Fire Resistant Design in Housing – Status and Opportunities

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Abstract

The fire hazard in housing results in approximately 3000 deaths and \$6,000,000 property loss each year and disproportionately impacts lower socio-economic segments in the U.S. This paper makes the case for research support that is proportionate to this hazard. The current prescriptive code environment will evolve to a performance-based code environment that will foster and reward innovation in fire resistant technology, but basic research is needed to pave the way for adoption of performance based codes. Advances in fire safety for housing require research in development of fire growth models, thermal degrade of materials used most commonly in housing, prediction of fire endurance, fundamental definitions of toxicity and flammability of materials, and improved understanding of human response to fire. While individual advances in these areas are needed, greatest impact can be achieved with research that integrates several of these subareas.

Keywords: fire, housing, gypsum board, performance-based codes

Introduction

The current status of fire resistance in residential construction is defined by a series of prescriptive requirements. Innovation in housing is tied to the building code regulations that govern their design. The building code environment creates the environment and incentives for innovating in building design. This paper addresses the need and opportunities for fire research in housing.

Although civilian fire deaths in the home have declined from a peak of 6,015 in 1978 to 2,670 in 2002, the fire hazard continues to be extremely significant in terms of loss of life and loss of property. The United States has historically had one of the highest fire death rates in the industrialized world (FEMA 1997) and surprisingly the fire death rate in residential construction in the U.S. is almost two times that of nearby Canada (Richardson 2001a). In 2002, over 75% of all structure fires occurred in residential construction and these fires resulted in an estimated \$6,055,000,000 property loss in one and two family dwellings, an 8% increase from 2001 (Karter 2003). The California wildfires caused approximately \$2B in property losses alone. Richardson (2001a) points out that in these smaller buildings, prescriptive code requirements provide an implicit but undefined level of fire safety. Nearly any statistical comparison will reveal that fire is a hazard far more significant in terms economic and life losses in the US than all other natural hazards combined and as statistics from the California fires are compiled this comparison will become even more clear. The number of fire fighters lost annually in residential structure collapses has tripled since the 1980's (NIST 2003). Residential fires also tend to strike those least able to minimize the fire risk. Statistics show that median fire death rates in cities with

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poverty rates greater than 25% are more than 7 times that of cities with poverty rates below 10% (Fahy and Norton 1989). Of even more concern, Hannon and Shai (2002) reveal that individuals living in low income and predominantly African American communities have exceptionally high fire death rates that are not explained by simply summing the two risk factors (race and poverty). Kose (1999) highlights the increased fire risk for a population that is aging and less able to protect themselves in the event of a fire.

Production trends show certain engineered wood products and prefabricated wood components growing in use and replacing or combining with conventional light frame construction in most housing markets. Since the late 1980's, individuals within the fire service have expressed concern about the fire performance of engineered wood structural products no matter whether the assemblies are built to code or not. Publications describing this debate include 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. In several instances, these concerns of firefighters have often been brought to city hall where municipal actions have been taken. Outright product bans of engineered wood component use in residential construction have been adopted in a growing number of municipalities especially in Illinois and Pennsylvania (Buckingham Township 1999, AF&PA These prohibitions are without documentation of a claimed "sudden collapse," but 1999). neither is there substantive scientific evidence to refute the claims (Richardson 1999). More than several states (CT, IL, MA, NJ, NY) have considered placard rules requiring posted notice of the use of engineered wood products (implying some sort of hazard) and other local jurisdictions (especially in Illinois) have mandated the use of sprinkler systems with wood products (AF&PA Clearly, there are significant concerns about the fire performance of residential 1999). construction products and fact-based research is needed to address these concerns to ensure that economical construction products are not needlessly restricted.

The Influence of the Regulatory Environment on AdvanceS in Fire Resistant Design

While the *development* of innovations in the fire resistance of housing is constrained only by the economics of research, the *implementation and motivation* for housing innovations is inextricably linked to the regulatory environment. Innovations must eventually be compatible with building codes.

Although residential fire resistant design and fire safety requirements vary from local jurisdiction to local jurisdiction, the International Residential Code (IRC) (ICC 2003) provides an example of the type and framework of typical requirements. Table 1 categorizes the different fire related concerns by function and reveals the general code-enforced strategies for fire resistance. As observed from Table 1, the fire resistant design requirements are very prescriptive and dispersed throughout the IRC. Structural fire protection relies heavily on passive strategies such as gypsum linings with the general intent to allow time for escape. The thickness of gypsum lining typically specified (12.5 mm) will provide some time for escape in a fire but generally does not provide the same level of protection as specified in fire-rated commercial construction. Other materials used in interior wall and ceiling linings are limited by their flame spread and smoke

generating characteristics. It is also clear that the protection is specified independent of the structural function and performance of the building.

The provisions in Table 1 are largely based on two test standards. ASTM E119 (2003) (or ISO 834 (1999) or a similar variant) is used world wide to test the longevity of a structural component or assembly to a time-temperature curve. All use standard time-temperature curves that are generally similar. Despite this acceptance, the standard fire test procedure as outline in ASTM E119 has many limitations and caveats. Richardson (2001b) provides insights into these caveats for light frame wood assemblies prevalent in housing. As articulated by Schaffer and Woeste (1988) the method does not realistically measure fire safety of structural components. The method allows comparison of one design to another with a one-point performance measure. ASTM E119 (2003) stipulates that the test specimen "be truly representative of the construction for which classification is desired, as to materials, workmanship and details..." Often, however, the test specimen (assembly) is constructed with considerable care to insure all materials are within specifications and fabrication is carefully conducted. At the same time, a full design load is applied (for allowable stress design) and the fire load is more severe than data indicates will occur in a real fire (König et al. 1995, Schaffer and Woeste 1988, Lie 1992, Grundahl 1992). There is a strong need to consider a fire exposure in residential construction that realistic reflects the interior materials and loads that statically occur in residential construction.

Function of requirement	IRC Provision	Description
Prevent ignition of	R309.3	Noncombustible garage floor
combustible materials	R808, R1003.13	Clearance requirements around heat producing devices and
		chimneys
Prevent rapid flame spread	R314	Restrictions including gypsum board covering for foam
in area of fire origin		plastics
	R315	Limit flame spread classification to less than 200 for wall and
		ceiling finishes
	R316	Flame spread and smoke density restrictions on insulation
	R502.12	Draft stopping requirements for floor/ceiling assemblies
Allow rapid exit of people	R310.1	Emergency escape and rescue openings for basements and
		bedrooms
	R311.2	Gypsum board lining under stairways
	R311.4	Exit door requirements
	R313	Smoke alarm provisions
	R314, R315, R316	Smoke-developed index restrictions for interior finishes and exposed insulation
Prevent fire spread beyond	R309, R 702.3.5	Gypsum board interior linings required to separate garage
area of origin		from habitable space
	R502.13, R602.8,	Provisions for fire blocking
	R1001.16	
	E3302.2, E3302.3	Limits electrical utility penetrations through fire stops
Prevent spread of fire to	R302	Separation requirements between dwellings (distance or
neighbor		gypsum board)
	R317, R802.1.3,	Separation requirements for two-family dwellings
	R803.2.1.2	

Table 1. Fire Related Provisions in the 2003 International Residential Code for One-And Two Family Dwellings (ICC 2003)

ASTM E84 (2003) is a second standard that forms the basis in building codes for limiting flame spread and smoke density of materials used in residential construction. Two limitations of this test are: 1) Tests of materials that melt, drip, and delaminate to the extent that the continuity of the flame front is destroyed may result in deceivingly low flame spread indices. 2) The effects of aggravated flame spread behavior of an assembly resulting from the proximity of combustible walls and ceiling are not evaluated.

The prescriptive standards are convenient in that they free building designers from technical knowledge of fire. Because the construction details are prescribed, there is often little opportunity for designers to innovate 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 that fire safety has been automatically achieved.

In contrast to the prescriptive code environment currently prevailing in North America, 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 to pursue 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 (Babrauskas 1996).

New Zealand moved from a prescriptive to a performance-based building code several years ago (Buchanan and Barnett 1995, Buchanan 1999) and Australia was reported to be 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). In local jurisdictions such as Cadoneghe, Italy performance-based codes are being developed and tried (Gottfried and De-Angelis 1999). The authors have observed that in those countries where performance-based codes reward. In many respects, the U.S. is falling technologically behind in residential fire safety.

In the United States, building code officials acknowledge that we are beginning a migration from prescriptive to performance-based standards (Zeller, 1997). There has been extensive discussion about performance based codes and code writing agencies are pursuing their development (Tubbs 1999). 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 bottom line is that performance based codes are coming to North American building construction and that conversion to such codes requires a new level of design technology that can predict fire performance accurately (Babrauskas 1996, Milke 1999) and oversight to ensure the technology is used correctly (Caldwell et al 1999). The advantages in performance based codes are that innovation in design will be allowed to occur and the professional debate will change from the meaning of words in the prescriptive code requirements to basic questions of fire safety (Buchanan 1999).

In addition to performance-based codes, more and more regions of the US are requiring an engineer's professional stamp for one or more aspects of residential design. This is particularly true for seismic and high wind regions of the US. It is only logical that the same degree of professional design be applied to the fire safety aspects of residential construction. The role of engineers in the design of structures for fire is being redefined (Almand and Hurley 2003).

Fire Research

Research in fire safety for housing can be categorized into five areas:

- 1) Fire growth
- 2) Thermal degrade of materials
- 3) Fire endurance
- 4) Toxicity and flammability of materials
- 5) Human behavior and response

A thorough review of these areas is beyond the scope of this paper but a brief description of each is provided below. Areas 2 and 3 are most germane to the focus area of structural design and materials in housing, but all the areas possess some degree of interconnection and all are required in the development of fire safety strategies for housing.

Fire Growth

Fire growth research has the objective to improve predictions of heat and smoke release rates, temperature development, and products of combustion. Fire growth models are critical for evaluating the risks to life safety for a variety of fire scenarios but are usually focused on pre-flashover fires. Models are typically classified as zone models or field models (Buchanan 2001). Most zone models are relatively simple and consider the fire zoen to be broken into two homogeneous layers. Conservation of mass, momentum and energy are applied to each zone along with flow of smoke. Several of these models have been produced by the fire research group at the Building and Fire Research Laboratory of the National Institute of Standards and Technology (NIST) - for example see Peacock (1993). Zhuman and Hadjisophocleous (2000) have presented physical models, numerical methods and verification examples for two-zone fire growth and smoke movement model for multicompartment buildings. This research is important in understanding the nature of structure fires and ultimately it will play a complimentary role in structural models that predict fire endurance.

Other studies have experimentally examined the fire growth introduced by particular materials. For example fiber reinforced composites are being proposed in a wide array of different components or reinforcement strategies for housing and buildings. Often these materials are

proposed for structural reasons and the impact on fire is overlooked emphasizing the need for integrated research that combines structural aspects with fire safety. Ohlemiller and Shields (1999) have examined the flammable aspects of these products and the effectiveness of coatings to inhibit fire growth.

Thermal Degrade of Materials

Understanding and predicting material behavior is key to ultimately developing fire endurance models. Thermal degrade models for materials represents one of the most critical gaps in the development of fire endurance models.

Gypsum board is the primary fire resistant component used in housing in North America and this is unlikely to change in the foreseeable future. In the past 20 years, shipments of gypsum board produced in the United States and Canada for construction in North America have more than doubled to approximately 3.1 billion square meters (12 mm thick basis) (Gypsum Association 2003). Typical use of gypsum board in residential walls and ceilings is prescribed by standard practice and/or by the building code to achieve a particular fire rating. For fire rated assemblies, the fire performance characteristics of a given gypsum board attached to a particular type of framing have been predetermined from results of ASTM E-119 tests for like assemblies. The E119 test lumps together the structural performance and fire performance of the membrane into one simple performance measure. Unlike many other aspects of the building, the structural engineer has no role in designing or specifying the gypsum board. Yet, the gypsum board frequently is a structural element in the design, providing lateral support to structural members and in wood design providing a basis for repetitive member increase. Research to achieve better gypsum board fire barriers represents one of the most achievable and readily implemented areas of advance to improve fire safety in housing.

Thermal properties of gypsum and associated heat transfer models have been reported (Mehaffey et al 1994, Clancy et al 1995, Clancy 2001, Thomas 2002). 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 (Takeda and Mehaffey 1996 and Clancy 1996). Schroeder and Williamson (2000) describe the chemical changes exhibited by gypsum board with increasing temperature. Tsantaridis et al. (1999) have examined the heat transfer through gysum board subassemblies with different sources thickness and noted the important role of the wood supporting frame in the performance of the gypsum board. 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).

Key missing information on the basic mechanical properties of gypsum board have hindered advanced use. Only recently, the mechanical properties of Type X gypsum board at elevated temperatures have been investigated by Cramer et al.(2003). It was hypothesized that if the material properties of gypsum board were known, the time and temperature conditions associated with gypsum board failure in an ASTM E-119 test or other fire condition can be computed. The significance of this research is that once the response of the gypsum board can be categorized and predicted, innovative designs that provide equivalent or superior fire safety can be designed.

Through a series of bending and load-free tests, properties were measured at ambient, 100?C, 200?C, 300?C and 400?C using small scale specimens and at temperatures up to 1000°C using intermediate scale specimens. Because of its ubiquitous use, better understanding and corresponding design changes in gypsum board protected systems has high practical value for enhancing the fire safety of housing.

Research on the thermal degrade of traditional materials such as wood, concrete and steel are fairly well established and further research cannot be deemed a high priority. But composites made of these materials or plastics present new situations that require research. Often the proposers of new materials overlook the need to establish fire performance before proposing use in buildings.

Fire retardant treatments and coatings to be applied to new or traditional construction products offer another aspect to thermal degrade research. Generally, these treatments suppress flame spread but are less effective in inhibiting the thermal degrade in engineering properties.

Fire Endurance

Fire endurance research consists of testing or computational procedures by which the survival time of a 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. A comprehensive test program examining fire endurance of light frame wood and steel assemblies subject to a standardize fire exposure has been conducted in Canada (Richardson 1999, Sultan and Benichou 2003). Sultan (2000) has presented test results that examine the wall to floor joints in multi-family housing.

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 an assembly require information or models at some level of complexity from all the major areas of fire research. 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). Milke (1999) provides a review of many of the fire endurance calculation methods.

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.

Toxicity and Flammability of Materials

Human safety in fire depends on the toxicity and flammability of materials. Table 1 outlined performance limits on the flame spread characteristics of interior linings of walls and ceilings. Housing regulations do not have specific requirements on toxicity. Research contributions in these areas have been sporadic in recent years and because of the prescriptive nature of the building codes, most investigations are directed toward simply establishing code compliance and never published. Blackmore and Delichatsios (2002) have examined different flammability measures of carpeting. Carroll (1996) examined the contribution of burning PVC pipe to the production of dioxin. Morikawa et al. (1993) have measured the production of toxic gases from house fires involving polymers.

Human Behavior and Response to Fire

The area of human behavior and response in fire is a growing area of research. Clearly human response in part defines the exit requirements of housing. Human preferences for open floor plans and fewer partitions influence the fire safety of residential construction. Bryan (1999) has recently provided a review of research in this area. Proulx (1999) and Kose (1999) in separate studies have suggested that usual assumptions of fire exiting are based on young, healthy adults. The aging of the population in developed countries will require a re-examination of the evacuation strategies and assumptions employed in building design. Brennan (1999) has examined human behavior and risk factors as it relates to fire fatalities.

Summary

Statistics show that fire presents one of the most significant hazards and threats to safe housing. Reducing fire-related deaths and property losses cannot rely strictly on rapid fire suppression by the fire service. Explicit engineering-based fire safety design holds the potential to reduce residential fire life and property losses. The emergence of performance-based codes offers a major opportunity for prompting fire safety research and allowing innovation to enter the housing construction market. Performance-based codes will demand 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. To develop these models, however, the database of high temperature properties for traditional and new construction materials must be expanded. While advances in each individual area are needed, the integration of these advances is needed for greatest impact. Current research efforts on fire with the exception of the contributions from NIST are ad hoc and come from a wide variety of organizations and disciplines with the majority of the contributions coming from researchers outside the US. Fire research in the US would be revitalized with a strategic initiative that stimulates and organizes fire research contributions under an umbrella.

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