walls systems were conducted. However, the mechanical response during fires was not sufficiently investigated for a typical wall height of 3 m.

Fire structural engineering is concerned with the total problem of initiation and spread of fire, the heat transfer to the structure as well as the structural system response to the fire. A number of researchers and organisations across the world have been investigating these issues with added urgency since the attacks on the World Trade Centre in 2001 which resulted in a fire design failure [26]. There are three fire resistance criteria for fire design, namely: integrity, insulation and load-bearing. The integrity failure which results in flame and/or smoke leakage from the fire compartment can result in significant loss of life as was exemplified by a fire in a residential block of flats in London [1].

Light non-load-bearing partition wall systems used in residential and commercial properties are required to provide a certified insulation and integrity fire resistance rating. In Europe, certification for fire resistance rating involves subjecting such walls to a standard fire according to the standard fire curve ISO834 as given in BS EN1991-1-2. Fire testing requirements for structural assemblies is mandatory in many countries for certification and fire classification purposes. BS EN 1363-1 [2] provides an outline of the fire resistance requirements and definition of fire resistance criteria. For non-load-bearing partition walls, the fire rating is determined as the duration of exposure to the standard fire until either the integrity or the insulation criterion is reached. Product manufacturers must obtain such certification before they market their systems. The certification process is quite costly and could involve repeated attempts to achieve the required fire rating with additional cost and loss of time. Accredited fire testing facilities are very limited, one or two per country. Therefore it is of huge value to develop numerical tools to be used during products development and modification in preparation for full-scale fire certification testing. Such tools can be used to predict the coupled thermo-mechanical behaviour of such systems. In addition, the performance-based and risk-based structural fire engineering design philosophy can also be made more reliable by using such numerical simulation tools and procedures.

Alfawakhiri et al. [3] provided a detailed review of the fire resistance aspects of load-bearing steel-studs walls protected by gypsum boards. The need to adopt a performance based fire engineering design was highlighted. The prescriptive design based on costly time consuming certification obtained by full-scale standard fire testing was highlighted as limiting. The criticism related to the narrow application of the standard fire testing was explored. The one-dimensional thermal model reported by Sultan [4] at the Institute for Research in Construction (IRC), National Research Council of Canada, was promising in the attempt to predict the thermal profile of such walls. Alfawakhiri et al. [3] highlighted the dearth in experimental data from full-scale fire testing which hindered the verification and calibration of numerical models. It was recommended that full-scale fire testing of such assemblies should include detailed measurements of both the thermal and the structural behaviour. The authors of this paper aimed to obtain and present qualitative and quantitative experimental data obtained from full scale fire testing on such assemblies. Sultan and Kodur [5] reported an experimental investigation involving lightweight partition walls constructed using either wood studs or steel studs. A number of important parameters related to such assemblies were experimentally investigated. One important conclusion was related to the effect of the presence and manner of installing insulation within the cavity of non-load bearing walls on the measured fire resistance of such assembly.

The thermal behaviour of gypsum-faced steel-stud panels were investigated by Feng et al. [6]. The panels were square 300×300 mm in size representing a small section of a steel-stud gypsum-faced wall. The results of eight fire tests were used to calibrate and verify a numerical model for thermal analysis. The predicted temperatures and calculated temperatures seemed to provide reasonable agreement in some locations but also significant differences at others. It is noteworthy that the research effort presented by Feng et al. [6] focused only on the thermal behaviour issues. Feng and Wang [7] carried out experimental study on thin-walled structural panels. The panels were of 2.2×2 m and loaded by a fraction of the ultimate load at ambient temperature. The thermal behaviour was established and the failure mode was noted. Failure as expected occurred as global buckling around the major axis of the stud C-sections. Local buckling in the C-section web was also observed around service opening in the studs. The effect of the stud-thickness on the fire resistance was investigated. It appears that studs with thickness less than 1.2 mm thick, had poor fire performance. The experimental data collected for panels 2.2×2 m regarding the thermal behaviour together with the thermal bowing behaviour were presented.

Feng and Wang [8] presented analysis calculations for the axially loaded 2.2×2 m panels which were tested under transient fire conditions and reported in their paper [7]. The analysis focused on comparison with the calculations presented by the ENV 1993 code of practice for designing steel buildings in Europe at that time. The effect of shifting of the neutral axis of steel sections during fire situations was investigated. Their work included mid-height deflection measurements during the fire test of the 2 m high panels. The estimated pure thermal bowing was compared to the measured thermal bowing taking into consideration the additional thermal bowing due to axial compression. In this paper, the authors reports significant experimental direct measurements of the pure thermal bowing of typical 3 m high light non-load bearing partition walls. A simplified numerical procedure is presented to conservatively predict the pure thermal bowing of partition walls during fire scenarios.

Mahendran and Ranawaka [9] investigated the distortional buckling behaviour of cold-formed steel columns subjected to high temperatures up to 800 °C. The investigation involved both experimental data as well as numerical simulation. The mechanical properties of the steel C-sections were determined at steady state elevated temperatures in the range 100–800 °C. Their paper included establishing relationship between temperatures and reduction of the mechanical properties, both yield stress and Young's modulus. The investigation involved short steel studs 190×290 mm. The studs were heated and the failure load as well as the axial shortening was determined at various temperatures. Finite element modelling of the studs' behaviour was carried out adopting shell elements S4 in ABAQUS solver software. The distortional buckling behaviour of the cold-formed light gauge steel columns was determined and the results informed the local code of practice in Australia.

Chen and Young [10] established the mechanical properties for cold-formed steel at elevated temperatures both the steady state and the transient behaviour. They introduced formulation for the mechanical properties of cold formed steel material constitutive