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Uncertainties in steel temperatures during fire

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ABSTRACT

In order to determine the fire resistance of steel members, steel temperatures must be estimated with a high confidence. There can be considerable uncertainty in temperatures of both protected and unprotected steels during fire exposure. This is due to uncertainty in the thermal boundary conditions and thermophysical properties. In this study, uncertainties in both unprotected and protected steel temperatures are estimated with the use of a Monte Carlo method in conjunction with a "Lumped Heat Capacity" approach for estimating steel temperatures. Computed data are compared with experimental measurements obtained during Cardington fire tests (bare steel) and National Institute of Standards and Technology (NIST) World Trade Center (WTC) tests (protected). Reasonable agreement was achieved.

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1. Introduction

Both spatial and temporal variations of temperatures need to be accounted for when evaluating the fire resistance of steels. The ability to predict with high confidence time-varying temperature profiles in structural members is necessary for a robust performance-based approach to the fire resistance design of structures. Therefore, uncertainties in steel temperatures must be accurately estimated. The focus of this study is to demonstrate a simple approach for estimating uncertainty in the predicted thermal response of both unprotected and protected steels during a fire event.

Temperature profiles in a steel section during fire exposure depend upon the temperature-dependent thermophysical properties of steel, the thermophysical properties of fireproofing (spray applied fire resistive material, SFRM) for protected steel and the convective and radiative heat transfer parameters associated with fire. However, there can be considerable uncertainty in estimates typically used for these parameters. For example, although SFRM thickness measurements are reported according to the ASTM E 605 standard, individual thickness measurements (as required by the standard) can vary, while an average measurement is reported. In most cases, the SFRM thickness will be greater than the stipulated value as overspray is normally not penalized. Uncertainties in SFRM thickness can result in increased uncertainty in steel temperatures [1]. The variability in SFRM density can also affect the overall uncertainties in steel temperatures. Density tests are performed following the ASTM E605 standard. Ref. [4] showed air dry density variability in the range of 10–20% for typical floor truss systems. The steel temperatures are influenced because of the effect of density variability on the volumetric heat capacity of SFRM. A sensitivity study can be conducted to determine which of these parameters (thermophysical and heat transfer) most significantly influence the thermal response of the steel. Influential parameters can be used to quantify the uncertainty in the predicted temperatures.

Uncertainties can be broadly classified into two basic types: aleatoric (random) and epistemic (systematic). Aleatoric uncertainties are due to inherent randomness and cannot be removed by further analysis or testing. For example, fuel load density (MJ/m^2) can be classified as inherently random. On the other hand, epistemic (also known as knowledge-based) uncertainties can be reduced by using improved models or algorithms. Estimation of both aleatoric and epistemic uncertainties can provide a confidence interval for time-varying estimates of structural temperatures during a fire event.

Uncertainties in measured temperatures of a steel section during fire exposure can be attributed to (a) inherent measurement uncertainty associated with measuring devices such as thermocouples, (b) uncertainties associated with thermophysical properties of steel due to variability associated with steel composition (e.g., steel web diagonals used in trusses can be sourced from different vendors or from a vendor using various heats for producing steels), (c) statistical randomness associated with true gas temperatures in fire in the vicinity of a measuring device, (d) uncertainties in heat transfer parameters such as emissivity

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of a steel surface and convective heat transfer coefficients (for example, emissivity of protected steel will vary at a location if the quality of fireproofing degrades due to unexpected or abrupt variation in gas temperatures). For steel sections, measured temperatures can be reported as mean temperatures with their uncertainty bounds. For example, one can report measured temperatures at top flange, bottom flange, and web as mean temperatures along with uncertainty bounds for each.

Simplified analytical models are often used for modeling heat transfer in structural members in fire. For example, the “Lumped Heat Capacity Method” is widely used for modeling heat transfer in steel members in fire [2]. The lumped heat capacity method is appropriate for steel because of its high thermal conductivity. It is useful to develop a simple and practical approach for computing uncertainties in structural temperatures when such simplified analytical approaches are used. This paper discusses a simplified approach, e.g., “Lumped Heat Capacity Method”, for modeling temperatures for both unprotected and protected steel and the use of the Monte Carlo method for computing uncertainties in steel temperatures. Computed uncertainties are compared with results of experimental measurements for validation of models for prediction of uncertainties in unprotected and protected steel temperatures during fire exposure. The following test data were used for validating computational approach for steel temperatures and prediction of uncertainties:

1. Cardington Test 1 for unprotected steel [3].
2. NIST fire resistance Test 4 for protected steel [4].

In the following section, a brief description is provided first about experimental measurements for both unprotected and protected steels. Then, the “Lumped Heat capacity” approach is described for computation of steel temperatures. Finally, computed steel temperatures and uncertainties in steel temperatures are compared with experimental measurements for both unprotected and protected steels.

The validation of the computational approach for determining uncertainties in steel temperatures in fire will allow for reasonable prediction of uncertainties in temperatures when similar steel members are exposed to an unknown fire as long as uncertainties in key parameters such as gas temperatures in fire are known.

2. Experimental data

2.1. Unprotected steel

Steel temperatures were taken from Cardington Test 1 [3]. Cardington Test 1 is a restrained beam test in which a 305 × 165 × 40 UB beam (British Universal Beam) was heated with a gas fired furnace over the middle 8 m of its 9 m length. The beam was instrumented with a number of thermocouples at the top flange, web, and bottom flange (see Fig. 1). Five sets of thermocouples were positioned along the length of the beam for this test. Temperature measurement data collected at the beam web were used in this study. This is because the heating of the web can be considered to be uniform and the influence of the floor slab (positioned above the beam) on the web temperatures was presumed to be minimal. This is necessary since measurement data are compared with those computed using a simplified approach that requires assuming no internal temperature gradient across steel section. This is described later in the text in more detail.

Fig. 1 shows the positions of the thermocouples at a beam cross section. Note that thermocouples 51 through 55 represent web temperatures at this section.

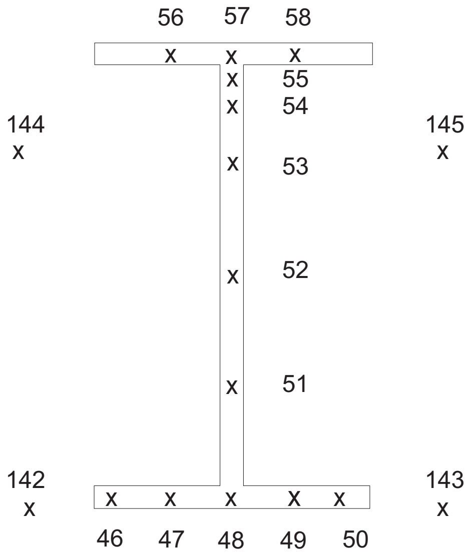

Fig. 1. Schematic representation of the location of the thermocouples used to collect steel temperatures during the Cardington Test 1 [3].

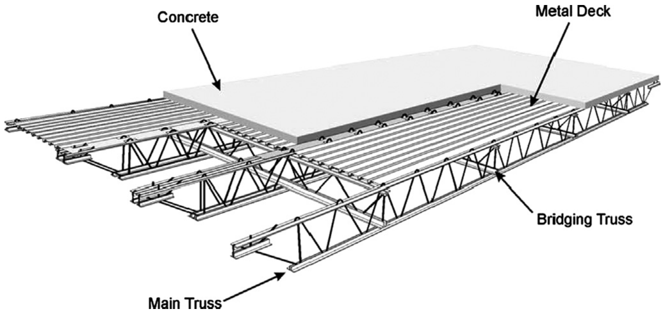

Fig. 2. Floor system of the WTC towers [6].

Mean web temperatures and standard deviations were computed using the five sets of web temperature data collected along the length of the beam. Furnace temperatures (e.g., thermocouples 142 through 145 at this section in Fig. 1) were used to yield mean fire temperatures and standard deviations as functions of time. These mean furnace temperatures and standard deviations were used in computing uncertainties in steel web temperatures as explained later in the text.

2.2. Protected steel

Protected steel temperature measurement data were taken from the NIST fire resistance Test 4 [4]. As part of its investigation into the World Trade Center (WTC) disaster, NIST conducted four standard fire tests of composite floor systems. Two full-scale tests (Test 1 and 2; span 35 ft. (10.7 m)) were conducted at the Underwriters Laboratories (UL) fire testing facility at Toronto, Canada and the other two (reduced scale; Test 3 and 4; span 17 ft. (5.2 m)) were conducted at Northbrook, IL. The UL test furnace was heated by 80 individual floor mounted burners following the American Society for Testing and Materials (ASTM) E119 standard time-temperature curve [5], and furnace temperatures were monitored at 16 locations in the furnace [4]. Time-temperature data were collected at specific locations along the truss near the top chord, at mid height of the web, and at the bottom chord.

The floor system used in the test consisted of a lightweight concrete floor slab supported by steel trusses. Fig. 2 shows a picture