Fire Performance Issues

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Abstract

The worldwide movement toward performance-based building codes is prompting the need for new computational methods to predict fire endurance of wood assemblies. Progress in the past twenty years in understanding fire endurance of individual solid wood components has been achieved in many different countries. The greatest opportunity for major advance in fire research is the development of computational fire endurance models that incorporate heat transfer, thermal degrade, and structural analysis algorithms for not only single components but multiple-component assemblies subject to standardized and natural fire scenarios. Full-scale test programs will also be needed to verify computational techniques and further develop thermal degradation theories.

Why Fire Research is Needed

Fire is a special design consideration addressed to minimize the risk of failure modes including structural collapse. Fire is not a loading condition in the traditional structural sense of applied forces, but instead an environmental condition that can have a dramatic impact on load carrying capacity and structure safety. The primary objective of fire resistant structural design is to maintain structural integrity during a fire for a sufficient period so that occupants may safely evacuate, fire fighters may safely extinguish the fire and to minimize property loss. This design process includes confining any potential fire with strategically-placed barriers and fire stops. Research on fire resistant design and construction in the United States appears to have diminished in recent years, although internationally it continues to be actively researched. In the U.S. fire resistant design receives much less research attention than similar efforts related to earthquake resistant design or the response of structures to wind events such as hurricanes. Can it

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be that fire resistant design in the U.S. is more than adequate, thus explaining the low level of research activity?

Generally available statistics show that 4000 to 5000 civilian deaths and 8 billion dollars of property damage result from approximately 600,000 structure fires in the United States per year (World Almanac 1997). Forty-three of these fires representing about 0.01 percent of all structure fires accounted for about 18 percent of the estimated structure fire dollar loss in 1995 (Badger 1996). Both the cumulative small house fires and the large loss fires are causing significant life and property costs. In contrast over the past 10 years, average yearly death rates from earthquakes and hurricanes (in the U.S.) have been less than 1 and 70 respectively. Clearly, the potential for severe human life and property loss exists from a single extreme earthquake (as evidenced recently in Kobe, Japan) or a hurricane. Nevertheless, recent statistics suggest that risk to human life per year in structure fires is higher than for earthquakes and hurricanes. Why then, do we not devote more research effort to fire resistant designs?

The fire performance of new engineered wood components continues to be challenged and questioned (Brannigan 1988, Corbett 1988, Grundahl 1992, Malanga 1995, Schaffer 1988). Some in the fire protection community have strongly questioned the fire performance of these components because they are less massive and thus less able to resist a rapid temperature rise than comparable solid wood components. Sometimes, prohibitions and restrictions in engineered wood component use have been proposed, but without a strong scientific basis to back their claim.

Fire-resistant construction practices for buildings in the United States have been controlled by prescriptive standards specified in building codes. Inclusion in the prescriptive standards has depended upon full-scale fire endurance testing of assemblies under ASTM E 119 or other similar international standards. These full scale tests are expensive, and slowly, accepted calculation procedures are being recognized by the codes as an alternative (White 1995). Prescriptive standards are convenient in that they free building designers from technical knowledge of fire. Because the construction details are prescribed (such as the minimum width of an exit corridor, etc.), there is often little opportunity for innovation in design without facing the daunting task of changes to the code. As a result, the prescriptive methods can lead to a perception that once the prescriptive requirement is met, what can be done has been done, and no further efforts or attentions are needed. Some believe that fire safety can be best improved by simply increasing enforcement of existing prescriptive requirements.

In contrast to the prescriptive code environment currently prevailing in the United States, performance-based fire safety regulations in building codes are being investigated and adopted in other countries. Performance-based code requirements present an objective and needed minimum result, as opposed to dictating construction details for achieving an unstated objective and an implied result as in prescriptive codes. The performance-based codes empower the designer with the possibility of a wide array of solution strategies for providing fire safety (Bukowski and Babrauskas 1994) with the possibility to provide better or equal performance at less cost and thus achieving a competitive advantage. However, such an array of solution strategies only comes from an understanding of fire performance and development of reliable calculation procedures to predict fire performance.

New Zealand moved from a prescriptive to a performance-based building code several years ago (Buchanan and Barnett 1995) and Australia is rapidly moving in that direction for fire safety (Clancy, et al. 1995). Japan and the United Kingdom have been working toward performance-based codes since 1982 (Tanaka 1994; Bukowski and Babrauskas 1994). Since 1994, Swedish building regulations BBR 94 and BKR 94 have been performance based and Norwegian building regulations have been undergoing review with the objective to develop performance-based design. Eurocode developments are also headed toward offering the option of performance-based requirements (Kruppa 1996, Konig 1994). The authors have observed that in those countries where performance-based codes have been adopted or are about to be adopted that fire performance research is vigorously pursued to meet the demand for technological innovation that the performance-based codes reward. Prescriptive codes in several countries prohibited wood frame construction greater than two stories The adoption of perfomance-based codes has fostered wood construction innovation such that three and four-story wood construction is now being accepted.

In the United States, building code officials acknowledge that we are beginning an increased migration from prescriptive to performance-based standards (Zeller, 1997). The wood products industry has identified participation in the fire aspects of performance-based code development as a top priority. As emphasized by Fewell (1997), the development of building codes in the United States is distinctly different from other countries but developments in the past five years have now led toward a single set of uniform model building code documents. While the end of this process is not clear, it seems to lay the ground work for major advances such as the eventual adoption of performance-based code provisions. The National Fire Protection Association points out that the issue is not if or when we will practice performance-based design, but how performance-based design can be supported (Puchovsky 1996).

The motivations for conducting fire resistant research are thus clear. It is likely that the United States will follow the evolution of code development and eventually move toward performance-based codes. The need for fire research knowledge and predictive tools in this environment will be urgent for designers. Puchovsky stating the position of the National Fire Protection Association: *"The completion of a performance-based design requires a technical understanding of fire safety principles, followed by the application of proven engineering methods and calculations. This process relies heavily on science and engineering."* As stated by Tanaka (1994), "fire models are indispensable to a performance-based design system..." Although, fire models have a role even in a prescriptive code environment as an alternative or supplement to standardized fire endurance testing, the main motivation for model development is the eventual application of the full flexibility of fire models with performance-based codes. The increased knowledge and model development needed to exploit performance-based codes will not spontaneously occur. Research must advance hand in hand and preferably ahead of the changes toward performance-based specifications. Failure to do so may put the U.S. construction industry at a competitive disadvantage compared with construction in other parts of the world.

Human life and property losses resulting from structure fires can be reduced as fire endurance is better understood and new construction practices are developed. Popular engineered wood structural members will be recognized for either the fire safety that they offer or fire-resistant weaknesses will be revealed, understood, and addressed with development of suitable fire endurance systems before catastrophic experience. This research may expose fire-resistant weaknesses in some products and designs but may also open new markets by showing acceptable fire endurance performance and gaining new code acceptance. Fire endurance research serves to sort fact from perception and can guide the development of economical fire safe designs.

Overview of Research Topics

The primary areas of fire research related to structural engineering are:

1) Fire growth
2) Thermal degrade
3) Fire endurance

The context and emphasis of these areas in fire research, and of subtopics within the areas, have changed considerably in the past ten years. Previously, the major emphasis was on understanding the fundamentals of fire growth. Less of an effort was directed toward fire endurance. In the past 10 years this trend has reversed and considerably effort has been directed toward understanding fire endurance and developing fire endurance models. Fire growth research offers the opportunity to measure and simulate the thermal conditions associated with actual fires. Thermal degrade research involves measuring and characterizing material behavior based upon thermal conditions and fundamental knowledge of wood and gypsum. Fire endurance research uses knowledge gained from the two other research areas and principles of structural analysis to predict the load carrying capability of wood components and assemblies under fire conditions.

Fire Growth Modeling

Fire growth research has the objective to improve predictions of heat and smoke release rates, temperature development, and products of combustion (SFPE 1995). Regulations based on fire test methodologies for such “reaction to fire” performance criteria affect the use of wood products and other combustible materials. Fire growth models are critical for evaluating the risks to life safety if a fire should occur. Generally, this type of research has not been conducted in the context of structural engineering nor incorporated in structural models or structural design. This research is important to understanding the nature of structure fires and ultimately it will play a complimentary role in structural models that predict fire endurance. Debate continues on how structures behave in standardized test fires such as those in ASTM E-119 versus natural fires (König and Norén 1995. Buchanan and Thomas 1996). Computer programs containing mathematical fire models, once verified, will allow a multitude of realistic structure fire scenarios to be examined for a design.

Related to fire growth are the topics of combustion toxicity and sprinklers. Combustion toxicity received tremendous attention during the 1980's but research has recently decreased in this area (Hall 1996). Yet, toxicity is the principal mechanism causing fire-related deaths. While outside the scope of structural engineering research and general fire endurance issues, combustion toxicity is a continuing research topic within fire safety. Automatic sprinkler systems provide options in building design pertaining to allowable floor areas and use of combustible materials. The use of the new engineered structural components has raised issues pertaining to the proper placement of the sprinklers.

Thermal Degrade of Wood Materials, Protective Sheathing and Connections

Understanding and predicting wood material behavior during and after pyrolysis is key to ultimately developing fire endurance models. This research consists of two interrelated steps:

a) heat transfer modeling of the transient thermal gradients occurring through the wood material and possible air zones around the wood as influenced by protective layers of sheathing and connections,

b) material characterization of the chemical changes associated with the exposure of wood to elevated temperatures.

Heat transfer models developed to simulate the influence of a protective layer of gypsum sheathing have been reported (Mehaffey et al 1994 and Clancy et al 1995). While these efforts provided a critical first step, modeling protective sheathing performance in a fire for variety of realistic construction scenarios (including the effect of construction joints and the ultimate failure of the gypsum sheathing) is very complicated and requires further study despite the recent progress (Takeda and Mehaffey 1996 and Clancy 1996). The possible break down of the protective sheathing as influenced by structural deflections is a problem that potentially limits the application of current fire endurance models (Cramer and White 1996).

At the time of the 1983 ASCE Workshop on Structural Wood Research (Itani and Faherty 1984), the action of most mechanical fasteners exposed to fire was unknown. The problem is complicated by the fact that the connectors act as thermal conductors and large temperature gradients exist in the wood surrounding the connector. Work on nail connections (Norén 1996) and metal plate connections (Shrestha et al 1995, White and

Cramer 1994) has provided some information. However, considerable research is still needed to define connection behavior. Better knowledge of thermal degrade of wood will facilitale understanding the behavior of different connection methods in wood structures exposed to fire.

Research on the thermal degrade of wood material has been conducted at several levels. Some models separate wood degrade into a two-material system consisting of charred wood and residual wood (Imaizumi 1962, Lie I 1977, Woeste and Schaffer 1981, and Bender et al. 1985). This requires knowledge of char rates (White and Nordheim 1992, White and Tran 1996) and includes an empirical thermal degrade factor for the residual wood. Knudson and Schniewind (1975) modeled the wood section as a composite of small elements with distinct properties. King and Glowinski (1988) considered the section as a series of layers and used transform section analysis to account for the resulting property differences. Other approaches treat the section as a homogenous cross section but compute a net property degrade across the section by accumulating the time of exposure (Cramer and White 1993, Shrestha et al. 1995). Schaffer (1973) examined the degrade characteristics of residual clear wood. More recent efforts have been directed at examining thermal degradation of full-scale lumber (Norén 1988, Shrestha et al. 1995, Lau and Barrett 1997). The fundamental roles of pyrolysis on creep and the role of time of exposure have been introduced in previous investigations but work remains in advancing these theories to a practical level that can be applied to full-scale lumber and wood composite components.

Fire retardant treatments and coatings offer another aspect to thermal degrade research but are beyond the scope of the structural engineering research (White 1984). Generally these treatments suppress flame spread but do not retard the thermal degrade in engineering properties.

Increasingly engineers and architects are faced with the need to evaluate and rehabilitate a wood structure following a fire. Information is very limited and applicable primarily to heavy timber members (Freas 1982). The need for research on the thermal degrade of wood properties also applies to the residual strength that remains after exposure to elevated temperatures.

Fire Endurance of Wood Structures

Fire endurance research consists of testing or computational procedures by which the survival time of a timber structural component or assembly is measured or predicted. This area differs from thermal degrade work in that fire endurance involves the combination of thermal modeling, thermal degrade, and structural calculations to assess survival time. If a testing approach is taken, numerous tests are needed to allow isolation of various effects and to allow interpretation of test variability. Testing programs are also needed to serve as verification of developed models. Currently, a large full-scale wood assembly fire test program is underway in Canada (Richardson and McPhee 1996).

Any fire endurance model requires the following components:

1) Knowledge or predictive model of fire growth,
2) Knowledge or predictive model for heat transfer,
3) Degrade model for main wood components,
4) Degrade model for connections,
5) Structural analysis model capable of accommodating changes in properties over time.

Fire endurance modeling is a culmination of both thermal and mechanical modeling of the interactions that occur between structure and fire. The needed components of a fire endurance model for a wood assembly require information or models at some level of complexity from all the major areas of fire research. Many of the references cited above under thermal degrade research also contain a structural computation component. Fire endurance model development is truly an interdisciplinary problem and cannot rely on structural engineering expertise alone. Various levels of simplification are suitable in some cases and have been applied selectively in existing models. For example, some models are geared toward predicting fire endurance of members in a standard fire endurance test, simplifying the need for fire growth knowledge (Lie 1992). Some methods are intended for design (Janssens 1994) and others are research tools. Sullivan et al. (1994) and Hosser et al. (1994) provide reviews and comparisons of existing numerical methods devoted to structural analysis and design for fire conditions. Sometimes, prediction of the fire endurance of a single representative component such as a joist, stud or truss may be adequate for estimating the fire endurance of a multiple component floor or wall assembly. In cases where material properties, fire temperatures, or structure characteristics vary substantially across the assembly, the assembly and these variations must be considered directly in models to predict fire endurance (Cramer and White 1996).

Fire endurance models quickly become very complex as their sophistication and range of applicability increase. The input needs for these models can quickly out pace our knowledge of material performance and render a model highly dependent on the uncertainty in largely unknown material and thermal response. The challenge in fire endurance research will not only be the development of computational models that can operate on a designer's desktop computer, but the development of reliable and robust models for which input properties are generally available.

The Need for Coordinated Research Efforts

When one compares the current state of structural wood fire endurance knowledge with that of twenty years ago (Schaffer 1977). considerable progress has been achieved. Most of the progress has consisted of individual efforts undertaken more or less in parallel around the world. Certainly, more could have been achieved had these efforts been coordinated and such coordination will be needed in the future to accelerate the next level of advance in fire endurance research.

Approximately ten years ago, a group of researchers formed together to share fire modeling research in an organization called the North American Wood Products Fire Research Consortium (NAWPFRC). This group meets yearly with an open-door policy for anyone conducting wood fire endurance modeling research to share their findings. The wood fire research community is small and spread far across the world. The NAWPFRC yearly exchange of information has prevented research from being duplicated in North America. Major future advances in fire endurance research can most effectively be achieved. by not only a sharing of research, but a formal integration of different advances achieved internationally. Most research efforts are nationally based and funding sources tend to discourage international research projects. Yet such collaboration offers the greatest potential for advance. An organized, integration of heat transfer modeling efforts, thermal degrade research, and fire endurance research is needed to achieve the most powerful fire endurance models. The international wood fire research community should actively seek funding mechanisms that will promote such a cooperative effort.

Summary

The emergence of performance-based codes is demanding greater knowledge of structural fire performance and the development of means to compute fire endurance. Greater understanding of fire growth, heat transfer processes, material property changes, and assembly performance is needed to support the move toward performance-based codes and improved fire safety. The most likely advances will consist of computer-based models that can be used by designers and researchers. While advances in each individual area are needed, the integration of these advances is needed for greatest impact. The interdisciplinary nature of fire endurance research increases the need and potential benefit for formal, collaborative research efforts that cross international boundaries.

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Appendix - References

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