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Fire behavior of composite beams with simple connections: Benchmarking of numerical models

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ABSTRACT

This paper focuses on the development and benchmarking of 3D finite element models for predicting the behavior and failure of composite beams with simple (shear) connections subjected to gravity loads and fire conditions, which include both heating and cooling phases. The simple connections included are the shear-tab, single-angle, and double-angle connections commonly used in the U.S. engineering practice. All the structural components including the steel beam, concrete slab, shear connectors, and connection elements (bolts, plates, angles etc.) were modeled in detail using appropriate finite elements, contact interaction models, and material and component behavior at elevated temperature. The detailed finite element models were benchmarked using results from large-scale tests of composite beams and connections subjected to fire loading including heating and cooling phases. The numerical results including the midspan displacement histories and the connection rotation histories were compared with those measured experimentally by the authors. These comparisons indicate that the detailed models reasonably predict the experimental deformation histories and observed failure modes. The models were used to provide additional insight into the axial forces developed in the connections, particularly during the cooling phase, thus enhancing experimental findings. The benchmarked model is recommended for conducting analytical parametric studies to supplement experimental investigations of composite beams and simple connections under fire.

1. Introduction and motivation

Numerical models and simulations are valuable in research, particularly when the corresponding large-scale tests are complex, expensive, and time consuming. Structural behavior under realistic fire loading (including loading, heating, and cooling phases) can be complex, and therefore difficult to replicate and observe experimentally. Numerous connection fire tests have been performed in the U.S. and around the world. The fire tests performed at Cardington in the UK [1] showed shear-tab connection failure due to large axial forces induced in the connection. Yu et al. [2] performed fire tests on shear-tab (fin-plate) connections at elevated temperatures. In these tests, a combination of shear and axial (tying) forces was applied to the connections and remained constant throughout the experiment. The test parameters included the number and grade of bolts. Isolated shear-tab connections were also tested by Hu and Englehardt [3]. These tests evaluated the effects of connection geometry and the grade of bolts on the bolt shear failure mode at elevated temperatures. These isolated connection tests provide insight into the behavior of shear-tab connections at elevated temperatures, but they do not focus on beam-to-column connections that are influenced by the geometry of the composite beam and concrete slab, and by the effects of restraint to deformations during the heating and cooling phases of the fire.

Previous researchers have used numerical models and tools to investigate the behavior of steel structures including composite floor systems and simple connections subjected to fire loading. These models have produced observations and results that warrant verification through experimental testing. The modeling techniques used by researchers in the UK [4–6] to simulate the behavior of simple connections in fire have provided the basis for modeling composite floor systems in fire by researchers in the U.S. [7–10]. However, there are few numerical investigations that include both the simple connection and the composite slab behavior. For example, the numerical investigations performed by Agarwal et al. [7,8] and Selamet and Garlock [9] on U.S. specific steel construction [11] have focused on the effects of fire loading on the behavior of simple connections, and thereby the overall structural system. These numerical investigations involved simplifications and idealizations. For example, Agarwal et al. [7,8] utilized component based macro models for the connections, and limited failure modes to bolt shear failure and plate bearing. Shear-tab fracture was not included explicitly in the models. Selamet and Garlock [9,10] utilized 3D finite element models to simulate connection behavior, but did not include the concrete slab, which is an integral part of steel buildings, and can

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improve the negative moment capacity of the composite beam system at the connections as discussed in [7,8]. All these researchers [7–10] indicate that shear-tab connections can fail during the cooling phase of the fire; however, single-angle and double-angle connections may perform adequately.

The authors [12–14] have conducted experimental investigations to verify these findings for U.S. specific steel construction [11]. A series of composite beams with simple connections to steel columns were tested by subjecting them to combined thermal and mechanical loading. The tests included loading, heating, and cooling phases, and provided valuable data regarding the structural fire behavior of composite beams with simple connections. Due to the limitations of the testing setup and available instrumentation, only the temperature histories, displacement histories, and connection rotation histories could be measured at specific points on the specimens during the tests. This paper presents the development and benchmarking of comprehensive 3D finite element models for predicting the behavior of the composite beams and simple connections tested by the authors [12–14]. These models are then used to supplement the experimental results, and gain additional insight into structural behavior and performance of the different types of simple connections tested. The benchmarked models will be used to conduct analytical parametric studies, and supplement the experimental database in a future paper.

The development and benchmarking presented in this paper focus on the tests conducted by the authors because they had access to comprehensive information regarding the testing conditions (loading and boundary), test setup, and specimen material and geometric properties, along with the observations and measurements from the experimental investigations. Additionally, the experimental investigations were quite diverse with different simple connection types, loading protocols and heating conditions, and observed failure modes. The intent for the benchmarked models presented in this paper is to expand the experimental database and conduct analytical parametric studies to evaluate the influence of additional geometric and material parameters that could not be considered experimentally due to practical and economic considerations. The results from the experimental and analytical parametric studies will be used eventually to develop structural performance based design guidelines or recommendations.

The outline of the paper is as follows: The following section presents additional background leading up to the experimental and numerical investigations of the fire behavior of composite beams and simple connections. This is followed by discussion of the general details of the 3D finite element models including modeling techniques for the steel beams, concrete slabs, shear studs, and the components of the connections. The steel and concrete material properties are also discussed in detail, where the NIST developed σ–ε–T (stress–strain–temperature) [15] model is utilized for the steel components. The paper presents detailed comparisons of the numerical and experimental results for each test, and additional results and behavioral insight generated by the numerical models to supplement the experimental findings. Conclusions from the experimental and numerical results are presented along with recommendations for numerical modeling of experimental behavior.

2. Background

Agarwal et al. [7,8] investigated collapse mechanisms of steel-frame buildings designed in accordance with US standards and codes [11] and subjected to realistic fires. Detailed FEM models were developed of the multi-story 3D building structures using temperature dependent thermal and mechanical material properties. These models accounted for large deformation theory and the various complexities of structural behavior including inelastic buckling of steel columns, yielding of steel beams, yielding of the metal deck and welded wire fabric shrinkage reinforcement in the slab, tensile cracking and compression inelasticity of the concrete slab, and partial composite action between the steel beam and concrete slab. The beam-end connections for the gravity floor systems were modeled as a series of springs that captured bolt shear and bolt bearing failure modes. These component models for connections were originally developed in the UK by researchers from the Univ. of Sheffield [2,16], and adapted for U.S. connections by Agarwal et al. [7,8]. The analytical investigations examined the collapse mechanisms of 3D steel-framed buildings with respect to fire location, fire intensity, and proximity of a fire to critical members in the building.

The analytical results indicated that large negative moments develop in simple connections during the fire due to expansion and rotation deformations induced in the floor systems. These connections were designed according to the U.S. building code [11] to resist only the vertical loads from gravity systems at ambient conditions. The results of the parametric study performed by Agarwal et al. [7,8] showed that bolt shear was a common failure mode of shear-tab connections during a fire. In each of the fires, the rotation of the beam-ends caused the bottom flange of the composite beams to come in contact with the gravity columns. This behavior caused large compressive forces in the bottom flange of the steel beams and large tensile forces in the bolts of the connections. In many cases, yielding of the composite beam bottom flange and the column flanges of the gravity frames was also observed.

Selamet and Garlock [9] performed analytical studies to investigate the behavior of shear-tab and all-bolted simple connections during a fire event. This investigation resulted in suggested modifications to typical connections used in steel buildings to improve their fire performance. One of the suggested modifications was a larger gap between the beam-end and the connected member. This would allow for more beam-end rotation during a fire without developing contact between the bottom flange and the connected member. Delaying the contact would reduce the contact force (compression) and buckling of the beam bottom flange, and would lower the tensile forces in the connection, which eventually causes connection failure during the fire. The results of this study also showed that shear-tab connections may exhibit more rotational capacity during a fire, but they are susceptible to fracture during the cooling phase of the fire.

In addition to the analysis of shear-tab connections, Selamet and Garlock [10] investigated the behavior of single-angle and double-angle connections during fire events. These simple connections did not exhibit fracture during the cooling phases. All of the connections evaluated behaved well during the heating phase of the fire. The shear-tab connection models were benchmarked using the results of experimental work performed at Cardington. However, the single-angle and double-angle numerical models developed by Selamet and Garlock were not verified by experimental testing [10].

Several researchers have developed techniques and tools for modeling steel-framed building components under fire. For example, component based spring models were developed for steel connections from the extensive testing program at the University of Sheffield [2,16]. These models were discussed in detail and adapted for US steel connections by Agarwal et al. [7,8]. However, these component models are not the focus of this study because they are limited to bolt shear and plate bearing failure modes. These models do not adequately model fracture of the shear-tab connection or prying of single-angle or double-angle connections.

Huang et al. [17] developed techniques for modeling composite floor beams during a fire event. The modeling procedure was integrated in the analysis program VULCAN, which was developed to simulate the fire behavior of steel-concrete composite structures. The modeling procedure was benchmarked with a number of composite beam tests performed at the University of Sheffield. The benchmarking analysis results showed that assuming full composite action between the steel beam and concrete slab resulted in conservative prediction of the midspan deflection at elevated temperatures. The comparisons between the experimental and analytical midspan deflections at elevated temperatures improved significantly when the models incorporated partial composite action between the concrete slab and steel beam. This analysis demonstrated the importance of modeling the behavior of shear studs at