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Sensitivity of composite floor system response at elevated temperatures to structural features

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ABSTRACT

The sensitivity of composite floor system response at elevated temperatures to variations in structural features is examined in a sensitivity study based on a 2^4 factorial design. Four structural features were varied between two values, based on the NIST investigation of the WTC 7 collapse. The effects of the four parameters, as well as their interaction effects, are evaluated relative to time to onset of damage and time to failure for the structural features.

Structural features that affected the response were ranked according to their influence. Of the four structural features varied in the analyses, floor beam length and connection type most influenced the structural response of the floor system, sometimes changing the time to damage onset or failure by more than 0.5 h. The presence or absence of girder studs and one- or two-sided girder framing influenced the structural response to a lesser extent. Interaction effects were apparent in the structural response, indicating that the structural features cannot be evaluated independently when considering the response of a composite floor system to fire effects.

The findings suggest that a broader view of the impact of heating and cooling phases of fire types (standard fires, compartment fires, and traveling fires) that are used for evaluating the performance of composite floor systems needs to be considered, particularly with regards to floor lengths, connection types, and restraint of thermal expansion.

1. Introduction

Studies of fire effects on composite floor systems have been conducted for the last 20 years. The first full scale fire tests were a series of compartment fire tests on an 8-story steel framed structure with composite floors that were conducted in 1995 and 1996 at the British Research Establishment Large Building Test Facility in Cardington, Bedfordshire, by British Steel [5] and other research partners. The Cardington test facility had 8 stories and 5 bays of 9 m beam lengths by 8 bays of 6 m beam lengths. The floor connections were either fin connections or flexible end plates bolted to the column flange. The Cardington fire tests protected beam-to-column connections except for one test where a column was also unprotected and locally buckled near the ceiling. During the heating phase, both fin and endplate connections performed adequately, but during the cooling phase bolts sheared in the fin connection and some end plate connections fractured. Cooling failures were due to the tensile strains that developed as plastic deformations, such as flange buckling, cooled in the deformed state.

The World Trade Center disaster in 2001 further demonstrated the need for better understanding of how steel framed structures and composite floor systems behave in real fire conditions. The performance of the WTC 7 building, in particular, provided an opportunity to examine the behavior of modern construction in an uncontrolled, severe fire environment. The fire-affected floors were not compartmented, so that flashover was never reached as the fires traveled from combustible to combustible. Such fires are often referred to as traveling fires [8]. The WTC 7 floor plan was not symmetric, and had floor beam lengths that ranged from 3 m to 17 m. The NIST investigation of the World Trade Center Building 7 (WTC 7) collapse identified structural features that played a role in the building response to uncontrolled, structurally significant fires [13]. The NIST report stated that:

> “Of particular concern are the effects of thermal expansion in buildings with one or more of the following features: (1) long-span floor systems which experience significant thermal expansion and sagging effects, (2) connection designs (especially shear connections) that cannot accommodate thermal effects, (3) floor framing that induces asymmetric thermally-induced (i.e., net lateral) forces on girders, (4) shear studs that could fail due to differential thermal expansion in composite floor systems, and (5) lack of shear studs on girders.”

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Other fire tests were conducted to further study the performance of composite floors as a system, with the goal of examining tensile membrane action in a partially insulated composite floor system during fire exposure. In 2008, a fire test was conducted in a furnace at Metz, France, as part of the FRACOF design concept [23]. The floor system had insulated 6.7 m girders, uninsulated 8.7 m floor beams, and flexible end plate and double angle connections. The composite floor was exposed to an ISO standard fire for 2 h and then allowed to cool. A similar test on a composite floor with 6.7 m floor beams and 3.2 m and 5.2 m girders was conducted in 2009 at the same furnace facility as part of the European research project COSSFIRE [22]. Other full scale tests have also been conducted in purpose built compartments or small buildings with composite floor systems that vary the degree of fire protection and the possibility of tensile membrane action when the steel beams are heated, such as the Mokrsko fire tests in Prague in 2008 [18], Dachau tests in Germany in 2010, and the Belfast tests in the United Kingdom in 2010. The buildings survived fire exposures that provided peak gas temperatures of approximately 1000 °C, except for the Mokrsko test in which the building unexpectedly collapsed. Wellman et al. [20] evaluated a composite floor system subject to fire effects that was tested with two different shear connections (shear tab and double angle), two fire scenarios (standard heating with different cooling rates), and two fire protection scenarios (with and without). The five connection types responded differently to the fire effects and tensile loading conditions, with failure modes that include web fracture, weld fracture, and bolt thread stripping.

Wang et al. [19] conducted ten fire tests on restrained steel beams, 2 m in length, subject to two point loads and a standard fire exposure. The tests investigated the relative behavior of the beam for two levels of axial restraint provided by columns and five connection types: fin plate, web cleat, flush endplate, flexible endplate, and extended endplate connections. As the steel framing heated, axial compressive forces developed until the steel beam began to deflect rapidly and tensile loads were applied to the connections. The temperatures in the beam lower flanges reached 700–750 °C. Some lower flange or web buckling was reported, but it appears to be a combination of greatly reduced material properties and contact with the column section. The reported connection failures all occurred for a tensile load state within the connection, with varying degrees of rotation depending on the column size and connection type. Failure modes under the elevated temperatures and tensile loads included web fracture, weld fracture, and bolt thread stripping.

Analyses of steel framing, floor connections, and shear studs have also been conducted to further understanding of their performance in fire conditions. Parametric studies of single plate shear (fin) connections [21,17,9] and double angle connections [14] identified critical dimensions and component interactions that control connection behavior at elevated temperatures. There is a little data for shear stud connections at elevated temperatures. Huang et al. [10] evaluated the role of shear stud connections by comparing models with varying levels of composite action against test data from the Cardington fire tests of composite beams.

The fire tests conducted at Cardington, and for the FRACOF and COSSFIRE programs showed that composite floors with beam lengths less than 9 m did not experience failures during the heating phase, but connection failures are more likely to occur during the cooling phase if significant deformation occurred in the floor beams during heating. The study by Wang et al. [19] found that connection types and axial restraint of a beam affect the response of floor systems, primarily during the cooling phase. In contrast, the WTC 7 composite floors experienced shear stud and connection failures during the heating phase at locations with floor beams of 15–17 m length. Analyses of fire tests and fire effects identify failure modes for the specific composite floor construction and framing components, but the relative contribution of the components to the system behavior and failure modes is not clear. The analyses in this paper were undertaken in an attempt to determine the relative role of each of the structural features listed above (beam length, connection type, shear studs, and asymmetric framing) in the overall response of the composite floor system to fire conditions during the heating phase. A factorial design approach [4] was used to conduct a sensitivity study to evaluate main and interaction effects of the input parameters (structural features) on the system response.

1.1. Composite floor models

The sensitivity studies were based on results of analyses conducted with ANSYS [3] that accounted for temperature-dependent material property degradation and component failure mechanisms. Failure criteria were developed to identify when a structural component was no longer contributing to the strength or stiffness of the structural system. Failed components were removed to prevent extreme impedance of analysis convergence, which are described in the next section.

The basic structural features of the analysis models are illustrated in Fig. 1. Floor beams span between the girder and exterior columns. The girder spans between interior and exterior columns, and is laterally restrained by floor beams framing into the girder on one side. Springs indicate where floor beams were included in some of the analyses to simulate lateral restraint of the girder by floor beams on both sides. The beam–girder connection occurs at the end of each floor beam. Beam–girder connection types were varied between a single shear plate (fin) connection with bolts in single shear and a double angle connection (*K*) with bolts in double shear. The beam-to-exterior column connection and the girder-to-column connections were seated connections with two top and two bottom construction bolts. Further connection modeling details are provided in McAllister et al. [12].

Fig. 2 illustrates the models used in the study. The skew framing of the northeast corner of the WTC 7 floor model was modified to orthogonal framing, which is typical for most buildings. Two beam lengths, 5 m (17 ft) and 15 m (50 ft), were selected to represent a range of typical compartment sizes and the longer spans that can be found in high-rise buildings. The steel framing for a single bay included columns extending above and below the floor framing to the next floor level (the columns in Fig. 2 are truncated in the graphics). Beam and girder member sizes for the 5 m (17 ft) floor beams were modified for the design gravity loads and are listed in Table 1. Beam188 elements which support temperature-dependent, nonlinear material models and linear temperature gradients across the flanges and beam depth and include shear deformation and warping of cross sections were used for floor beams, girders and columns. Beam element lengths ranged from 0.3 to 0.9 m in length.

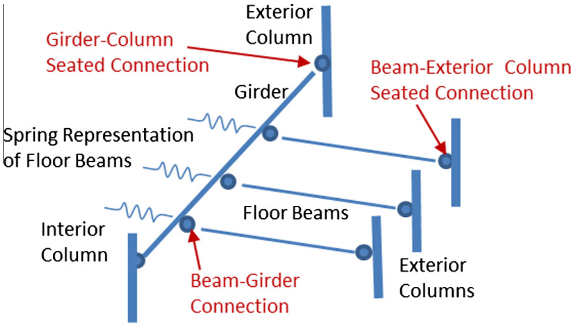

Fig. 1. Schematic drawing of model components.