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Fire resilience of composite beams with simple connections: Parametric studies and design

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ABSTRACT

Simple (shear) connections are designed to resist vertical shear forces resulting from gravity loading. During a fire event, floor systems expand and rotate, imposing axial forces (compressive and tensile) on simple connections. This paper presents the results of analytical parametric studies conducted to expand the experimental database and evaluate the structural response of composite beams with simple connections subjected to combined gravity loads and design fire scenarios. The parametric studies were conducted using 3D finite element models of partial frame assemblies consisting of composite beams with simple connections. These models were developed and benchmarked previously by the authors [1] using experimental data [2, 3]. These models explicitly accounted for the effects of geometric and material nonlinearity including concrete cracking and crushing, steel yielding and fracture, and the interaction between various structural components. The parameters included in the analytical studies were the connection type (shear-tab, single-angle, double-angle), deck type (flat slab, perpendicular metal deck), composite slab continuity across multiple bays, slab reinforcement type (wire mesh, mild steel), fire resistance rating of the design, and the design fire scenario (1 hour fire with cooling, 2 hour fire with cooling, E119). The results from the parametric studies indicated that for typical composite beams and simple connections designed with certain (n-hour) fire resistance rating, and subjected to design fire scenario with the same (n-hour) heating followed by cooling, there was no premature fracture failure of the connection leading to collapse of the composite beams. The continuity of composite slab across bays and the steel reinforcement has a significant influence on the performance of the simple connections, and the resilience of the composite beam system.

1. Introduction and motivation

Simple (shear) connections are commonly used in U.S. building construction and engineering practice. These simple connections include shear-tab, single-angle, and double-angle connections that are designed to resist vertical shear forces at ambient temperature. During a fire event, the composite beams and floor system undergo excessive deflections and rotations, which subject the simple connections to large axial force (compressive and tensile) demands and end rotations. Simple connections provide lateral restraint to gravity columns. Connection failure due to axial forces and end rotation demands can lead to the failure of the floor system, and potentially to progressive collapse of the structure. However, this potential for progressive failure has not been evaluated extensively in the literature. Previous research on the structural behavior of steel-frame buildings during fire has shown that the axial force and rotation capacity of simple connections governs the resistance of floor systems to fire [4–8]. Beitel [9] and Agarwal et al. [8, 10] indicated that under certain conditions, the failure of simple connections can lead to collapse of floor assemblies. Previous researchers [11–14] have conducted numerical investigations on composite floor systems with simple connections. These studies, however, do not adequately consider the geometric parameters of the composite beam, or the axial restraint of deformations during the heating and cooling phases of the fire. Selamet and Garlock [11,12] simulated simple connection behavior during fire using 3D finite element models. These simulations were performed on steel floor systems without the presence of concrete slabs. The results of these simulations showed that bolt shear fracture and shear-tab fracture were potential failure modes during the cooling phase of fires. The research performed by Selamet and Garlock [11,12] provides insight into the mechanical behavior of simple connections for steel floor assemblies subjected to fire without direct consideration of the concrete slab.

Leston-Jones et al. [14] developed models of steel beams with shear-tab (fin-plate) connections. These models were benchmarked against experimental data, and simulated the interaction of connection elements (bolt bearing on beam web and shear-tab). The tests and FEM

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models provided insight into the structural and thermal behaviors of shear-tab (fin-plate) connections during fire conditions. However, the tests and the finite element models did not include a concrete slab, which is present in real building conditions. Previous researchers [8, 10] have shown that the concrete slab can improve the performance of steel beams with simple connections in fire by preventing progressive collapse of the building. The simulations and results presented in this paper include the effects of the concrete slab on the performance of steel-frame buildings in fire.

Agarwal et al. [8,10] investigated the progressive collapse failure of steel buildings subjected to design fire scenarios using finite element models of 10-story three-dimensional buildings. The 10-story buildings were designed per U.S. building codes and standards [15,16]. The finite element models were developed and analyzed using commercially available finite element modeling (FEM) program ABAQUS. The steel columns and beams were modeled using (B31) shear flexible beam elements with linear interpolation and steel material properties as provided by Eurocode. The steel floor beams and girders were composite with the concrete slab, which was modeled using (S4R) 4-node shell elements with reduced integration and concrete material properties including smeared cracking, compression plasticity, and welded wire fabric (WWF) reinforcement. Shear-tab connections were used extensively in the building design, and their behavior was modeled using component spring models developed by Agarwal et al. [8,10] based on the work of Sarraj et al. [13]. Sarraj et al. [13] developed 3D finite element models of the steel beam with shear-tab (fin plate) connections, and analyzed them to simulate their axial force-displacement response at different temperatures. These axial force-displacement-temperature (P-δ-T) responses were used to calibrate component spring models for the connections. Agarwal et al. [8,10] extended this work to: (i) include the connection moment-rotation responses, (ii) account for gap closure behavior at the bottom flange of the steel beam, and (iii) develop axial force-displacement-moment-rotation-temperature (P-δ-M-θ-T) responses for the connections. The connection P-δ-M-θ-T relationships were used in the 3D full building models. However, Agarwal et al. did not consider the shear tab fracture as a potential failure mode, and the force-slip behavior of the shear studs in the composite beam [17].

Based on their investigations, Agarwal et al. [8,10] concluded that gravity columns are the critical structural component for overall stability of steel-frame buildings during fire. When all of the structural components (columns, beams, girders, connections, and floor slabs) were protected with their design FRR (1 h), the gravity columns were most likely to reach their critical stability limit before any other structural component (beams, girders, connections) due to their high utility ratios. When gravity columns are protected for more than the design FRR, the beam-to-girder shear-tab (simple) connections failed in bolt fracture due large deflections of the interior secondary beams. These results provided the motivation for experimental testing of a series of large-scale composite beams with simple connections [2,18] performed by the authors.

2. Prior experimental and numerical research

The authors [2,3] experimentally evaluated the structural and thermal behaviors of simple connections during fire to verify the analytical results of Agarwal et al. [8,10]. Seven composite beams with different connections (shear-tab, single-angle, and double-angle) were tested to experimentally quantify the behavior of simple connections during fire using the experimental setup shown in Fig. 1a. The composite beams were subjected to gravity loading, which was sustained while thermal loading (heating) was applied to the composite beams. Temperature distributions throughout the composite beam and connections, displacement histories, and connection rotation data were measured during the tests. These experiments provided insight into the thermal and structural behaviors of simple connections during fire conditions. The connections were tested as part of a frame to simulate the behavior of simple (shear) connections in steel-frame buildings. However, limitations of the laboratory and instrumentation constrained the dimensions of the specimens and data collected during the tests. The experimental results, behavior and failure modes of the tested specimens are discussed in detail in [2,3].

Additionally, the authors developed and benchmarked detailed 3D finite element models for computing the behavior of the tested specimens. The details of the 3D finite element models and their benchmarking using experimental result are discussed in detail in [1]. These benchmarked models were developed using ABAQUS [19] and provided further insight into the behavior of the simple connections during the experiments such as: axial force in the connection, stress distribution in the bolts and shear-tabs. Fig. 1b shows a schematic view of the benchmarked finite element model developed for the tested specimen (shown in Fig. 1a). Failure modes such as shear-tab fracture, bolt shear deformation, and prying action of double-angle and single-angle connections during the cooling phase of a fire were simulated accurately. Numerical results from the benchmarked models were used to supplement the experimental results and data collected during the tests. The experimental and numerical results together provided significant behavioral insights into fire performance of connections, which could not be assessed using the experimental results alone.

3. Objective and approach

The objective of this paper is to expand and complement prior experimental and numerical studies by conducting numerical parametric studies to evaluate the effects of various geometric, detailing, and fire loading and protection parameters on the behavior of composite beams with simple connections subjected to combined thermal and mechanical loading due to gravity load and the fire event. The parameters included are: (i) coped bottom flange of steel beams, (ii) slotted holes, (ii) connection type (shear-tab, single-angle, double-angle), (iii) deck type (flat slab, perpendicular metal deck), (iv) continuity of composite slab, (v) reinforcement type (wire mesh, mild steel), (vi) fire resistance rating, and (vii) fire loading scenario (ASTM E119, 1 h fire with cooling, 2 h fire with cooling).

Prior experimental and numerical studies were constrained in size, scale, loading, and heating parameters and the number of tests that could be conducted due to the practical limitations of the laboratory and equipment. The benchmarked modeling approach was used in this paper to develop 3D finite element models and conduct parametric studies on the composite beam and simple connections of a single bay of a representative, full-scale steel structure designed using US codes and standards. The corresponding structure was a 10-story office building designed and detailed by Agarwal et al. [8,10] in a low seismic region such as Chicago, US.

The benchmarked modeling approach was used to simulate the behavior and conduct parametric studies (with varying geometric, detailing, and fire loading and protection parameters) on the behavior of a one-bay 3D FEM model. Fig. 2 shows the location of the one-bay 3D FEM model within the structural floor plan of the fifth story of the 10-story office building. As shown, the composite beam of the one-bay structure represents the gravity framing girder, and the columns represent the corresponding gravity columns. The models presented in this paper consider various parameters for the connection details and slab reinforcement, while the dimensions (length and spacing) of the composite beam are maintained constant because: (i) they represent typical designs of composite beams in steel-frame buildings, and (ii) changing length and spacing would result in different composite beam depths and connection designs. As mentioned earlier, the purpose of this study was to evaluate the influence of various geometric, detailing, fire loading and protection parameters, and the potential for improving the fire resistance of a given composite beam and simple connection by modifying connection detailing or adding reinforcement in the composite deck rather than increasing the size or depth of the composite beam.