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B.5 Limitation of Current U.S. Standards and Challenges of Proposed Performance-Based Standards

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Background

There is widespread interest in developing performance-based standards in the U.S. for building applications. Such standards will differ from the current system of standards by explicitly identifying fire safety goals and objectives which will be achieved by a particular design. Statements of goals and objectives will be presented in terms which are amenable to evaluation via quantitative methods. Performance measures will need to be identified along with acceptance criteria for each of the measures to determine the acceptability of a design.

Development of a performance-based standard for fire resistance will require a reformulation of the traditional process of evaluating fire resistance. Explicit statements of goals and objectives are needed. In addition, the appropriateness of the standard test method, related measurements and acceptance criteria needs to be assessed.

Fire resistance refers to the ability of a building assembly to withstand the effects of fire. The goals for fire resistant assemblies are to accomplish one or both of the following:

- restrict the spread of fire beyond the compartment of fire involvement
- support a load, despite exposure to a fire

Failure of a barrier to restrict fire spread may be caused by excessive heat transmission to the unexposed side of the barrier. Heat transmission limits are established to prevent the ignition of combustibles in contact with the unexposed side of the assembly [Schwartz and Lie, 1985]. Typically, heat transmission limits are expressed as a maximum increase in temperature on the unexposed side [ASTM, 1995][1].

Failure of a barrier to restrict fire spread may also be caused by a breach of the barrier as a result of burn-through, development of large cracks or failure to maintain its structural integrity. A breach

[1] The standard test method is documented in ASTM E119. NFPA 251 and UL 263. For simplicity. the standard test method will be referred to as ASTM E 119 throughout this paper.

in the barrier may alter the ventilation characteristics of the fire compartment or provide additional paths for smoke and fire spread from the fire compartment.

Structural failure or collapse is relevant for load-bearing members. Failure of a loadbearing member may result in a local collapse or wide-spread structural failure if load transfer to adjoining members is unsuccessful. To a limited extent, structural failure of non-load-bearing assemblies is of interest, because the assembly still must be able to sustain its own dead weight and maintain integrity to restrict fire spread.

Another possible goal receiving increased attention is the post-fire integrity of building assemblies. This interest reflects concerns for scenarios where the structure is able to withstand the impact of the fire exposure during the incident, but requires substantial repair prior to returning to use.

Possible objectives related to the three goals include the following:

A barrier needs to limit the heat transmission to the unexposed side such that ignition of ordinary combustibles in contact with the barrier is prevented. A structural member needs to have sufficient load-carrying ability to sustain applied loads, despite the increase in temperature and possible imposition of temperature gradients within the member. A structural member needs to have sufficient residual load-carrying ability so that the member will be reusable after the fire without repair.

Considering the noted goals and objectives, the following performance measures can be proposed to assess the fire resistance of construction assemblies:

<u>Thermal</u> temperature on unexposed side
• temperature of steel structural components

<u>Structural load or moment capacity</u> (as a function of temperature)
• stability
• deflection

<u>Post-fire usability</u>
• residual load or moment capacity

Currently, fire resistance analyses are typically conducted via a standard test [ASTM, 1995]. The test is used only as a comparative measure and is not intended to provide data for predicting the response of an assembly exposed to actual fire conditions. The endpoints for the test include the two thermal performance measures and the ability to sustain the applied load, comparable to the first two structural performance measures. Post-fire serviceability is not addressed by the standard test.

Because the test intends to be comparative in nature, application of the results from the standard fire resistance test is constrained until the following aspects are addressed. Given that performance-based design will consider a variety of design fires, the relevance of the heating conditions associated with the standard test to those of selected design fires needs to be demonstrated. Loading conditions associated with a particular project may be different than those used in the standard test. Whereas the loading conditions associated with the standard test intend to provide the greatest applied stress to the component, tests of flexural elements are only designed to develop the maximum normal stress in the element and not the maximum shear. Samples are large-scale samples, though not full scale, without any attempt to provide structural end conditions to replicate full-scale behavior. Finally, the objectivity of the endpoint criterion "sustaining the applied load" can be improved by adding deflection criteria.

Development of an Engineering Practice Standard

In lieu of conducting very specialized fire resistance tests to address the specific aspects of a particular design, engineering practice standards can be developed which document calculation methods to determine the response of structural assemblies to a fire exposure. This is a current area of activity within the American Society of Civil Engineers and Society of Fire Protection Engineers.

Analysis of the response of fire-exposed structural assemblies requires consideration of the following four aspects:

- fire exposure
- material properties at elevated temperatures
- thermal response of the structure
- structural response of the heated assembly.

The relationship of these four aspects in a performance-based approach for evaluating fire resistance is reflected in Figure 1. As indicated, one aspect provides input to one or two other aspects. However, in reality, the aspects are actually inter-related, suggesting that the arrows in the diagram should point in both directions in many cases. For example, the thermal response of a wall assembly affects the temperature of the exposing smoke by altering the energy exchange between the smoke and the enclosure. In addition, if the wall assembly collapses, additional ventilation will be provided to alter the course of the fire.

A description of the fire exposure is used to characterize the radiative and convective heating conditions associated with a particular fire scenario. The heating conditions are described in terms of parameters such as the temperature history of the gases or smoke layer within the compartment, radiation characteristics of the smoke layer and flames, and duration of the exposure. Results from the fire exposure analysis are used as input for the thermal response analysis.

Both the thermal and structural response analyses are influenced by the material properties at elevated temperature. Thermophysical and mechanical material properties are temperature dependent. Thermophysical properties used in the thermal response analysis include the thermal conductivity, specific heat, density, porosity and permeability. The mechanical properties of interest include the elastic moduli, strengths, coefficient of thermal expansion and creep parameters. In addition, heat absorption or generation due to changes in material composition or physical phase occurring at elevated temperature also need to be considered.

Thermal response is analyzed for two reasons: heat transmission to the unexposed side of the assembly and impact on structural integrity of load-carrying members. The temperature on the unexposed side of an assembly can be determined from a heat transfer analysis. Temperature on the unexposed side of the assembly is limited in order to prevent ignition of combustibles or injury to occupants in contact with the unexposed side of the assembly. In addition, results from a thermal response analysis are important in providing input for the analysis of structural response, accounting for thermal strains, creep strains and the dependence of material properties on temperature.

Generally, the thermal response of a construction assembly is evaluated via a conduction heat transfer analysis. Boundary conditions are stipulated for any fire exposed surfaces based on the characteristics of the fire exposure and for any unexposed surfaces based on environment conditions. Where cavities are provided within the assembly, the convection and radiation across the cavity needs to be considered. For materials containing moisture, moisture migration and evaporation will affect the heat transfer within the assembly and should be considered in the analysis.

Evaluation of structural response addresses the impact of degraded materials, reductions in material property values and thermally-induced stresses on the integrity of load-carrying members. Examples of structural response analyses include moment-bearing capacity analyses for beams and slabs, stability analyses for slender columns and deflection analyses for beams and slabs. In addition to the analysis of structural response on the integrity of a particular load carrying member, the effect of the response of the fire-exposed member on adjoining structural members also needs to be evaluated.

In 1985, an SFPE task force concluded that analytical methods were available to determine the fire resistance of a wide variety of assemblies comprised of concrete, steel and wood [Milke, 1985]. This conclusion was repeated by Pettersson in 1986. Summaries of calculation methods to conduct performance-based analyses of the fire resistance of many different assemblies have been published recently [Lie, 1992][Milke, 1995][Fleischmann, 1995] [White, 1995] [Hosser, et al., 1994].

Existing analytical methods range from parametric expressions to numerical calculations. Typically, parametric expressions are limited to comparisons of the fire resistance of one assembly to another. Numerical calculations range from the application of graphical analyses and empirical correlations to finite element computer models to conduct heat transfer or structural analyses, accounting for unique property values, loading conditions and fire exposure attributes.

Integrated analysis methods involving the fire behavior, material effects, thermal response and structural response have been documented. One of the earliest versions of such an analytical approach was developed by Pettersson, Magnusson, and Thor for steel members [1976].

Subsequently, many other documents have been compiled, such as: ECCS [1983], ECCS [1985], CIB [1986], Eurocodes standards for each of the major structural materials and a recent design guide for steel members [Schleich, 1993]. All of these documents address the response of a building assembly to an uncontrolled, fully-developed fire.

Of particular interest in the integrated design guides are the following:

1. establishment of material properties as a function of temperature
2. safety factors to add conservatism in the areas of applied loads/moments, fire severity and duration.
3. establishment of charring rates for wood
4. establishment of heat transfer parameters describing fire exposure

All of these calculation methods require input data pertaining to the four aspects illustrated in Figure 1. In particular, heating conditions associated with the fire exposure need to be described. Heating conditions are described in terms of the heat flux as a function of time. Heat flux may be described explicitly or implicitly via the provision of temperature, convection coefficient and radiation parameters associated with the exposure. Heat flux or temperature is routinely provided in fire growth models [Walton, 1995] [Babrauskas, 1979]. Convection and radiation parameters are generally assumed and rarely determined.

Material properties as a function of temperature are required for the thermal and structural response analyses. For the thermal response analysis, the following properties are among those needed:

thermophysical properties
thermal conductivity, specific heat, density

chemical changes
decomposition, pyrolysis

physical changes
phase change, moisture migration, spalling, swelling/shrinkage

For the structural response analyses, the following mechanical properties are among those needed:

mechanical properties
yield strength/ultimate strength, modulus of elasticity, shear modulus, Poisson's ratio, coefficient of thermal expansion, creep parameters.

In each case, test procedures need to be agreed upon to yield consistent property values. For example, the strengths and moduli are functions of the heating and loading rate and sequence of heat and load imposition [Phan, 1996]. A task group within the Fire Tests Committee of the National Fire Protection Association is currently involved in listing standard test methods to determine the thermophysical and mechanical properties at elevated temperature.

Conclusion

Engineering practice standards to determine fire resistance are being developed to support the development of performance based codes. However, one of the principal constraints on the ability of calculation methods to predict fire resistance is the shortage of material property data at elevated temperature and the lack of widely-accepted methods to determine such properties.

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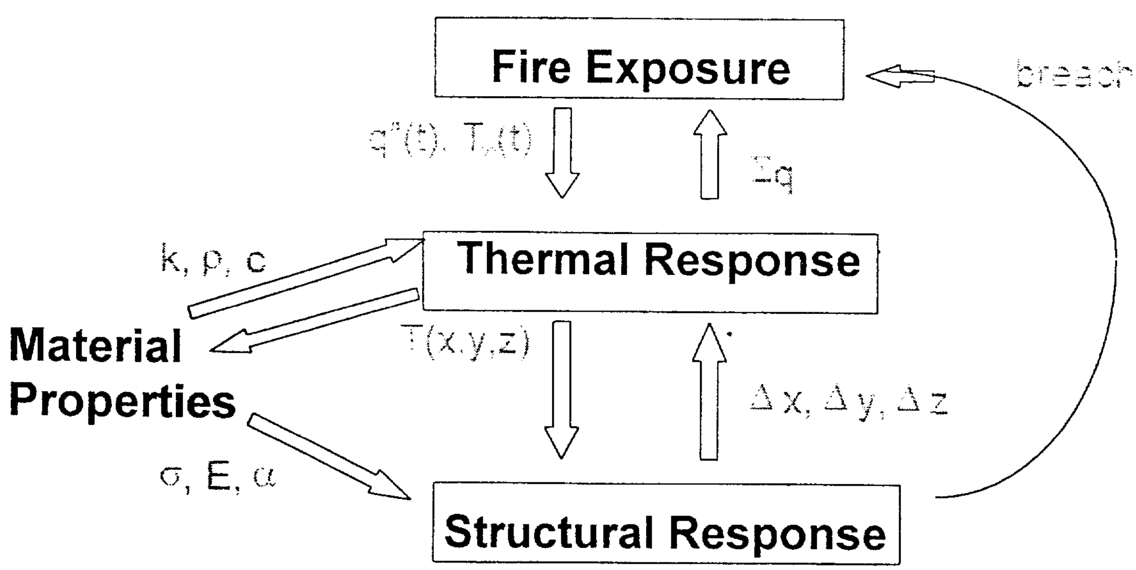

Figure 1. Procedure for Performance-Based Assessment of Fire Resistance