ABSTRACT

Selden, Kristi L. Ph.D., Purdue University, August 2014. Structural Behavior and Design of Composite Beams Subjected to Fire. Major Professor: Amit H. Varma.

Fire is a rare but extreme event that subjects a structure to a unique set of demands. The fire resistance of the structure depends on its ability to resist the combination of the structural gravity loads and the effects of fire without undergoing failure during both heating and cooling. While many studies have been conducted internationally on steel-framed building components in fire, a limited number have focused on composite beams designed according to U.S. codes and standards.

This project focused on the thermal and structural behavior of composite beams used in steel building floor systems through both experimental and numerical investigations. These floor systems typically consist of steel beams with a concrete deck cast on top of the beams, where composite action is developed through the use of steel headed shear studs welded to the top flange of the beam. The experimental approach included the use of high-temperature ceramic radiant heaters, vertical loading, and innovative high-temperature instrumentation techniques, including close-range photogrammetry. Isolated concrete slabs representing the concrete portion of the composite floor system were subjected to one-sided heating without the application of load to evaluate the response to a thermal gradient. Large-scale partial composite beams with simple shear beam-to-column connections were then subjected to the combination of heating and loading. There was a reduction in the composite beam load carrying capacity as a result of heating, both at elevated temperatures as well as post-fire ambient conditions. The composite beam was able to sustain service level loads with heating to steel temperatures up to 700°C. Concrete compression failure was an observed failure mode for composite beams with flat slabs at moderate steel temperatures (350-500°C) and overloading.

Two modeling techniques were developed and benchmarked using experimental test data: (i) a sequentially-coupled thermal-structural 3D finite element model for evaluating both the thermal and structural response of composite beams and (ii) a 2D fiber-based model for determining the moment-curvature-temperature relationship (M-Φ-T) for a composite beam cross-section. Both approaches account for temperature-dependent material properties and the force-slip behavior of the shear studs. An extensive parametric study was conducted to evaluate the effects of various parameters on the flexural capacity of composite beams at elevated temperatures. Variations in cross-section geometry, concrete deck type and orientation, percentage composite action, and thermal gradient were considered.

Current U.S. design provisions for steel-concrete composite beams rely upon a strength-based approach as outlined by the American Institute of Steel Construction (AISC). In partial composite beams, the headed studs transferring interfacial shear between the concrete and steel can undergo significant slip, which is not accounted for directly in design. Results from the parametric study revealed a complex inter-relationship between the beam length, stud slip capacity, and the minimum level of partial composite action that may be permitted for design. A temperature-dependent retention factor was developed for use with the AISC method to predict the flexural capacity at elevated temperatures. Because this retention factor is a function of only the bottom flange temperature, it provides a straight-forward design method to determine the elevated temperature capacity of a composite beam, without having to do conduct an extensive thermal and structural analysis.