A Fiber-Based Heat Transfer Element for Modeling the Thermal Response of Structural Members Subjected to Fire

Authors:

Ann E. Jeffers, Virginia Tech, Blacksburg, VA 24061, Email: annj@vt.edu
Elisa D. Sotelino, Ph.D., Virginia Tech, Blacksburg, VA 24061, Email: sotelino@vt.edu

ABSTRACT

Methods for analyzing the thermal response of structures subjected to fire range in complexity from simple calculation methods to advanced computational analyses (e.g., finite element analyses). Simplistic approaches may fail to capture important aspects of the response, while advanced numerical approaches can be computationally expensive, particularly when three-dimensional (3D) problems are considered. As the profession adopts performance-based approaches to structural fire design, there is a significant need for computational tools that can accurately and efficiently evaluate the response of building structures subjected to realistic fire scenarios.

This paper presents a novel type of heat transfer finite element that can be used to capture the 3D thermal response of structural beams and columns subjected to realistic fire conditions. Shown in Figure 1, the fiber heat transfer element is a 3-node finite element that is discretized into a series of longitudinal fibers. The element is formulated explicitly to be compatible with any fiber beam-column element in a sequentially-coupled thermal-mechanical analysis of structural frames subjected to fire. While the element combines finite element and finite difference approximations of the thermal response, the element equations are in a form that can easily be implemented in an existing finite element analysis program. The element can account for nonlinear material behavior and can be used to model members comprising more than one material (e.g., steel-concrete composite members). Preliminary analyses have shown that the element offers superior accuracy with minimal computational expense. The element will ultimately be used to model the thermal response of structural frames subjected to realistic (non-uniform) fire conditions.

To illustrate the capabilities of the fiber heat transfer element, two examples considering heat transfer in a rectangular steel bar are shown in Figure 2. The first example (shown in Figure 2a) considers 2D heat transfer across the bar's cross-section. Discrete fiber temperatures and

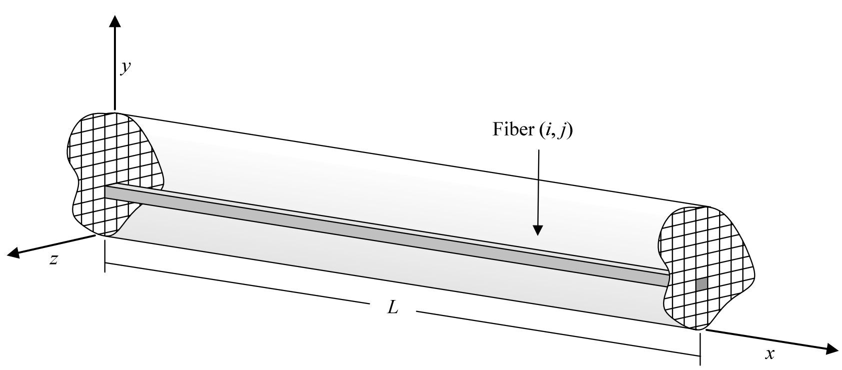

Figure 1: The fiber heat transfer element

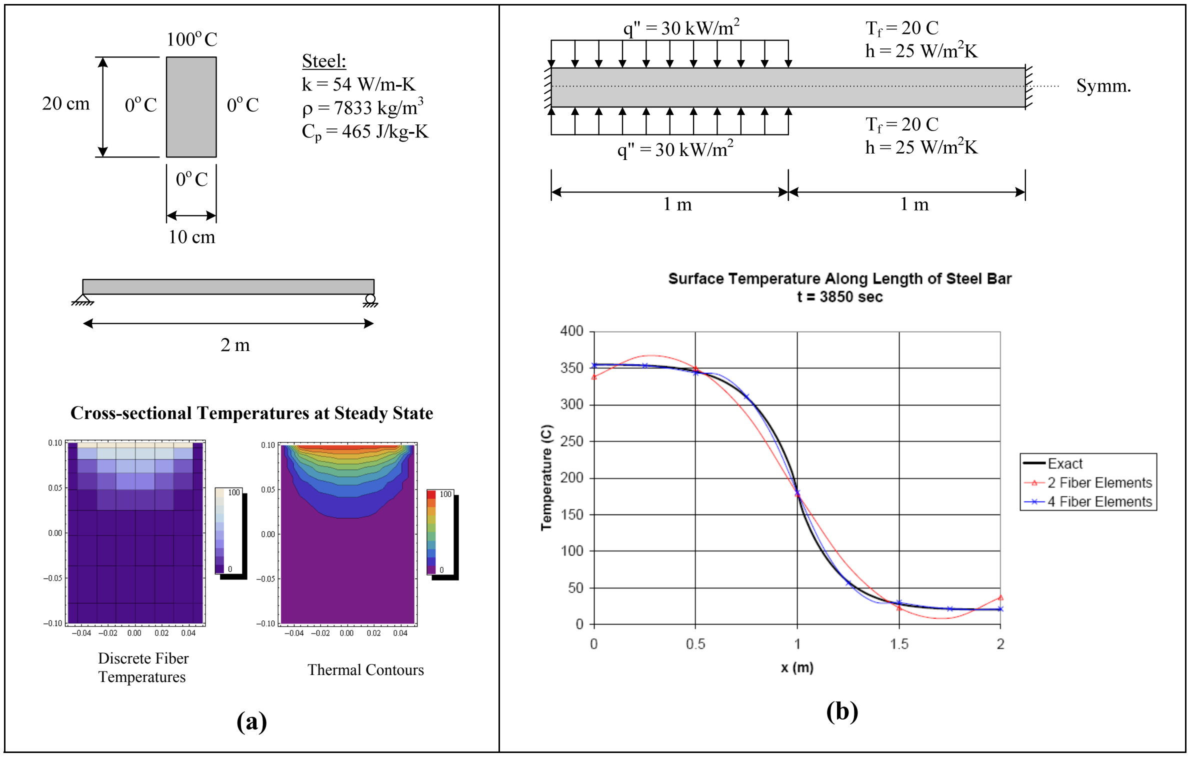

Figure 2: Selected results: (a) 2D heat transfer in a rectangular steel bar, (b) Non-uniform heating of a rectangular steel bar

thermal contours obtained using a single fiber heat transfer element are shown. The second example (shown in Figure 2b) considers non-uniform heating along the length of the steel bar. Surface temperatures are calculated using 2 and 4 fiber elements along the length. For both examples, the fiber heat transfer element provides excellent agreement with the exact solution. To demonstrate the efficiency of the fiber element, simulation times for the fiber heat transfer element are compared to heat transfer analyses conducted using 3D solid finite elements. Results are summarized in Table 1. Note that, for the same level of accuracy, the fiber heat transfer element requires only a fraction of the calculation time needed to perform a 3D analysis using traditional finite elements. Further significant time savings will be attained when this element is used in conjunction with a fiber beam column element to simulate the thermo-mechanical response of a frame element under fire and mechanical loading.

Table 1: CPU Times for the Example in Figure 2a

	Total CPU Time (sec)
1 Fiber Heat Transfer Element	0.80
3D Continuum Elements	3.50