Improving Fire Safety by Understanding the Fire Performance of Engineered Floor Systems and Providing the Fire Service with Information for Tactical Decision Making

Stephen Kerber, PE
Research Engineer, Corporate Research
Daniel Madrzykowski, PE
Fire Protection Engineer, NIST
James Dalton
Contractor, Corporate Research
Bob Backstrom
Research Engineer, Corporate Research

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Author(s)	**Department**	**Email**
Stephen Kerber	Corporate Research	Stephen.Kerber@ul.com
Daniel Madrzykowski	NIST	madrzy@nist.gov
James Dalton	Contractor	James.Dalton@ul.com
Robert Backstrom	Corporate Research	Robert.G.Backstrom@ul.com

EXECUTIVE SUMMARY

This research project was a collaboration of several research organizations, product manufacturers and fire service representatives to examine hazards associated with residential flooring systems to improve firefighter safety. Funding for this project was provided through the National Institute of Standards and Technology's American Recovery and Reinvestment Act Grant Program. The main objective of this study was to improve firefighter safety by increasing the level of knowledge on the response of residential flooring systems to fire. Several types (or series) of experiments were conducted and analyzed to expand the body of knowledge on the impact of fire on residential flooring systems. The results of the study have been prepared to provide tactical considerations for the fire service to enable improved decision making on the fire scene.

Experiments were conducted to examine several types of floor joists including, dimensional lumber, engineered I-joists, metal plate connected wood trusses, steel C-joists, castellated I-joists and hybrid trusses. Experiments were performed at multiple scales to examine single floor system joists in a laboratory up through a full floor system in an acquired structure. Applied load, ventilation, fuel load, span and protection methods were altered to provide important information about the impact of these variables to structural stability and firefighter safety.

There are several tactical considerations that result from this research that firefighters can use immediately to improve their understanding, safety and decision making when sizing up a fire in a one or two family home.

- Collapse times of all unprotected wood floor systems are within the operational time frame of the fire service regardless of response time.
- Size-up should include the location of the basement fire as well as the amount of ventilation. Collapse always originated above the fire and the more ventilation available the faster the time to floor collapse.
- When possible the floor should be inspected from below prior to operating on top of it. Signs of collapse vary by floor system; Dimensional lumber should be inspected for joist rupture or complete burn through, Engineered I-joists should be inspected for web burn through and separation from subflooring, Parallel Chord Trusses should be inspected for connection failure, and Metal C-joists should be inspected for deformation and subfloor connection failure.
- Sounding the floor for stability is not reliable and therefore should be combined with other tactics to increase safety.
- Thermal imagers may help indicate there is a basement fire but can't be used to assess structural integrity from above.
- Attacking a basement fire from a stairway places firefighters in a high risk location due to being in the flow path of hot gases flowing up the stairs and working over the fire on a flooring system which has the potential to collapse due to fire exposure.
- It has been thought that if a firefighter quickly descended the stairs cooler temperatures would be found at the bottom of the basement stairs. The experiments in this study showed that temperatures at the bottom of the basement stairs where often worse than the temperatures at the top of the stairs.

- Coordinating ventilation is extremely important. Ventilating the basement created a flow path up the stairs and out through the front door of the structure, almost doubling the speed of the hot gases and increasing temperatures of the gases to levels that could cause injury or death to a fully protected firefighter.
- Floor sag is a poor indicator of floor collapse, as it may be very difficult to determine the amount of deflection while moving through a structure.
- Gas temperatures in the room above the fire can be a poor indicator of both the fire conditions below and the structural integrity of the flooring system.
- Charged hoselines should be available when opening up void spaces to expose wood floor systems.

During all of these controlled experiments where the varaiables were systematically controlled there were no reliable and repeatable warning signs of collapse. In the real world, the fire service will never response to two fires that are exactly the same. On the fire ground there are many variables to consider and most of the parameters being considered are often unknown which makes decision making that much more difficult. Information such as how long the fire has been burning, what type of floor system, was it built to code or altered at any point, is it protected with gypsum board, what is the loading on the floor and how long is the span are all unknown to the responding firefighters. There are also no collapse indicators that guarantee the floor system is safe to operate on top of. Sounding the floor, floor sag, gas temperatures on the floor above and thermal imager readings even when taken all together do not provide enough information to guarantee that the floor will not collapse below you. Flooring system components and floor covering materials are composed of materials that work to limit the flow of thermal energy through them. As a result flooring materials could be on fire on the bootom side (basement side) while only exhibiting modest temperature increases on the top side of the floor.

In addition, rapid changes in fire dynamics can result from flow paths created by ventilating the basement and first floor of a structure. These flow paths combined with the fast spreading fire that results from the ignition of an unprotected wood floor system can place firefighters on the floor above the fire in a vulnerable position with little time to react. It is ackowledged that there are times where firefighters may choose to operate on top of a basement fire to carry out their life safety mission however this decision must be made understanding the potential for catastrophic consequences. There are also alternative tactics to consider in order to control the fire without first commiting crews above the fire such as suppression initiated from a basement window or doorway. Coordination to control the basement fire prior to opening the first floor and committing crews on the first floor is essential.

This report summarizes the results from each of the experimental series and provides discussion and conclusions of the results. Each series of experiments was also documented and analyzed independently and these documents are attached as appendices of this report. There is also an online training program that was developed for the fire service based on all of the material included in this research project. It can be accessed for free at www.ul.com/fireservice (Click on “Basement Fires”)

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1. Introduction

This research project was a collaboration of several research organizations, product manufacturers and fire service representatives to examine hazards associated with residential flooring systems to improve firefighter safety. Funding for this project was provided through the National Institute of Standards and Technology's American Recovery and Reinvestment Act Grant Program. The main objective of this study was to improve firefighter safety by increasing the level of knowledge on the response of residential flooring systems to fire. Several types (or series) of experiments were conducted and analyzed to expand the body of knowledge on the impact of fire on residential flooring systems. The results of the study have been prepared to provide tactical considerations for the fire service to enable improved decision making on the fire scene.

Six series of full-scale experiments were conducted to attempt to bridge the gap between single floor system members, sections of floor systems, entire floor systems and floor systems as part of a structure. Variables examined included: fuel load, ventilation, mechanical load, floor support members, and floor system protection methods. Fuel load/thermal exposure was varied as experiments were conducted under standard conditions in a furnace and with fuel loads representative of what would be found in a home. Ventilation was examined by providing varying levels of oxygen to the fire and conducting simulated fire service sequenced ventilation. Mechanical load was varied to examine conservative loads that could be found in a home through full design load as specified in standard test methods. Various joist members were examined to include dimensional lumber, engineered I-joists, metal plate connected wood trusses, steel C-joists, castellated I-joists and hybrid trusses. Floor system protection methods were varied to examine products that are available on the market, technologies that could potentially be deployed and potential code compliant protection methods. In addition to the experiments, modeling of some of the experiments was conducted to further examine the failure mechanisms of the floor systems.

There are many potential contributing factors that influence outcomes during fire ground incidents outside the scope of this research project. Each incident presents a unique set of circumstances addressing the interaction of the responding department to the fire event and circumstances specific to each arriving firefighter. There is a growing concern in the fire service related to whether firefighters receive the degree of training and experience necessary to properly assess the risks on the fire ground. The number of structure fires is decreasing; therefore firefighters need additional resources to gain the knowledge to understand fire progression, fire behavior and what happens to the structural integrity of a building under fire conditions.

This project seeks to limit its investigation to the parameters that can be evaluated through experimentation to examine the cause and effect relationships regarding the topics of fire behavior, the impact of exposed combustible structural elements under fire conditions and the potential for structural collapse of the effected assemblies. The work reported in this report is intended to provide tactical considerations determined by the research results to allow for better firefighter training and education to assist firefighters with risk analysis and decision making. Decision making based on the results of formalized fire research may in fact be one way to assist firefighters in making up for the loss of actual fire ground experience due to a continuing reduction in structure fires.

This report brings the results from each of the experimental series together and provides discussion and conclusions of the results. Each series of experiments was also documented and analyzed independently and these documents are attached as appendices of this report.

2. Objectives and Technical Plan

The objectives of this research project include:

- Improving firefighter safety by further educating them of the hazards associated with fires involving residential flooring systems.
- Understanding the impact of span, fuel load, ventilation and fire location to system failure.
- Working with the engineered products manufacturers to design products to meet fire performance and mechanical performance standards.
- Examine different fire protection methods and develop data to assess their effectiveness.
- Effectively model the impact of fire insult on engineered flooring systems.
- Provide scientific data to substantiate code changes related to residential floor systems to result in improved building fire safety.
- Provide valuable test database to the fire community for validation of computer-aided engineering models.

The technical plan for this project includes Tasks 1 through 11 as shown in Figure 1. Each of the six experimental series is described below with the Appendix location of the full report for each series.

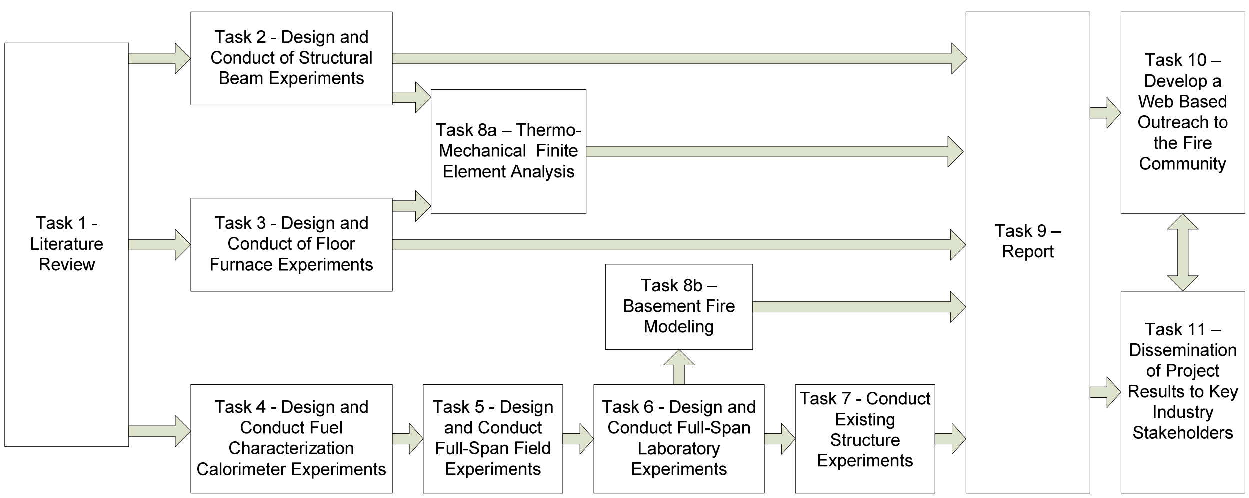

Figure 1. Experimental Flow Chart

Literature Review (Task 1): Prior to the start of experimentation a variety of related topics were researched: documented Line of Duty Injuries (LODI) and Line of Duty Deaths (LODD) involving unprotected combustible dimensional and engineered lumber assemblies, the fire endurance performance of unsheathed combustible wood assemblies; inclusive of informal fire service testing, floor furnace testing, full scale laboratory and site testing, and a review of related fire service publications. The literature search was conducted in order to review and evaluate previous research methodologies utilized in the testing of unsheathed combustible dimensional and engineered lumber assemblies. This information was then referenced during the development of the various research variables for the current study.

The literature search was composed of six main activities: a review of the National Engineered Lightweight Construction Fire Research Project (NELCFRP) sponsored by the National Fire Protection Research Foundation (NFPRF) in October of 1992 (Grundahl, 1992), a complete review of the literature cited in the NFPRF bibliography, a review of documented injuries in the International Association of Fire Chiefs (IAFC) firefighter near miss reporting system, a review of the documented LODDs in the NIOSH Firefighter Fatality Investigation Program, a general internet search, a technical publication search and a fire service publication search.

Structural Beam Experiments (Task 2): To accomplish this experimental series UL partnered with Michigan State University. To evaluate the fire resistance of these engineered wood joist systems, fourteen wood beams were tested at MSU's structural fire test facility (Figure 2). The tests covered four types of wood joists used in traditional and more modern construction. The test variables included type of wood joist, support conditions, fire insulation, and load level. The fire resistance tests were carried out by exposing the loaded wood joists to ASTM E-119 fire exposure. Results from these tests indicate that legacy dimensional lumber performs significantly better under fire exposure than engineered joists. Data generated from the fire resistance tests including temperatures, displacements, and strains in fourteen tested beams are presented in Appendix A. Also, data from the fire tests is utilized to discuss the effect of different parameters on the fire resistance of wooden floor joists.

Figure 2. MSU's Beam Testing Furnace

Floor Furnace Experiments (Task 3): Seven fire experiments were conducted on floor systems constructed on UL's floor furnace (Figure 3), to develop comparable fire performance data. All assemblies were intended to represent typical residential construction and included dimensional lumber, engineered wood "I" joists and trusses. The assemblies did not include a ceiling and were considered unprotected floor assemblies representative of a basement with no ceiling membrane. Two of the assemblies were coated with a topical treatment to assess its ability to provide protect the wood floor components from thermal exposure.

Figure 3. UL Floor Furnace from Above

The seven fire experiments complied with the requirements of ASTM E119 however the applied structural load was modified for 4 of the 7 assemblies. For these assemblies, a uniform load was applied on the floor to fully stress the supporting structural members. The other 3 assemblies had a load placed on them that was intended to represent a conservative residential loading condition. A load of 40 lb/ft^2 was placed along two of the four edges of the floor assemblies to represent loads around a perimeter of a room, such as furniture. On each sample, two 300 pound concentrated loads were placed near the center of the sample. A mannequin, intended to simulate fire service personnel, represented each concentrated load. Data generated from theses seven fire resistance tests included temperatures, displacements, pressures and oxygen concentrations which are presented in detail in Appendix B.

Fuel Characterization Calorimeter Experiments (Task 4): UL conducted a series of experiments to characterize the fuel load selected for the subsequent full-span experiments (Figure 4). Three experiments were conducted examining the burning characteristics of combinations of pallets, boxes filled with expanded polystyrene trays. This allowed for measurement of heat release rates to better understand the fire behavior in the subsequent experiments. Ventilation and the amount of available oxygen play an important role in the fire behavior and spread. The fuel load was chosen to simulate contents that could be found in a residential basement and to be easily reproducible. The boxes of foam have similar burning characteristics to synthetic products such as polyurethane upholstered furniture and plastic storage bins or toys. The pallets have similar burning characteristics as natural products such as wood furniture. Together the fuel load was designed to create sustained burning and ventilation limited conditions to represent those that would be seen in an actual fire event. Full details of the results of these experiments are located in Appendix C.

Figure 4. UL's Calorimeter Test Laboratory

Full-Span Field Experiments (Task 5): A series of 10 experiments was conducted by UL in collaboration with NIST at a fire training academy to examine 4 different residential flooring systems while varying, ventilation parameters, fuel load and floor loading (Figure 5). The purpose was to test engineered systems at their full span capabilities under simulated realistic fire conditions. These experiments consist of a simulated basement covered by a floor/truss system and a stairwell to an enclosed first floor.

This series of experiments allowed for the assessment of variables that have not been thoroughly analyzed in previous studies, such as the use of longer and more realistic floor span lengths, more realistic and varied fire loads, different ignition locations in the basement, bounded and more realistic ventilation scenarios, and additional engineered floor system products. A detailed structural analysis compares modes of failure between the different experiments, code change implications are discussed and most importantly the impact of firefighter operations is examined based on all of the experimental results. Detailed analysis and results of these experiments are located in Appendix C.

Figure 5. Field Experiment Test Structures

Full-Span Laboratory Experiments (Task 6): UL conducted four real-scale experiments in its large-scale fire test facility. The structure used for these experiments was of the same dimensions as the field experiments with the same openings (Figure 6). The differences include wood stud walls as opposed to concrete block and the lack of an enclosed first floor above the basement. This structure had the stairwell going up to the first floor but the doorway was open to the outside with no enclosure. These experiments

Figure 6. Laboratory Experiment Test Structure

utilized two wood I-joist floor systems and 2 parallel chord wood truss floor systems. The fuel load was the same as that described in the heat release rate experiments, the loading was similar to that used in the field experiments and the ventilation was “maximum” for all of these experiments. The main variable that was able to be controlled during these experiments was the weather. Temperature was regulated and there were no wind effects during these experiments. The complete analysis of this series of experiments is located in Appendix C.

Existing Structure Experiments (Task 7): UL and NIST collaborated to conduct 4 experiments in two homes scheduled for demolition in Bensenville, IL (Figure 7). Each experiment was ignited in the fuel package in the basement. One experiment in each home was with all of the basement windows closed and the second was with the basement windows opened. The second experiment in each home continued until floor collapse and eventual total home involvement in fire. Temperatures were measured throughout the home and other measurements included gas velocity, gas concentrations and heat flux. The complete analysis of this series of experiments is located in Appendix D.

Figure 7. Two Structures used for Experiments

Thermal and Structural Finite Element Modeling (Task 8): Finite element models for two assemblies were be built based on data developed from the previous tests to develop inputs for and to validate fire models and compared to fire performance demonstrated in the other experiments (Figure 8). The validation process of these two assemblies was carried out in multiple steps. The support structures for these two assemblies were modeled and compared with the data from Task 2. Task 3 was used to assess the performance of the two assemblies subjected to the standard fire curve described within the ASTM E 119/ UL 263. Finally, the predictions of the two full-scale models were compared against data from Tasks 4/5.

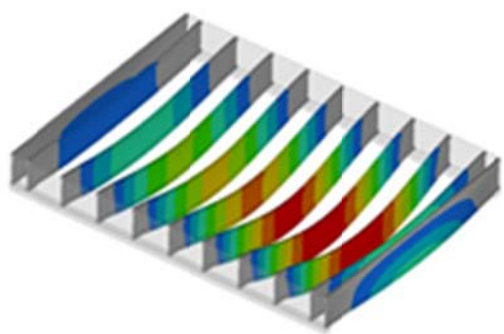

Figure 8. Finite Element Model of an Engineered I-joist Floor System

Report (Task 9): Each series of experiments completed as part of this study has its own stand-alone report that is included as appendices in this summary report.

Develop a Web-based Outreach for the Fire Community (Task 10): An interactive web based training program for firefighters and other members of the fire community was developed and is available at www.ul.com/fireservice. It consists of 8 modules and includes videos and outlines the results of this research program.

Dissemination of Project Results to Key Industry Stakeholders (Task 11): The results of this research program are available to all industry stakeholders at www.ul.com/fireservice.

3. Background

Light-weight engineered floor systems provide architectural, economic and productivity benefits to the homeowner and the construction industry with assumed status quo in fire safety. However, under fire conditions, these light-weight engineered floor systems lead to greater risk of structural failure in a shorter time as a consequence of the reduced cross-sectional dimensions of the engineered products as compared to traditional dimensional lumber floor systems. So, despite the superior structural performance of these new products to traditional lumber construction under 'normal' conditions, the trend reverses in a fire environment. This is highlighted by the increasing number of firefighter fatalities due to collapse of these engineered systems under fire conditions. The National Institute for Occupational Safety and Health (NIOSH) issued a report, Preventing Injuries and Deaths of Fire Fighters Due to Truss System Failures,highlighting the risks of injury and death that can occur during fire-fighting operations involving engineered floor truss systems.

Recent research by various organizations, including UL , NIST , NFPA and National Research Council Canada , provided evidence of the greater risk in structural failure of engineered floor systems in fire events. This research work was limited to validating the problem in a single scenario (single floor span length, single fire location and limited engineered lumber products). For example, previous research focused on exposing engineered wood assemblies to fire conditions at a 14 ft. span comparable to that achievable by dimensional lumber. One of the significant advantages of the engineered floor systems is their ability to span longer distances in excess of 30 ft. However, anecdotal evidence suggests that the longer spans potentially create greater hazards to failure when exposed to fire conditions.

The construction industry is continually introducing new engineered products that provide better structural stability, allow for faster construction time and are more cost effective. Additionally, the market for green or environmentally sustainable building materials experienced a growth rate of 23% through 2006 and is expected to continue growing at a rate of 17% through 2011 according to Green Building Materials in the U.S. The increased market demand for environmentally sustainable products is driving engineered lumber products to further reduce material mass that could potentially result in even further concern for fire safety in building construction today.

Engineered floor products provide financial and structural benefits to building construction, however, adequate fire performance needs to be addressed as well. Adequate fire performance provides a necessary level of safety for building occupants and emergency responders responsible for mitigating fire incidents. Additional research is needed to assess other typical scenarios (including longer floor span lengths, various fire locations, other engineered floor system products) and fire protection technologies to protect engineered products to identify and validate potential solutions to address and mitigate the critical fire safety problem.

4. Literature Review

Several research projects that have been undertaken to evaluate the fire endurance performance issues of unprotected wood assemblies. Prior to the start of this experimentation a variety of related topics were researched: documented Line of Duty Injuries (LODI) and Line of Duty

Deaths (LODD) involving unprotected combustible dimensional and engineered lumber assemblies, the fire endurance performance of unprotected combustible wood assemblies; inclusive of informal fire service testing, floor furnace testing, full scale laboratory and site testing, and a review of related fire service publications. The literature search was conducted in order to review and evaluate previous research methodologies utilized in the testing of unprotected combustible dimensional and engineered lumber assemblies. This information was then considered during the development of the various research parameters for the current study.

There has been an overall decline in the numbers of U.S. firefighter deaths since 1977. (Fahy, 2010) This fact is aligned with similar declines in the annual number of structure fires for the same period. However, while there has been an overall decline in both the number of fires and the number of fire fighter fatalities, statistically firefighters are more likely to experience a traumatic injury while operating inside of a structure.

Dr. Rita Fahy cited this counterintuitive trend, "The one area that had shown marked increases over the period is the rate of deaths due to traumatic injury while operating inside a structure. In the late 1970s, traumatic deaths inside structure fires occurred at a rate of 1.8 deaths per 100,000 structures fires and by the late 1990s had risen to approximately 3 deaths per 100,000 structure fires". (Fahy, 2010) The major causes of these traumatic injuries inside structures were determined to be firefighters becoming lost inside, structural collapse, and rapid fire progression (including backdraft, flashover and explosion).

Specific to this research project is the nature of firefighter injuries and deaths due to structural collapse, more specifically the structural collapse of dimensional lumber and/or engineered lumber floor and/or roof assemblies. General trends for incidents investigated by the National Institute of Occupational Safety and Health (NIOSH) Firefighter Fatality Investigation Program were analyzed for the purposes of determining the involved structural systems. The NIOSH Firefighter Fatality Investigation Program provides the most detailed public incident data for fatalities that have occurred since the inception of the program in 1997. There have been 18 collapses documented by the program, 11 dimensional lumber systems and 7 engineered floor systems, 4 roof assemblies and 14 floor assemblies.

Fatalities that have been investigated by the NIOSH Fatality Investigation program alone does not provide the entire picture regarding the number of overall annual occurrences of residential structural collapse on the fire ground. Another web-based database created in 2005 by the International Association of Fire Chiefs (IAFC) with the sponsorship of a Department of Homeland Security, Federal Emergency Management Agency (DHS/FEMA) Assistance to Firefighters Grant (AFG) allows for the reporting of firefighter near-miss occurrences. Another website, www.firefighterclosecalls.com has been set up to describe near-miss incidents. This site identifies the injured firefighters and fire departments.

The National Institute of Standards and Technology (NIST) conducted a review of data from both websites for the period from January 2005 to March 2011. There were 118 incidents reported that involved residential structural collapse. Seventy-six incidents resulted in 128 firefighters being injured. (Madrzykowski, 2011)

Fire resistive testing methodologies are very well established for combustible assemblies designed to achieve an hourly fire resistive rating with passive fire protection. Less understood is the structural stability of unprotected combustible dimensional and engineered lumber assemblies exposed to fire conditions. When combustible wood assemblies are constructed without the protection of passive fire resistive technologies or active suppression systems, both dimensional and engineered lumber assemblies are vulnerable to collapse within the operational timeline of fire suppression operations.

Subsequent to numerous LODI and LODDs fire service organizations have attempted to highlight performance failures noted during real life fire incidents through non-standard demonstrative testing methods. Due to a lack of adequate funding, testing experience and proper facilities these demonstrative tests document the failure times of the unprotected combustible assemblies without consistency with respect to the parametric criteria normally accounted for by standardized fire resistance testing methodologies, i.e. demonstrative testing was traditional conducted in open air environments which added a degree of ventilation variability and may not represent the ventilation limited environment of a basement or attic.

Fire service demonstration examples include roof system demonstrations completed by the Los Angeles City Fire Department in 1981 (Mittendorf, 1982), floor system collapse demonstrations by the Illinois Fire Service Institute in 1986 (Straseske, 1988). Collapse times ranged from: 4 minutes and 40 seconds for the engineered I-Joist floor system, 13 minutes for the 2x10 dimensional lumber floor system, and 15 minutes and 45 seconds for the floor constructed with metal plate connected trusses.

Numerous agencies have gone beyond demonstrations to examine unprotected floor assemblies. There are a limited number of documented Non-Standardized tests of unprotected combustible assemblies that conform to the ASTM E119, "Standard Methods of Fire Tests for Building Construction and Materials." Non-standardized tests conform to most of the requirements of the ASTM E119 standard, the exception being loading.

The National Engineered Lightweight Construction Fire Research Project (NELCFRP) sponsored by the National Fire Protection Research Foundation (FPRF) in October of 1992 (Grundahl, 1992), was utilized as a resource for referenced literature published prior to 1992. One overall objective of the NELCFRP was to define the actual fire performance characteristics of engineered components through a review of existing documented research. The components examined solid-sawn (e.g., nominal 2 x 10) wood joists, metal plate connected (MPC) wood trusses, MPC metal-web wood trusses, pin-end connected steel-web wood trusses, engineered wooden I -joists, composite wood joists, steel bar joists, and light gauge steel C joists.

The components examined in this study include: metal plate connected (MPC) wood trusses, MPC metal-web wood trusses, pin-end connected steel-web wood trusses, wooden I -joists, solid-sawn (e.g., 2 x 10) wood joists, composite wood joists, steel bar joists, and steel C joists. Table 1 provides a summary of the testing cited for Non-Standardized ASTM E-119 furnace testing conducted with modified loading conditions respective of the structural elements being examined for this research project.

Table 1. Non-Standardized ASTM E-119 Furnace Testing (Grundahl, 1992)

Test	Structural Member	Spacing	Structural Failure (min:sec)	Loading (psf) - % Design Stress
NBS 421346 (Son B. , Fire Endurance Tests of Unprotected Wood-Floor Construcitons for Single Family Residences: NBSIR 73-263, 1973)	2 x 10; ½ in. ply. w/blk	16 in. o.c.	11:38	21.0[1] (40%)
FPL (R.H. White, 1983)	2 x 10	16 in. o.c.	13:06	40.0[1]
FPL (R.H. White, 1983)	2 x 10; 23/32" ply.	16 in. o.c.	16:48	11.35[1]
FPL (R.H. White, 1983)	2 x 10; 23/32" ply.	16 in. o.c.	18:00	11.35[1]
FPL (R.H. White, 1983)	2 x 10; 23/32" ply.	16 in. o.c.	18:24	11.35[1]
FPL (R.H. White, 1983)	2 x 10; 23/32" ply.	16 in. o.c.	18:30	11.35[1]
NBSIR 73-141 (Son B. a., 1973)	6 x 1¾ in. C-joist; 3/4" ply. w/carpet	24 in. o.c.	3:45	51.4[1]
NBSIR 73-164 (Son B. , Fire Endurance Test of a Steel Sandwich Panel Floor Construciton, NBSIR 73-164, 1973)	6 x 3 in. 14 ga C-joist; top and bottom 3/8” ply.	48 in. o.c.	9:00	40.0[1]
BMS 92 (Subcommittee on Fire Resistence Classifications of the Central Housing Committee on Research, 1942)	2 x 10; 3/4” ply.	16 in. o.c.	N/A[2]	N/A[3]

1 Assumed to be a limited load test. Loading not 100% of design load.

2 Ultimate fire resistance time period for exposed wood joists was 15 min.

3 Loading developing 1000psi maximum fiber bending stress.

In 2008, Underwriters Laboratories Inc. conducted floor furnace tests on nine assemblies as part of a fire research and education grant sponsored by the Fire Prevention and Safety Grants under the direction of the Department of Home Security/Federal Emergency Management Agency/Assistance to Firefighters Grants. The nine fire tests complied with the requirements of ASTM E119 but the applied structural load was non-traditional. Typically, a uniform load is applied on the floor or roof to fully stress the supporting structural members. This load is generally higher than the minimum design load of 40 psf specified by the building code for residential construction. For the tests conducted in this study the loading was modified to represent typical conditions during a residential fire. A load of 40 psf was placed along two of the four edges of the floor – ceiling assemblies to represent loads around a perimeter of a room. On each sample, two 300 pound concentrated loads were placed near the center of the sample. A mannequin, intended to simulate fire service personnel, represented each concentrated load. Table 2 details the tests and their collapse times.

Table 2. Summary of Test Samples (Underwriters Laboratories, Inc., 2008)

Assembly	Supports	Ceiling	Floor or Roof	Collapse Time (mm:ss)
1	2 by 10s @ 16 inch centers	None	1 by 6 subfloor & 1 by 4 finish floor	18:45
2	12 inch deep "I" joist @ 24 inch centers	None	23/32 inch OSB subfloor, carpet padding & carpet	06:03
3	2 by 10s @ 16 inch centers	1/2 inch gypsum wallboard	1 by 6 subfloor & 1 by 4 finish floor	44:45
4	12 inch deep "I" joist @ 24 inch centers	1/2 inch gypsum wallboard	23/32 inch OSB subfloor, carpet padding & carpet	26:45
5	Parallel chord truss with steel gusset plate connections, 14 inch deep @ 24 inch centers	1/2 inch gypsum wallboard	23/32 inch OSB subfloor, carpet padding & carpet	29:15
6	Parallel chord truss with glued connections, 14 inch deep @ 24 inch centers	1/2 inch gypsum wallboard	23/32 inch OSB subfloor, carpet padding & carpet	26:45
7	2 by 6s @ 16 inch centers with 2/12 pitch	1/2 inch gypsum wallboard	1 by 6 roof deck covered with asphalt shingles	40:00
8	2 by 10s @ 16 inch centers	3/4 inch plaster	1 by 6 subfloor & 1 by 4 finish floor	79:45
9	Roof truss with steel gusset plate connections @ 24 inch centers with 2/12 pitch	1/2 inch gypsum wallboard	7/16 inch OSB covered with asphalt shingles	23:15

There have also been floor furnace experiments conducted to the ASTM E119 standard with loading of 100 percent of the design stress. These tests were compiled as part of the National Engineered Lightweight Construction Fire Research Project (NELCFRP) sponsored by the National Fire Protection Research Foundation (FPRF) in October of 1992 (Grundahl, 1992). The majority of the tests conducted were of unprotected dimensional lumber floor assemblies. A summary of these tests results is shown in Table 3.

Table 3. Standardized ASTM E-119 Furnace Testing (Grundahl, 1992)

Test	Structural Member	Spacing	Structural Failure (min:sec)	Loading (psf) - % Design Stress
FM FC 209 (Factory Mutual Research, 1974)	2 x 10; 23/32" ply. w/vnl	24 in. o.c.	13:34	62.1 (100%)
FM FC 212 (Factory Mutual Research , 1974)	2 x 10; 23/32"ply. w/cpt	24 in. o.c.	12:06	62.4 (100%)
NBS 421346 (Son B. , Fire Endurance Tests of Unprotected Wood-Floor Construcitons for Single Family Residences: NBSIR 73-263, 1973)	2 x 10; 1/2" & 5/8" ply.	16 in. o.c.	11:38	63.7 (100%)
FPL (R.H. White, 1983)	2 x 10; 23/32" ply.	16 in. o.c.	6:12	79.2 (100%)
FPL (R.H. White, 1983)	2 x 10; 23/32" ply.	16 in. o.c.	6:48	79.2 (100%)
FPL (R.H. White, 1983)	2 x 10; 23/32" ply.	16 in. o.c.	7:30	79.2 (100%)
FPL (R.H. White, 1983)	2 x 10; 23/32" ply.	16 in. o.c.	5:30	79.2 (100%)
FPL (R.H. White, 1983)	2 x 10; 23/32" ply.	16 in. o.c.	6:18	79.2 (100%)
FM FC 250 (Factory Mutual Research , 1977)	12 in. MPCT; 3/4" ply.	24 in. o.c.	10:12	60.0 (100%)
FM FC 208 (Factory Mutual Research , 1974)	7¼ in. Steel C-joist; 23/32"ply. w/vnl	24 in. o.c.	7:30	69.8 (100%)
FM FC 211 (Factory Mutual Research, 1974)	7¼ in. Steel C-joist; 23/32"ply. w/cpt	24 in. o.c.	5:12	69.8 (100%)

In December of 1980 the Center for Fire Research at the National Engineering Laboratory National Bureau of Standards authored, "Fire Performance of Selected Residential Floor Construction Under Room Burnout Conditions" (Fang, 1980). A series of seven large-scale room burnout fire tests were conducted with a set of selected residential floor to ceiling assemblies to provide data on the performance of the assemblies; these assemblies were then compared to future tests on the same constructions in a fire endurance furnace. Four wood frame and three light gauge steel-frame, load bearing assemblies, each measuring 10.7'x 10.7' in size, were exposed from the underside to a fire environment produced from the burning of typical furniture and interior finished material in a room. A summary of these tests results is shown in Table 4.

Table 4. Non-Standardized Test Results (Fang J. , 1980).

Structural Member	Spacing	Plywood Subfloor Thickness	Structural Failure (min:sec)	Loading (psf)
2 x 8 wood joist	16 in. o.c.	5/8	10:43	40.00
7-1/4 steel joist	24 in. o.c.	5/8	3:47	72.00
7-1/4 steel joist	32 in. o.c.	3/4	3:59	40.00
2 x 8 wood joist	24 in. o.c.	23/32	12:00	40.00
7-1/4 steel joist	24 in. o.c.	23/32	15:58*	67.0
12 MPCT[1]	24 in. o.c.	23/32	18:34	67.0
2 x 8 wood joist	24 in. o.c.	23/32	35:18*	40.0

[1] MPCT = Metal Plate Connected Truss

* No joist collapse, times refer to excessive deflection rate.

In 2008, Tyco International conducted a series of five comparative demonstrative tests. This project was entitled, "The Performance of Composite Wood Joists Under Realistic Fire Conditions" (Tyco Fire Suppression & Building Products , 2008). This project created a simulated one room furnished basement fire. The test setup represented a seating area that had been located in a basement. The room measured 16 ft. x 16 ft. with a ceiling height of 8 ft. to 9 ft. 2 in. depending upon the floor assembly tested. The ceiling was constructed of 11-7/8 in. deep composite wood I-joists spaced at 24 in. centers. The floor was loaded with a total live load of 1280 lbs or about 5 lbs/ft2. The load consisted of two 300 pounds firefighter mannequins and concrete cinder blocks. Three sprinkler scenarios were evaluated as part of this program; including a single sidewall sprinkler, four pendent sprinklers and a single pendent sprinkler. The remaining two unsprinklered tests (i.e. "freeburn") were performed using the same fire scenario and structural loading as the sprinklered tests with exposed composite wood joists. The report documents the ability for the three sprinkler designs tested to significantly control the fire event, limit the fire damage to areas local to the ignition source and inhibit the fires ability to involve and compromise the structural elements. Two unsprinklered tests were conducted. The first unsprinklered "freeburn" test documented flashover at 7:09 with structural collapse at 11:30. The second unsprinklered "freeburn" test documented flashover at 5:15 and structural collapse at 8:34.

In 2009, the National Research Council Institute for Research in Construction (NRC-IRC) conducted the experiments in the report titled, "Fire Performance of Houses. Phase I Study of Unprotected Floor Assemblies in Basement Fire Scenario" (Su, 2009). This project seeks to research fires in single-family houses to determine factors that affect the life safety of occupants. The safety of emergency responders in a fire originating in single-family houses was not within the scope of the NRC-IRC research project. The research established a typical sequence of events such as the smoke alarm activation, onset of untenable conditions, and structural failure of test assemblies, using specific fire test scenarios in a full-scale test facility. This test facility (referred to as the test house hereafter) simulated a typical two-story detached single-family house with a basement, which complied with the minimum requirements in the National Building Code of Canada (NBCC).

The experimental facility represented a typical two-story single-family house with a basement. Each story of the test facility had a floor area of 1022 ft2 and a ceiling height of 8 ft. The basement was partitioned to create a fire room (17'- 4" by 17'-1" wide) representing a basement living area. The structure provided for a doorway from basement and the first floor, removable exterior windows and operable interior doorways. Ventilation utilizing these devices were provided to replicate the timeline of fire induced ventilation conditions coupled with additional ventilation provided by occupant evacuation.

The full-scale experiments addressed the life safety and egress of occupants from the perspective of tenability for occupants and structural integrity of structural elements as egress routes. A range of engineered floor systems, including wood I-joist, steel C-joist, metal plate and metal web wood truss assemblies as well as solid wood joist assemblies, were used in the full-scale fire experiments. A single layer of oriented strand board (OSB) was used for the subfloor of all assemblies without additional floor finishing materials on the test floor assemblies. Floor assemblies loaded with self-weight assembly dead loads and a uniform imposed live load of 20 psf. A summary of these tests results is shown in Table 5.

Table 5. Non-Standardized Test Results (Su, 2009)

	Open Basement Doorway		Closed Basement Doorway	
Assemblies Tested	**Test**	**Structural Failure (min:sec)**	**Test**	**Structural Failure (min:sec)**
2x10 Solid Wood Joist	UF-01	12:20	UF-02	20:00
11-7/8 in. Wood I-Joist A	UF-03	8:10	UF-09	12:58
8 in. Steel C-Joist	UF-04	7:42	-	
12 in. Metal-plate wood truss	UF-05	7:49	-	
11-7/8 in. Wood I-Joist B	UF-06.	6:22	-	
	UF-06R	6:20	-	
	UF-06RR	6:54	-	
12 in. Metal web wood truss	UF-07	5:25	UF-08	7:54

Note:

1. In addition to the solid wood joists assembly, two engineered floor assemblies – one with the longest time and the other with the shortest time to reach failure in the open basement doorway scenario – were selected for testing with the closed basement doorway.

In all experiments with the open basement doorway, the structural failure occurred after the inside of the test house had reached untenable (incapacitating) conditions. Results from replicate tests gave very repeatable durations to structural failure. Having a closed door to the basement limited the air available for combustion, given the relatively small size of the basement window opening, and prolonged the times for the test assemblies to reach structure failure (from 50-60% longer than with the open basement doorway).

In 2011, the National Research Council Institute for Research in Construction (NRC-IRC) issued Summary Report NRCC-54007, "Fire Performance of Protected Ceiling / floor assemblies and impact on tenability." (Su, 2009). This project seeks to research fires in single-family houses with protected ceiling and floor assemblies to determine factors that affect the life safety of occupants.

After a previous study of unprotected floor/ceiling assemblies under basement fire scenarios, a further experimental program was undertaken to investigate the performance of protected floor/ceiling assemblies and the tenability conditions in a test facility representing a two-story detached single-family house.

A series of full-scale fire experiments were conducted using four types of floor systems (wood I-joist, steel C-joist, metal web wood truss and solid wood joist assemblies), which were selected from the assemblies that had been tested in the previous study. The test floor assemblies were protected on the basement side (the fire exposure side) by a regular gypsum board ceiling, residential sprinklers or a suspended ceiling. Table 6 details the failure times for each experiment.

Table 6. Comparative Structural Performance Timelines for Experiment (in seconds)

Test Number	Test Assembly Structure	Structural Failure	Increased Time for Structure*
Protection by Gypsum Board			
PF-01	Solid-sawn wood joist	1320	580
PF-02	Steel C-joist	1320	858
PF-04	Wood I-joist	1247	757
PF-06C	Metal-web wood truss	1424	1099
Protection by Suspended Ceiling			
PF-05	Wood I-joist	638	148
Protection by Residential Sprinklers			
PF-03	Wood I-joist	not reached	unlimited
PF-03B	Wood I-joist	not reached	unlimited
PF-06	Metal-web wood truss	not reached	unlimited

* The increase in the time taken to reach structural failure from the unprotected assembly from previous experiments as compared to a similar protected assembly.

In 2011, Four real-scale experiments were conducted by the National Institute of Standards and Technology to measure the temperatures above and below a wood floor assembly exposed to fire conditions from below (Madrzykowski, 2011). The objectives of the experiments were: 1) to examine the heat transfer through a wood floor assembly and 2) to examine the ability of a thermal imager to determine the potential severity of the fire beneath the floor assembly and the ability to provide a sense of the structural integrity of the floor assembly in order to provide improved situational awareness.

Each experiment was conducted in a wood framed two story structure. Each story consisted of a single compartment with interior dimensions of approximately 15.3 ft x 15.9 ft x 8.0 ft high. The initial fuel in each experiment consisted of six wood pallets and hay in the center of the lower level compartment. Three of the experiments had engineered I-joist floor systems and one had a solid sawn limber floor system.

Gas temperatures of the upper and lower compartments as well as the surface temperatures of the floor assembly were measured with thermocouples (TCs). Three commercially available thermal imagers (TIs), each with a different type of sensor were used to view and record the thermal conditions of the top of the floor assembly from the open doorway in the upper compartment. Times to collapse of each floor were also noted. Given the insulating effects of the OSB and the floor coverings, the temperature increase or thermal signatures viewed by the TIs were small given the fact that the ceiling temperatures below the OSB were in excess of 1112 ºF.

These experiments demonstrated that TIs alone cannot be relied upon to determine the structural integrity of a wood floor system. Therefore, it is critical for the fire service to review their practice of size-up and other fire ground tactics needed to enable the location of the fire prior to conducting fire operations inside a building. The United States Fire Administration (USFA) provided support for this project.

4.1 Literature Review Summary

A significant amount of work has been conducted, utilizing a variety of scales and methods, to evaluate the performance of unprotected combustible wood floor assemblies. An identified trend exists in the most recent research to conduct full scale testing using equivalent content fire loading to evaluate the anticipated fire behavior and structural performance encountered during actual fire events. A more complete literature review can be found in Appendix C.

This study will continue the full scale experiment trend and in addition will include a variety of ventilation conditions to evaluate the structural performance of unprotected residential floor assemblies under a multitude of possible developed fire conditions.

The current project will also seek to address gaps in the previous literature with regard to standardized testing methodologies. Although there is a significant amount of data in this area, currently gaps exists in the area of unprotected assembly testing and newly developed technologies introduced into the residential market place.

The testing parameters developed for this project will determine a comparative timeline of performance for the assemblies tested with respect to national fire department response and operational timelines as compared to both structural instability as well as structural collapse. Additional efforts will also be made to provide a consistent description and analysis of the failure mechanisms for the tested assemblies with the intent of providing the fire service with an understanding regarding the identification of a potentially dangerous damaged floor assembly.

5. Experimental Series and Results

A brief description and summary of the results for each series of experiments described in the technical plan is included in this section. Due to the magnitude of each of these experimental series they were each documented such that they could stand-alone in their own report. These reports that contain the details of experimental set-up, methodology, and instrumentation can be found in the Appendix.

5.1. Fire Resistance Tests on Wood and Composite Wood Beams

For this study, beams were tested at MSU's structural fire test facility subjected both to mechanical loadings and thermal loadings following the ASTM E-119 fire exposure profile. A series of fourteen fire tests were conducted on both dimensional lumber and three types of modern engineered lumber. Table 7 shows the experimental series and the variables examined.

Table 7. Beam Experimental Series

Joist #	Joist Type	Joist Depth (in)	Axially Restrained	Sheathing	Joist Insulation	% of Design Load	Special Features	Failure Time (min:sec)
T1	Dimensional lumber	9 1/4	No	No	-	~70	-	15:35
T2	Dimensional lumber	9 1/4	Yes	No	-	~70	-	13:05
T3	Dimensional lumber	9 1/4	No	Yes	-	~50	-	16:40
T4	Dimensional lumber	9 1/4	Yes	Yes	-	~50	-	20:40
T5	Dimensional lumber	9 1/4	Yes	Yes	-	~70	-	16:50
E1	Engineered I-joist	11 7/8	No	Yes	-	~50	-	6:15
E2	Engineered I-joist	11 7/8	Yes	Yes	-	~50	-	6:25
E3	Engineered I-joist	11 7/8	Yes	Yes	Intumescent coating	~50	-	24:05
C1	Castellated I-joist	16	No	Yes	-	~50	-	7:10
C2	Castellated I-joist	16	Yes	Yes	-	~50	-	6:50
H1	Hybrid joist	14	No	Yes	-	~50	-	6:00
H2	Hybrid joist	14	Yes	Yes	-	~50	-	6:00
H3	Hybrid joist	14	Yes	Yes	-	~50	Reinforced connection	6:20
H4	Hybrid joist	14	Yes	Yes	-	~50	Reinforced connection	6:50

The beam only tests confirm the significant performance difference observed for full flooring systems. Traditional lumber beam with rectangular cross section did outperform the engineered wood I-joist in these fire tests. These results show the potential for assessing the fire performance of new wood-based constructions using simple single beam fire tests.

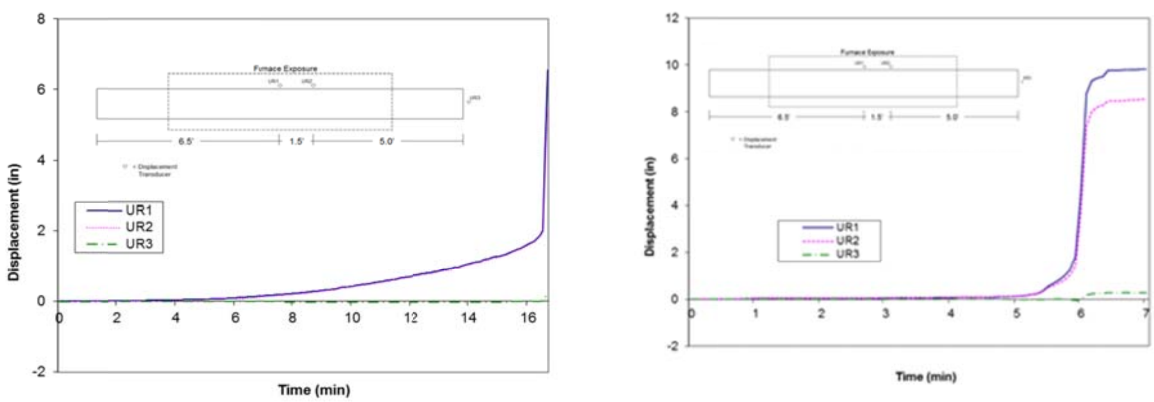

Figure 9. Deflections for traditional lumber beam (left) and engineered wood I-joist (right)

In addition, the availability of video of the burning process for the beams provided insight into the failure path. For the engineered wood I-joists, the failure sequence involves the burnout of the thin web, thereby creating a sudden drop in stiffness as the lower chord, though mostly un-burnt is no longer available for loading sharing.

Figure 10. Image from video of flaming of web for I-joist fire test

The design of these beam only tests gave consideration to the use of the test data for validation of computer models. In such cases, the test must be designed to provide measurements throughout the specimen especially at key locations where high gradients in variables such as temperature or deflection are expected. In addition, the boundary conditions must be constructed in a manner that allows for quantification within the model. Now with the test data and detailed information available on these beam fire tests, a valuable database has now been created to help advance the use of computer modeling tools in understanding the fire performance of structures.

The results coming out of this research are:

- Wood joists made with dimensional lumber provide higher fire resistance as compared to engineered floor joists. In this test program, traditional lumber joists failed at about 16 minutes, while engineered floor joists failed at about 6 minutes under ASTM E-119 fire exposure.
- The webs of engineered I-joists and castellated I-joists are the weakest parts in these joists, and failure occurred through the burn-out of the web.
- The application of an intumescent coating to an engineered I-joist can enhance its fire resistance.
- The connections in the steel/wood hybrid joists are the weak link during fire exposure and influence the resulting fire resistance.
- Reinforcing the steel/wood connection of the hybrid joists with screws does not enhance fire resistance.
- The presence of plywood sheathing on a joist enhances fire resistance and better simulates being part of a floor system.
- The presence of axial restraint conditions does not significantly influence the fire resistance of wood joists.
- The load level has an influence on the fire resistance of wood joists. The higher the load level, the lower the fire resistance will be.

5.2. Fire Service Collapse Hazard Floor Furnace Experiments

Seven floor furnace experiments were conducted utilizing the standard ASTM E119 fire exposure curve on representative floor construction to develop comparable fire performance data. All assemblies were intended to represent typical residential construction and included dimensional lumber, engineered wood "I" joists and trusses. The assemblies did not include a ceiling and were considered unprotected floor assemblies representative of a basement with no ceiling membrane. Two of the assemblies were coated with a topical treatment to assess its ability to provide additional structural integrity. These experiments are one task of a larger project that examined residential floor systems in different scales of experiments, examining several variables to provide information to the fire service to add to their knowledge of basement fire dynamics and collapse hazards.

Figure 11. UL's Floor Furnace

Figure 12. Floor system prior to the experiment

Floor collapse times ranged from 2:20 to 18:05. Three fire service tactical considerations were identified and several code implications were discussed. The results of these experiments were combined with a series of experiments conducted by UL in 2008, which took place on the same floor furnace. It was highlighted that the collapse of all unprotected floor systems, including dimensional lumber, happened well within the potential operational timeframe of the fire service. Two additional considerations examine procedures used to determine the structural integrity of the floor is not necessarily reliable, sounding of the floor and the use of thermal imaging cameras.

Table 8. Floor Furnace Experimental Results

Assembly	Time of 250°F avg. temperature rise on surface of floor (min:sec)	Time of 325°F max. temperature rise on surface of floor (min:sec)	Flame passage through floor (min:sec)	Time of Structural Failure (min:sec)
1. Engineered I Joists with Openings	*	*	8:10	8:10
2. Engineered Wood and Metal Hybrid Trusses	*	*	5:30	5:30
3. Engineered I Joists w/ Intumescent Coating	*	*	15:10	17:50
4. Engineered I Joists (100% Load)	*	*	2:20	2:20
5. Engineered I Joists w/ Fire Retardant Coating	*	*	8:40	8:40
6. Nominal 2 in by 10 in Dimensional Lumber (100% Load)	*	*	7:04	7:04
7. Legacy Nominal 2 in by 8 in Dimensional Lumber (100% Load)	15:40	14:20	15:45	18:05

Code implications discussed include the inability of spray applied fire retardants or intumescents to provide “equivalent” protection to that of a ½ inch layer of gypsum board. Additionally that dimensional lumber and its structural stability when exposed to fire may have changed over time. Older nominal 2 x 8’s did not collapse until after 18 minutes while the newer nominal 2 x 10 collapsed at 7 minutes.

5.3. Full-Scale Floor System Field and Laboratory Fire Experiments

UL conducted a series of 17 full-scale fire experiments. Three experiments characterized the fuel by measuring the heat release rate of the fuel package. Ten full-scale simulated basement fire experiments were conducted in collaboration with NIST at a fire training facility to examine the impact of floor system, ventilation, fuel load, and loading on firefighter safety. Finally, four simulated basement fires of the same scale as the field experiments were conducted in the laboratory to examine void space fires, fuel load and code implications.

Figure 13. Field Experiment Structure

Figure 14. Laboratory Experiment Structure

During the experiments 4 different floor systems were examined. Floor collapse times ranged from 3:28 to 12:45 during the experiments at the training academy. The dimensional lumber experiments collapsed at an average of 11:57 while the engineered floor systems collapsed at an average of 7:00.

Table 9. Field Experiment Overview

Experiment Number	Floor Support	Ventilation Description	Collapse
1	Dimensional Lumber (2 x12)	Max Vent	11:09
2	Dimensional Lumber (2 x12)	Sequenced Vent	12:45
3	Engineered Wood I-Joist (12 in.)	Max Vent	6:00
4	Engineered Wood I-Joist (12 in.)	No Vent	6:49
5	Engineered Wood I-Joist (12 in.)	No Vent/No boxes	8:27
6	Engineered Wood I-Joist (12 in.)	Max Vent/Furnace DHS load	6:49
7	Steel C-Joist (12 in.)	Max Vent	8:15 (6:11 exceeds ISO 834:1)
8	Steel C-Joist (12 in.)	Sequenced Vent	14:04* (10:08 exceeds ISO 834:1)
9	Parallel Chord MPCWT**	No Vent	6:08
10	Parallel Chord MPCWT	Max Vent	3:28

* water from barrels at 11:10, also deflection max at 9:53
** MPCWT = Metal Plate Connected Wood Truss

Table 10. Laboratory Experiment Overview

Experiment Number	Floor Support	Ventilation Description	Collapse
A	Engineered Wood I-Joist (12 in.)	Max Vent / Same as Exp. 3	6:20
B	Engineered Wood I-Joist (12 in.)	Max Vent / Torch ignition	31:25
C	Parallel Chord MPCWT	Max Vent / Void Ignition	44:46
D	Parallel Chord MPCWT	No Vent / 80 ft^2 exposed	13:10

Fuel load was varied to examine a representative basement fuel load down to just the floor system as the fuel load. These experiments showed that the main component of the fuel load was the floor system itself. Both variations of the fuel load resulted in collapse times within 100 seconds of each other.

Ventilation or the amount of air available to the fire plays a significant role in the fire dynamics of a house fire. In an attempt to bound the problem the ventilation parameters were chosen at the extremes (Maximum and No Ventilation) and a simulated realistic scenario could be considered somewhere in the middle (Sequenced Ventilation). The engineered I-joist and parallel chord truss floor system collapsed before 8 minutes therefore doing a sequenced scenario was not possible with these systems. Limiting ventilation slowed the dimensional lumber floor collapse by 1:36, engineered I-joist floor by 0:49, metal C-joist floor by 1:53 and MPCWT floor by 2:40.

Floor loading was varied to examine a representative loading found in a home to a lighter load consisting of perimeter loading simulating furniture and two 300 lb firefighters in the center of the floor. Ultimately the load on the floor system did not play a significant role in determining the time to collapse but rather the degradation of the floor system as it was consumed and weakened by the fire.

Several tactical considerations for the fire service were developed from the experimental results including topics of operational timeframe, size-up, basement fire attack, collpase predictors or lack there of, ventilation, inspection and overhaul.

5.4. Basement Fire Growth Experiments in Residential Structures

Many of the structural collapse experiments that have been conducted to aid the fire service have been carried out under laboratory conditions, such as a furnace test or a test prop assembled in the lab. These previous experiments have provided data on a wide variety floor assemblies and the knowledge base has been greatly expanded during the past few years. However, these experiments have not examined the impact on the growth of a fire being started in a closed residential structure, below ground level, with limited ventilation. These factors in addition to the volume and the type of construction of the structure may have significant impact on the fire growth and the resulting hazard to fire fighters at their time of arrival to the fire ground.
The objectives of these experiments were to:

1. Examine the development of a fire in the basement of an acquired structure with the windows and doors to the structure closed.

2. Examine the development of a fire in the basement of an acquired structure with the basement windows and the doors to the structure on the 1st floor open.

The National Institute of Standards and Technology (NIST) and Underwriters Laboratories (UL) collaborated to conduct four experiments in two acquired structures in Bensenville, IL. A two story colonial with an unprotected wood I-beam floor assembly and a single story bungalow with an unprotected solid wood floor joist assembly. In each experiment a replicable fuel package was ignited in the basement. Two experiments were conducted in each structure. Key differences between the two experiments in each structure were the ventilation and the initial fuel package ignited. In the second experiment in each house the fire was allowed to develop until the structure collapsed.

A wide variety of measurements were taken both in the laboratory and in the acquired structures to support this study. This provides an overview of the types of measurements made and the type of instruments used to make them. Full details of the report including specifics on the number of instruments, the estimated measurement uncertainty, the instrument location and the results are presented in Appendix D.

To assess the fuel load, heat release rate (HRR) and weight measurements of the furnishings similar to the ones used in these experiments were conducted. The HRR measurements were taken using a 6.0 m × 6.0 m (20 m x 20 m) square oxygen consumption calorimeter at the NIST Large Fire Laboratory (LFL). The weights of the fuels were measured using a mass load cell. The dimensions of the houses and the fuel loads and the locations of the fuels were measured with a steel measuring tape. Temperature was measured with type K, bare bead thermocouples. The heat flux gauges used in the basements were Schmidt-Boelter type, water cooled gauges with embedded type K thermocouples. Gas velocities were measured at basement windows and the basement doors using bidirectional probes and type K, 1.6 mm (0063 in) diameter, inconel shielded thermocouples. Oxygen, carbon dioxide, and carbon monoxide were measured in the basement. Oxygen was measured using paramagnetic analyzers. Carbon monoxide and carbon dioxide were measured using non-dispersive infrared (NDIR) analyzers. In addition, three types of commercially available, battery operated smoke alarms were installed throughout the structures to see when occupants might be made aware of the basement fire based on the activation times.

NIST and UL conducted a series of experiments to characterize the fuel load selected for the basement experiments. Two rectangular, end tables, one oval, coffee table, two upholstered chairs, a couch, and a lamp were positioned in a typical seating arrangement in the basement of the each house (Figure 15). In addition to the furniture, sets of cardboard boxes filled with polystyrene foam meat trays (Figure 16) were arranged on wooden pallets and distributed to multiple locations in the basement. The fuel packages were similar in both houses.

Figure 15. Picture of the furniture in the basement

Figure 16. Picture of the polystyrene meat trays in each cardboard box

The colonial house has 420 m^2 (4500 ft^2) of floor space and a total volume of 1100 m^3 (39,000 ft^2) based on the interior measurements. Figure 17 is a photograph of the front of the house and Figure 18 is the floor plan of the basement of the colonial style home. In the basement, where the fires were first ignited, there was one 1.14 m × 1.14 m (45 in. × 45 in.), two 0.84 m × 0.71 m (33 in. × 28 in.), and one 0.46 m × 0.74 m (18 in. × 29 in.) windows. The basement windows in this house were each single pane, aluminum framed. The rest of the house had double pane windows with vinyl frames. The ceiling in the basement was a wood floor assembly for the ground level of the structure, which was exposed and opens to the conditions in the basement. The wood floor assembly was composed of, beginning at the top and working down, 19 mm (0.75 in) hardwood flooring, 19 mm (0.75 in) thick plywood subflooring, and supported by wooden I–beams on 0.406 m (16 in) centers. The wood I-beams had a span of 3.9 m (12.8 ft) or less. The wood flooring assembly was supported by a pair of parallel steel I-Beams, with centers 3.9 m (12.8 ft) from the outer walls and 2.2 m (7.2 ft) apart, in a direction perpendicular to the axis of the wood joists. Each steel I-beam had three steel columns spaced along its length for support. The joists were wooden I-beams with solid sawn lumber top and bottom chords permanently attached to oriented strand board (OSB) webs. The wooden floor joists had a beam depth of 0.24 m (9.5 in.), flange width of 0.064 m (2.5 in.), and a flange thickness of 38 mm (1.5 in.). The web was composed of OSB and was approximately 13 mm (0.5 in.) thick.

Figure 17. Side A of the two story colonial house

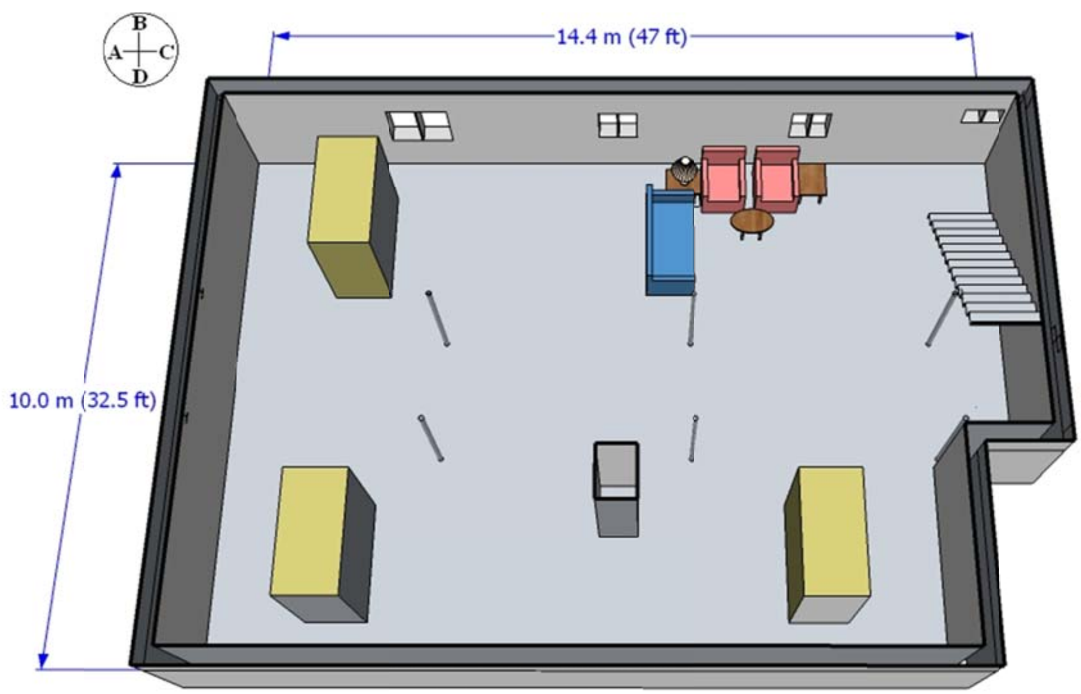

Figure 18. Floor plan of basement with fuel package locations.

The bungalow has 190 m^2 (2000 ft^2) of floor space and a total volume of 420 m^3 (15000 ft^2) based on the interior measurements. Pictures of the exterior of the house can be found in Figure 19. Figure 20 is view of the basement floor plan. In the basement, there were four windows with the following dimensions: 0.34 m × 0.79 m (13.5 in. × 31 in.), 0.34 m × 0.81 m (13.5 in. × 32 in.), 0.60 m × 0.80 m (24 in. × 31.5 in.), and 0.36 m × 0.76 m (14 in. × 30 in.). Three of the basement windows in this house were single paned glass with wooden frames. The rear, side B window was plexiglass inside a wooden frame. Note that the windows were arranged to support cross ventilation. The floor assembly in the bungalow was also exposed and was composed of dimensional lumber. The main support beam was a 0.18 m (7 in.) wide and 0.13 m (5 in.) deep solid wood beam. The main support beam was held into place by four 0.1397 m by 0.1397 m (5.5 in. by 5.5 in.) wooden columns. The floor joists were 0.19 m by 0.045 m (7.5 in. by 1.75 in.) wooden beams with 0.406 m (16 in.).

Figure 19. Side A of the bungalow

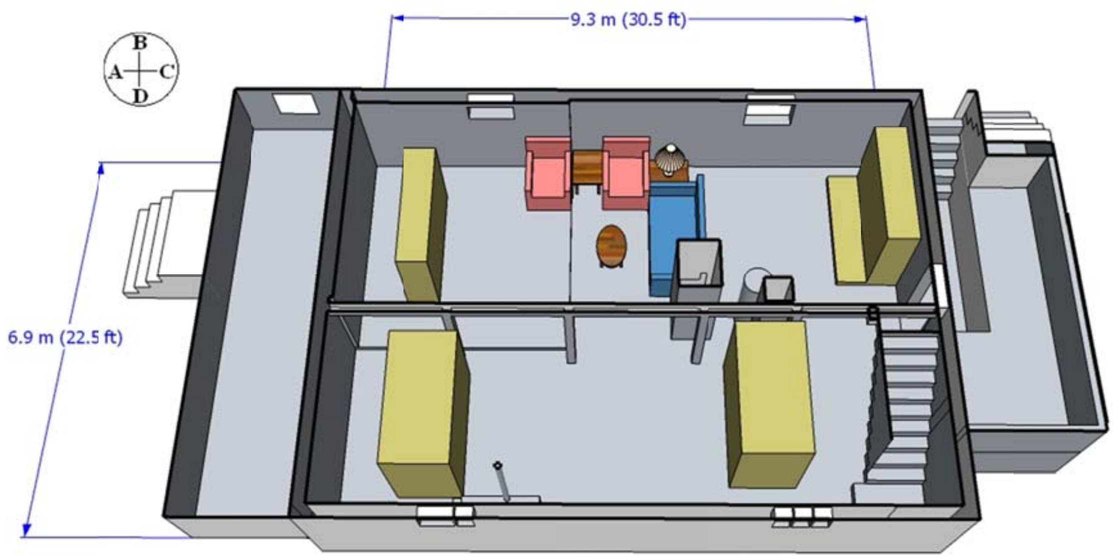

Figure 20. Floor plan of basement with fuel package locations.

In Experiment 1 and Experiment 3, the first experiments in each structure, the houses initially had no vents to the exterior. The sofa was ignited with a small flaming source in each basement.

The sofa became fully involved in fire and the fire spread to other pieces of furniture. However this initial growth of the fires was not sufficient to fail any of the basement windows and the heat release rate of the fires decreased which resulted in a decrease in the hot gas temperatures in the basements. A sequence of venting the windows began at approximately 10 minutes after ignition, the fire continued to burn out the furniture fuel package without extending to the structure. There was no visible thermal damage to any of the exposed wood floor assembly components in either structure.

In Experiment 2 and Experiment 4, all of the vents that were opened in Experiment 1 and Experiment 3 were left opened. In addition, a door on the first floor was left open to provide a flow path to the basement. The initial fuel load ignited was changed to a stack of the cardboard boxes, filled with polystyrene trays on wood pallets in these experiments. With the increased ventilation and a fast burning, source fire, the fire spread to the exposed wood floor assemblies in both structures and the structures burned until complete collapse.

The temperature at 30 cm (12 in.) below the ceiling near the initial fuel package is presented in Figure 21 for each experiment. Within the first 100 s (1 min. 40 s), the temperatures from Experiment 2 and Experiment 4 (vents open) reached and sustained temperatures in excess of 500 °C (932 °F) while the temperatures from Experiment 1 and Experiment 3 (vents closed) with exception of a brief peak, stayed below 300 °C (572 °F).

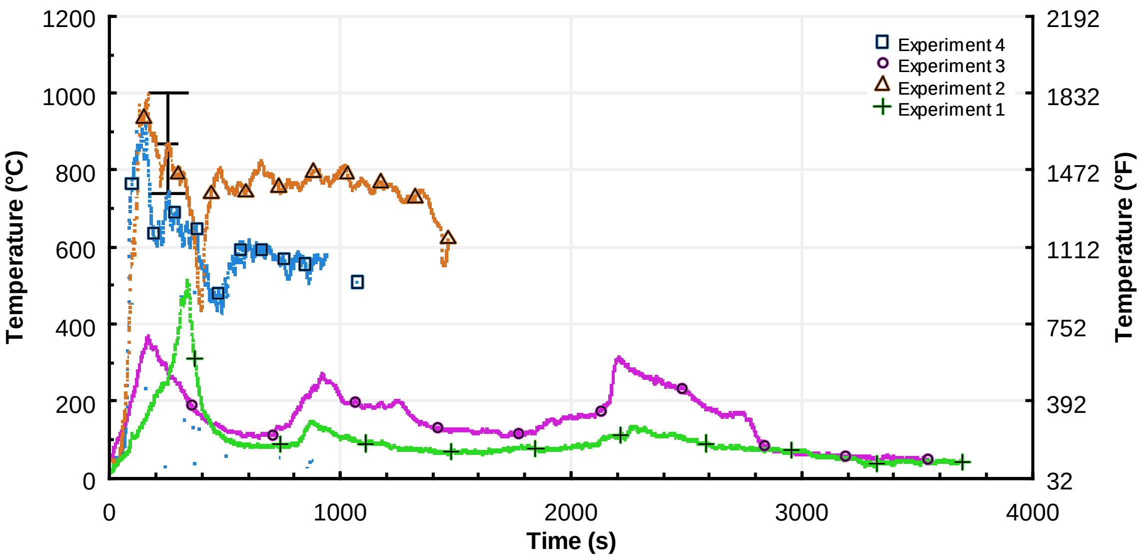

Figure 21. Temperature at 30 cm from ceiling at the side B location for each experiment.

The deflection of the first level floor in both houses was assessed by wires weighted with markers on the exteriors of the houses that were connected to the firefighter mannequins in the living rooms and videoed throughout the experiments to monitor their position. The upward movement of the wood indicated the downward deflection of the floor. For the colonial structure, Experiment 2 (vents open) the floor began to deflect at approximately 6 minutes after ignition. The last clear visual of the markers before the floor collapsed occurred at approximately 22 minutes after ignition, at that point the floor deflection is in excess of 150 mm (6 in.). Based on changes to the fire conditions throughout the structure, a portion of the first floor collapsed at approximately 23 minutes after ignition.

In the bungalow experiment 4 (vents open), smoke from basement fire obscured the deflection markers throughout the experiment. The last time that the markers could be seen was approximately 12 minutes after ignition and no floor deflection was discernible. The floor collapse began at approximately 18 minutes and 45 seconds after ignition. It is important to note that a direct comparison of the collapse times based on type of construction, between the colonial and bungalow, cannot be made due to differences in the ventilation and volume of the space.

Regarding the potential for firefighter to make an interior attack on the basement fire, the temperatures were measured at the top of the stairs leading down to the basement for experiments 2 and 4 (vents open) are given below. In both cases, untenable conditions for a fully protected fire fighter were generated in the basement stairway.

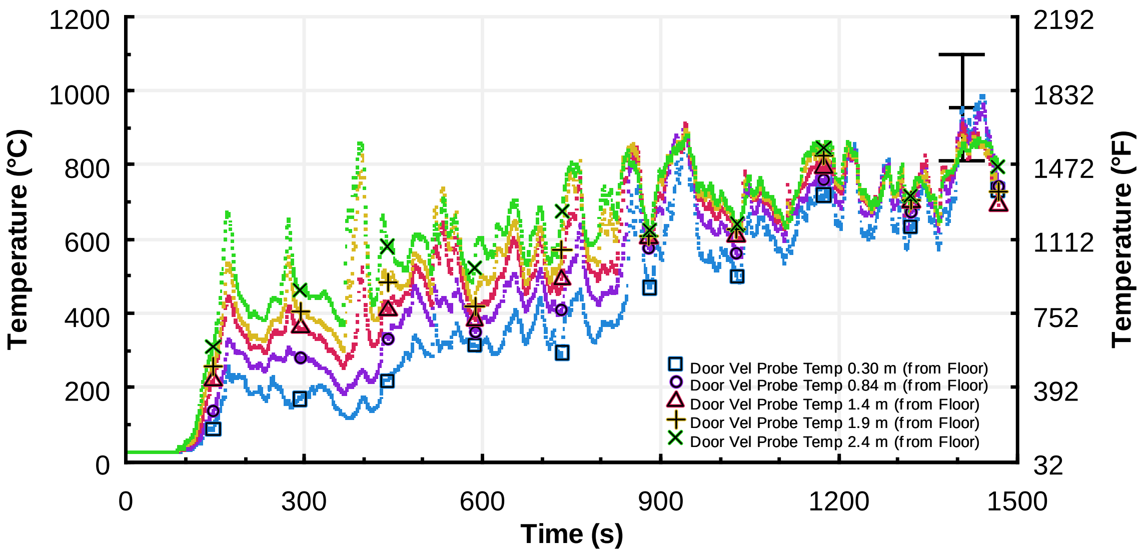

Figure 22. Temperature profile of the thermocouples attached to the bidirectional probes at the top of the basement stairs in the colonial experiment 2.

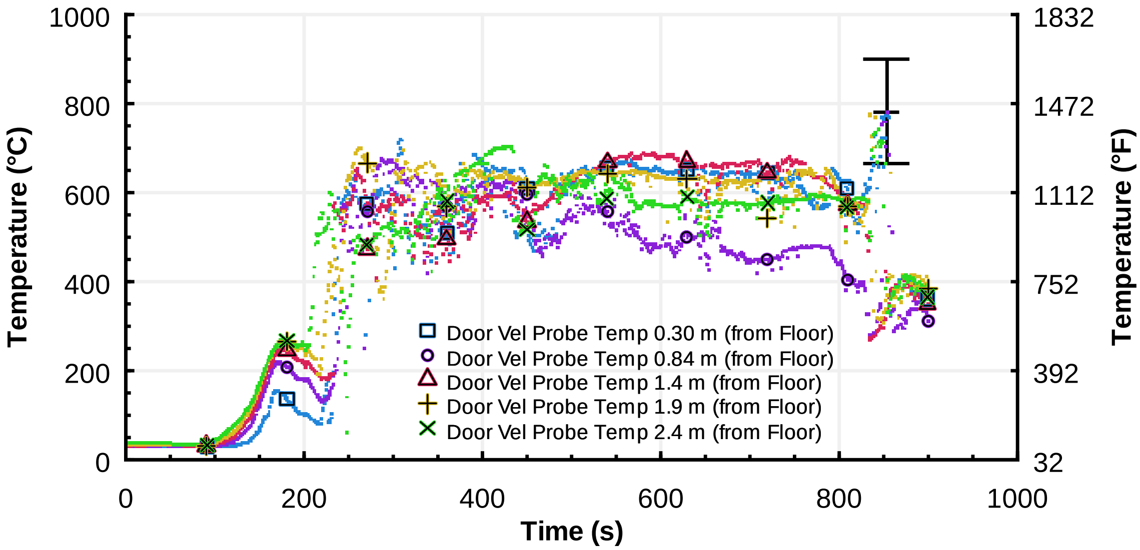

Figure 23. Temperature profile of the thermocouples attached to the bidirectional probes at the top of the basement stairs in the bungalow experiment 4.

In summary, several observations based on these acquired structure experiments can be made:

- Collapse times of both the structures with unprotected wood floor systems were within the operational time frame of the fire service.
- Size-up should include the location of the basement fire as well as the amount of ventilation.
- Without any exterior openings the fires consumed the available oxygen in the basement and did not grow beyond the incipient stage. In the unvented cases, the fire did not fail (auto vent) any of the basement windows and did not lead to the ignition of any of the exposed wood floor system components.
- By opening the basement windows and igniting a faster developing fuel package, the additional oxygen allowed the fire to grow and led to the ignition of the exposed wood floor systems which then led to structural collapse.
- Attacking a basement fire from a stairway places firefighters in a high risk location due to being in the flow path of hot gases flowing up the stairs and working over the fire on a flooring system which has the potential to collapse due to fire exposure.
- Floor temperatures above the fire can be a poor indicator of both the fire conditions below and the structural integrity of the flooring system.

5.5. Modeling the Thermal and Structural Behavior of Wood Beams in a Fire Environment

This research extends the predictive capabilities of high-performance computing tools, specifically finite element (FE) analysis tools, for the fire performance of building components. This research specifically focused on the fire performance of two types of wood products common in residential constructions: dimensional lumber and engineered wood. For both wood types, fire tests were conducted on individual beams (Kodur & et al., 2011) and flooring systems (Backstrom & et al., 2010) according to standard fire tests in a furnace. The purpose of this building block approach was to assist with FE model trouble shooting and validation.

For the dimensional lumber samples, the cross sections of the beam were rectangular while for the engineered wood samples, the cross-section was an I-profile. The reason for selecting wood is its prevalence in residential and commercial constructions as innovative wood engineered products enter the marketplace. In wood structures, oriented strand board (OSB) and plywood are the most prevalent materials for composite panels. In the last few years, UL fire research (Backstrom & et al., 2010) has shown that flooring systems supported by engineered products, though perform admirably in normal conditions, show a degraded fire performance vis-à-vis solid lumber beam supports when unprotected, typical of unfinished basements.

The research demonstrated the capabilities of current state of art in finite element analysis using a 'smart simplifications in simulation' framework. The results in this study show that advanced analysis of wood-based structural components in a fire environment is possible where:

- Effective material properties can be used to implicitly incorporate a variety of physical phenomena.
- Thermal properties from the Eurocodes with some alterations, mainly in the charred sections, provide a very good starting point when material properties from testing of wood specimen of interest are not available.
- FE deflections can be very sensitive to the values of the coefficient of thermal expansions.
- The overall analysis can be conducted using a one-way coupling between the thermal analysis and the structural analysis.
- For the structural analysis, a static analysis can provide sufficient accuracy up to the point of instability.
- A collaborative effort between analyst and test engineers to produce 'designed' experiments can greatly help the building block approach to model troubleshooting and confidence.
- A relatively simple model for heat source, furnace, including radiation and convection heat transfer can still lead to meaningful results.
- An analysis of the model charring rate and charring section can be based upon review of isotherms.

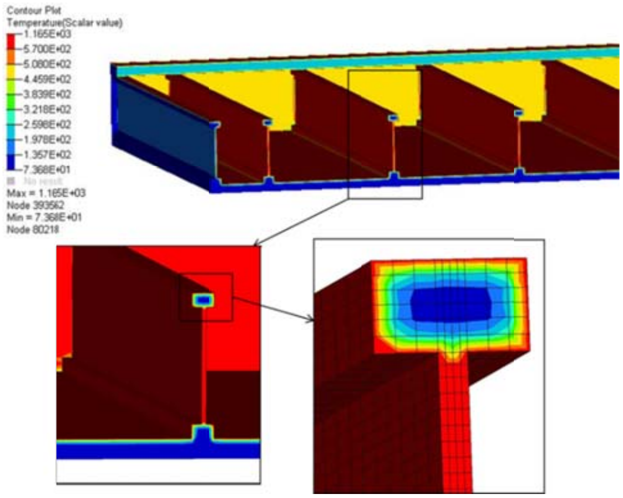

Figure 24. Temperature contours for engineered wood I-joist supported floor

The results for the two types of wood beam supports match very well with observations and measurements during testing on individual beams and flooring systems. A single dimensional lumber rectangular section beam (or a flooring system supported by such beams) performs considerably better than a similarly loaded single engineered wood I-beam (or flooring system supported by such beams). For the thermal analysis, temperatures at surfaces and interfaces were compared and found to match well with measurements from testing. In addition, charring rates from the model based on 300°C (570°C) isotherms and was found to compare favorably with the range of data in the published literature.

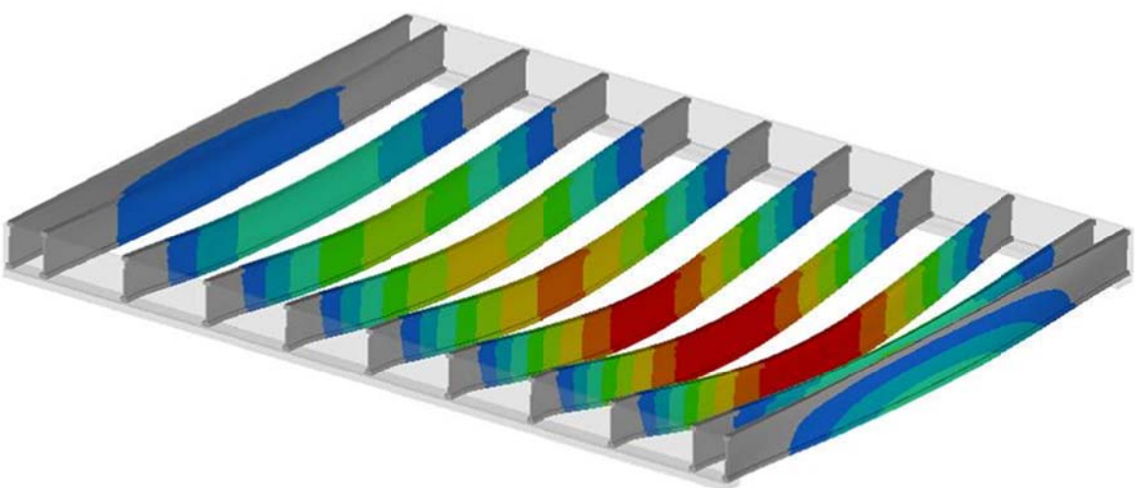

Figure 25. Displacement contours for engineered wood I-joist supported floor assembly

The model also reveals that for the engineered wood beams (individual and supporting flooring systems), the main failure path is the burn-out of the web thereby transferring loading sharing to the top chord as the lower chord, though mostly un-burnt, is now separated. For the dimensional lumber rectangular cross section support beam (individual and supporting flooring systems), the beam mainly reduce cross section through 3-sided heating and through a combination of weakened material properties and reduced cross section, eventually fail to sustain the load. The model was able to predict the onset of instability where deflection rate increased substantially.

With such a model in hand, sensitivity analyses can help assess the effect of a variety of factors such as beam spacing, profile, etc. on the fire performance as long as the expected failure mode is not very different.

5.6. Fire Modeling of Basement with Wood Ceiling

This objective of this research was to help advance the use of computer modeling tools, specifically the Fire Dynamics Simulator (FDS) from NIST, in the field of fire engineering and science. The specific example concerned the fire dynamics within a basement with openings and an unprotected wood ceiling with geometric complexity.

The results in this study show that predicting the fire growth within basements with wood ceilings can be achieved reasonably well with FDS and that sensitivity analysis could be carried out, expanding this exercise to include some of the other experiments that were conducted as part of this overall research program. Results from the basement model appeared to compare well with discrete test measurements for temperature and velocity. The model did deviate in some instances quantitatively yet qualitative trends were very similar. In general, the bulk temperatures within the compartment were more accurate than those near openings. However some areas of improvement are noted below.

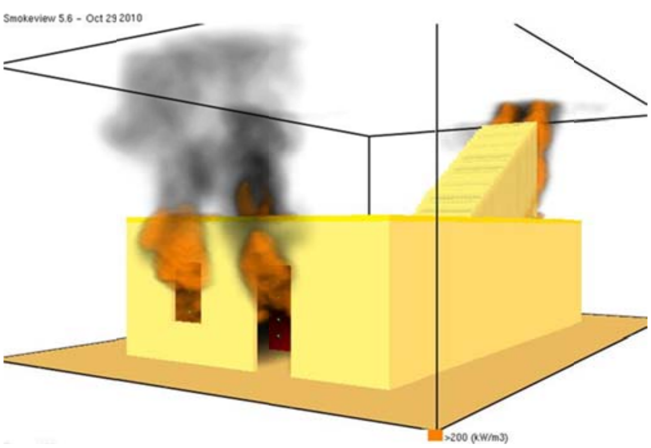

Figure 26. Model and experimental comparison

First and foremost, this exercise demonstrates the importance of accounting for the validation needs of modeling versus ordinary testing during the planning phase. For model validation, the selection of validation points is not always obvious. There are some guidelines such as measurements in regions where high gradients in key parameters are expected. For this basement, with the parallel joist configuration, the placement of velocity sensors, between the joists, would have been very helpful. This would have contributed data on the approach in FDS for modeling surface flows. In FDS, for an LES simulation, the boundary layer is not well resolved especially with only a few cells capturing the gap between the joists. This is expected to be a possible source of error for the flow between the parallel joists.

Since all the heat is generated by the box/pallets sets and the wood ceiling, both described by prescribing a heat release rate relationship, any inaccuracies would certainly have a big impact. For instance, for the heat release rate of wood, no profiles were readily available from published literature only single values.

For solids, the thermal conduction model is only 1-D and surfaces of the same obstacle do not communicate thermally. As such, FDS cannot account for burning through of the wood which is actually happening in this case. Since the joists were comprised of engineered wood I-beams, it is known that for these beams, the thin webs burnout first, creating through holes for flames and air, eventually causing the lower chord to fall down. With an ability to model this aspect the air flow between the joists, the predictions will be less accurate especially in the region over the heat source as time progresses in the simulation.

6. Discussion

The multiple series of experiments allow for the comparison of important variables. The impact of scale can be examined by comparing the component level experiments to the larger assembly level experiments. Floor system types, loading, ventilation, fuel load, span distance and protection methods will be discussed as they pertain to the different types of experiments.

6.1. Scale

Four different types of experiments were conducted with real-scale, commercially available structural components. Component experiments were conducted in a structural furnace, standard assembly experiments were conducted on a standard floor furnace, full-spanfield and laboratory experiments were conducted with a simulated basement structure and full-scale realistic house experiments were conducted on homes scheduled for demolition.

Table 11. Progression of experiments

Component Experiments		
Standard Assembly Experiments		
Full-Span Field Assembly Experiments		
Full-Span Laboratory Assembly Experiments		
Full-Scale Realistic House Experiments		

Comparing the four different types of experiments conducted with the engineered I-joist experiments yields a trend in failure times. Just examining the failure times gives a range from 2 minutes and 20 seconds for a 100 loaded percent floor assembly furnace test to 23 minutes and

10 seconds for the full house experiment. With the exception of the two experiments at the extremes of the range the collapse times of the six moderately loaded (< 65% of the design load), 11 7/8 in. deep I-joists failed at an average of 6:18 with a maximum of 6:49 and a minimum of 6:00 (Table 12). The house experiment which had 9 ½ in. deep joists and it collapsed at approximately 23:10 after ignition. The comparison of these failure times is presented to note the differences based on fire exposure, ventilation, span and loading. It is interesting that for six of the experiments which were different in design, fire exposure, ventilation, span and loading the time to failure was very similar.

Table 12. Engineered I-joist Experiments at Different Scales

Experiment	Span	Spacing (i.o.c.)	Depth (in)	Load	Details	Failure Time
MSU Beam Furnace	12 ft.	NA	11 7/8	50%	Axially Unrestrained	6:15
MSU Beam Furnace	12 ft.	NA	11 7/8	50%	Axially Restrained	6:25
UL Floor Furnace	13 ft. 4 in.	24	11 7/8	100%		2:20
UL Floor Furnace	13 ft. 4 in.	24	11 7/8	Modified		6:00
Full-Span Field Experiment	20 ft.	16	11 7/8	65%	Maximum Ventilation	6:00
Full-Span Field Experiment	20 ft.	16	11 7/8	65%	Minimum Ventilation	6:49
Full-Span Laboratory Experiment	20 ft.	16	11 7/8	65%	Maximum Ventilation	6:20
House Experiment	12 ft. 7 in.	16	9 ½	Modified	Limited Ventilation (4 windows on one side of the basement and one open stair)	23:10

Engineered I-joist were also protected with an intumescent coating and tested at two different scales, in the component level furnace and in the assembly level floor furnace. The span was 1 ft. 4 in. longer in the assembly experiment and the load was applied differently and there was an approximately 6 minute earlier failure in the assembly scale experiment (Table 13).

Table 13. Engineered I-joist with Intumescent Coating Experiments at Different Scales

Experiment	Span	Spacing (i.o.c.)	Depth (in)	Load	Details	Failure Time
MSU Beam Furnace	12 ft.	NA	11 7/8	50%	Axially Restrained	24:05
UL Floor Furnace	13 ft. 4 in.	24	11 7/8	Modified		17:50

Table 14 compares all of the different type of dimensional lumber experiments. Just examining the failure times shows that failure times ranged from 7:04 to 20:40. The component furnace experiments that were loaded to 50 % had an average failure time of 18:40 (minimum of 16:40 and maximum of 20:40) which is very close to the assembly furnace experiment conducted as part of the previous UL research program which failed at 18:35. The full span field experiment floor assemblies with nominal 2 by 12's with 65% loading failed at 11:09 and 12:45 depending on ventilation conditions and the component scale nominal 2 by 10's with 70 % loading experiments failed at 15:35 and 13:05 dependent upon restraint conditions. While the components were larger in the full-span fireld experiments, the span was also larger but the average failure times were within 17%. The two experiments with older nominal 2 by 8's, in the floor furnace experiment (1 ⅝ in. by 7 ½ in. actual) and the actual house experiment (1 ¾ in. by 7 ½ in. actual) both failed within 15 seconds of each other at 18:05 and 18:20 respectively.

Table 14. Dimensional Lumber Experiments at Different Scales

Experiment	Span	Spacing (i.o.c.)	Depth (in)	Load	Details	Failure Time
MSU Beam Furnace	12 ft.	NA	9 1/4	70%	Axially Unrestrained	15:35
MSU Beam Furnace	12 ft.	NA	9 1/4	70%	Axially Restrained	13:05
MSU Beam Furnace	12 ft.	NA	9 1/4	50%	Axially Unrestrained	16:40
MSU Beam Furnace	12 ft.	NA	9 1/4	50%	Axially Restrained	20:40
MSU Beam Furnace	12 ft.	NA	9 1/4	70%	Axially Restrained	16:50
UL Floor Furnace	13 ft. 4 in.	16	9 1/4	100%		7:04
UL Floor Furnace	13 ft. 4 in.	16	9 1/4	Modified	Previous UL Experiment (Backstrom & et al., 2010)	18:35
UL Floor Furnace	13 ft. 4 in.	16	7 1/2	100%	Reclaimed Lumber from 1940's House	18:05
Full-Span Field Experiment	16 ft.	16	11 1/2	65%	Maximum Ventilation	11:09
Full-Span Field Experiment	16 ft.	16	11 1/2	65%	Sequenced Ventilation	12:45
House Experiment	12 ft. 5 in.	16	7 1/2	Modified	Maximum Ventilation (2 windows (4 total) on each side of the allowing for cross ventilation, one stair leading up to the kitchen and one door leading directly outside.)	18:45

Two additional joist types can be compared at the component beam furnace test and the standard floor assembly test, the castellated Engineered I-joists (Table 15) and the Engineered Wood and Metal Hybrid Trusses (Table 16). The castellated I-joists had an average failure time of 7:00 (minimum of 6:50 and maximum of 7:10) in the component scale experiments and a failure time of 8:10 in the standard floor assembly scale experiment, yielding a difference of approximately 15%. The engineered wood and metal hybrid trusses had a failure time of 6:00 for both component scale experiments and a failure time of 5:30 in the standard floor assembly scale experiment, yielding a difference of 10%.

Table 15. Castellated I-Joist (with openings) Experiments at Different Scales

Experiment	Span	Spacing (i.o.c.)	Depth (in)	Load	Details	Failure Time
MSU Beam Furnace	12 ft.	NA	16	50%	Axially Unrestrained	7:10
MSU Beam Furnace	12 ft.	NA	16	50%	Axially Restrained	6:50
UL Floor Furnace	13 ft. 4 in.	24	16	Modified		8:10

Table 16. Engineered Wood and Metal Hybrid Trusses Experiments at Different Scales

Experiment	Span	Spacing (i.o.c.)	Depth (in)	Load	Details	Failure Time
MSU Beam Furnace	12 ft.	NA	14	50%	Axially Unrestrained	6:00
MSU Beam Furnace	12 ft.	NA	14	50%	Axially Restrained	6:00
UL Floor Furnace	13 ft. 4 in.	24	14	Modified		5:30

6.2. Floor Joist Types

During the five series of experiments 6 types of floor joists were tested. Ten dimensional lumber, thirteen engineered I-joist, three castellated I-joist, five hybrid trusses, two steel C-joist and four metal plate connected wood truss experiments were conducted. Removing the protected assemblies and ignoring all other variables the maximum, minimum, average failure times and the standard deviations of each joist type is shown in Table 17. Every experiment with the exception of the full-scale actual house experiment with an engineered I-joist floor system was within 2 standard deviations of the average. Comparing all of the engineered joist types yields an average failure time that is approximately one half that of the dimensional lumber joists.

Table 17. Joist Type Failure Comparison

Joist Type	Experimental Count	Average	Minimum	Maximum	Standard Deviation
Dimensional Lumber	10	15:01	7:04	20:40	4:01
Engineered I-joist	8	8:17	2:20	23:10	3:54
Castellated I-joist	3	7:23	6:50	8:10	0:42
Hybrid Trusses	3	5:50	5:30	6:00	0:17
Steel C-joist	2	8:10	6:11	10:08	2:48
MPC Wood Truss	2	4:48	3:28	6:08	1:53
All Engineered Joist Types	18	6:52	2:20	15:00	2:39

6.3. Load

Several pairs of experiments were conducted to isolate the variable of loading. The first was examining the dimensional lumber in the component experiments. With all other variables constant the load was increased from 50 % to 70 %. The resultant failure time was decreased from 20:40 to 16:50. The second pair was a dimensional lumber nominal 2 by 10 floor assembly tested on the standard floor furnace. One experiment was conducted as part of the previous UL research with a modified loading of 2 – 300 lb. simulated firefighters and 40 lb/ft^2 of simulated furnishings along two edges of the assembly (total load of 5,010 lb, this experiment also had a hardwood finish floor installed), while the other had the standard loading of 100% of the design load (59.7 lb/ft^2, total load of 15,082 lb) (Figure 27 and Figure 28). The modified load experiment failed at 18:35 and the standard load failed at 7:04. Increasing the load decreased failure time by 263%.

Figure 27. Modified Loading

Figure 28. Standard Loading

A similar comparison can be made with an engineered I-joist floor assembly on the standard floor furnace. One experiment was conducted as part of the previous UL research with a modified loading of 2 – 300 lb. simulated firefighters and 40 lb/ft^2 of simulated furnishings along two edges of the assembly (total load of 5,010 lb, this experiment also had a carpet with padding finish floor installed), while the other had the standard loading of 100% of the design load (75.9

lb/ft^2, total load of 19,175 lb). The modified load experiment failed at 6:00 and the standard load failed at 2:20. Increasing the load decreased the failure time by 257%.

The last comparison is also with engineered I-joists except it was during the full-span field experiments. One experiment was conducted with barrels weighted to provide 65% of the design load (Figure 30) while the other simulated the modified loading from the furnace experiments by placing 2 – 300 lb. barrels in the center of the span and placing barrels along two edges of the floor weighted to 40 lb/ft^2 (Figure 29). The modified load experiment failed at 6:49 and the uniform loading failed at 6:00 after ignition.

Figure 29. Modified Loading

Figure 30. Uniform Loading

6.4. Ventilation

Experiments were designed to examine ventilation in the full-scale field experiments and the full-scale actual house experiments. In an attempt to bound the problem the ventilation parameters were chosen at the extremes (Maximum and No Ventilation) and a simulated realistic scenario could be considered somewhere in the middle (Sequenced Ventilation) (Figure 31). In some cases the floor system collapsed before 8 minutes after ignition, the time to begin the sequenced ventilation. Therefore doing a sequenced scenario was not possible with the engineered I-joist or parallel chord truss floor systems.

The ventilation openings were sized based on the 2009 International Residential Code Section R303 LIGHT, VENTILATION AND HEATING which states, "All habitable rooms shall have an aggregate glazing area of not less than 8 percent of the floor area of such rooms. Natural *ventilation* shall be through windows, doors, louvers or other *approved* openings to the outdoor air. Such openings shall be provided with ready access or shall otherwise be readily controllable by the building occupants. Assuming this entire basement is habitable with the exception of the area of the stairwell, 54 ft^2 of glazing is required. Therefore, a door and 3 windows were built into the basement of the structure. Window and door openings were closed with plugs that were able to be opened and closed as desired as opposed to glass that could fail in an unrepeatable manner.

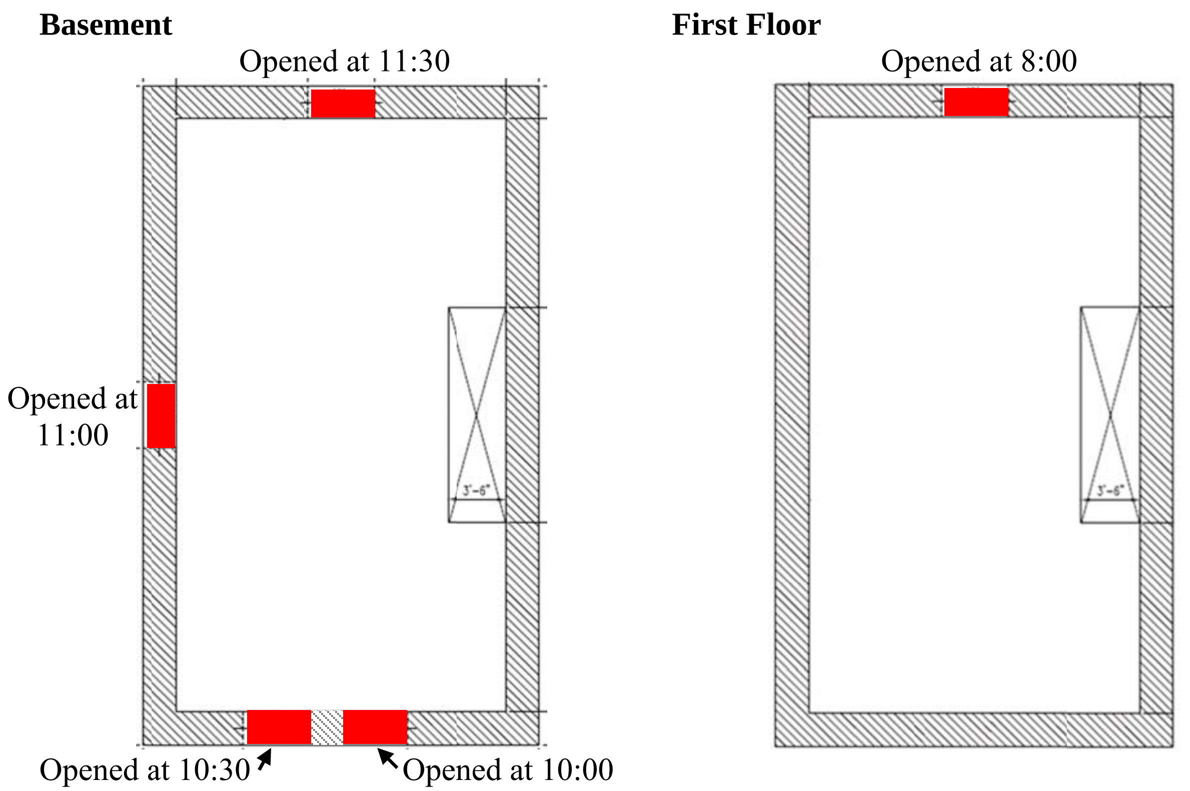

Figure 31. Sequenced Ventilation Details

The first comparison was the dimensional lumber floor system. One experiment was conducted with maximum ventilation or all of the openings in the open position and a second experiment was opened sequentially simulating fire department operations. The maximum ventilation experiment experienced failure at 11:09and the sequenced ventilation experiment failed at 12:45 after ignition. Failure of the maximum ventilated experiment occurred 12% faster than the sequenced ventilation experiment.

The second comparison was the engineered I-joist floor system. One experiment was conducted with maximum ventilation or all of the openings in the open position and a second experiment was conducted with no change in ventilation, in other words all of the doors and windows remained closed. The maximum ventilation experiment experienced collapse at 6:00 and the no ventilation experiment failed at 6:49 after ignition. Failure of the maximum ventilated experiment occurred 12% faster than the no ventilation experiment.

The third ventilation comparison was the steel C-joist floor system. One experiment was conducted with maximum ventilation or all of the openings in the open position and a second experiment was conducted with no ventilation or all of the doors and windows closed. The maximum ventilation experiment experienced failure at 6:11 and the no ventilation experiment failed at 10:08 after ignition. Failure of the maximum ventilated experiment occurred 39% faster than the no ventilation experiment.

The fourth ventilation comparison was the MPCWT floor system. One experiment was conducted with maximum ventilation or all of the openings in the open position and a second experiment was conducted with no ventilation or all of the doors and windows closed. The maximum ventilation experiment experienced failure at 3:28 and the no ventilation experiment failed at 6:08 after ignition. Failure of the maximum ventilated experiment occurred 43% faster than the no ventilation experiment.

As expected the more air available to burn the faster the time to failure. However in most of the experiments with the engineered floor systems there was enough air contained within the structure or being entrained through leaks into the structure itself to allow for enough burning to lead to failure. Given this test arrangement, the ventilation scenarios were meant to show the extremes therefore any other type or amount of natural ventilation under similar experimental conditions could be expected to fail between the bounding failure times. This was not a large window for most of the floor system types.

6.5. Fuel Load

Fuel load is often a topic that gets focused on in collapse experiments so the different experiments were designed to try to bound the impact of the fuel load and to examine the impact of the floor system itself instead of just the moveable fuel loading. A common misconception when analyzing the collapse of wood floor systems is neglecting the impact the floor system itself plays in the fuel load needed to grow the fire. Usually the focus is on the fuel load in the room and not necessarily on the amount and geometry of wood available to burn.

Two sets of experiments can be compared from the field and laboratory experimental series based on different fuel loads. The first is experiments 4 and 5, where the floor system (Engineered I Joist) was the same, the loading was the same, but the fuel load was different. Experiment 4 had the full fuel load consisting of wood pallets with cardboard boxes of expanded polystyrene trays on top of them. Experiment 5 had just the wood pallets and no boxes. Figure 32 shows the 3 temperature measurement locations in the basement at 6 ft above the floor or 3 ft. below the decking. It also shows the time of collapse for each experiment which was within 100 s of each other. If you compare the time from ignition of the floor system above the fuel load to collapse time both experiments are within 36 seconds of each other. Table 18 shows the peak temperatures and temperatures 10 seconds before collapse of each experiment and they are all with 10% of each other demonstrating that the temperatures in the basement are independent of the change in fuel load. Experiment 4 with the larger fuel load did not burn hotter than Experiment 5, the most significant difference was the time to ignition of the flooring systems. The ventilation conditions for both Experiment 4 and 5 were the same.

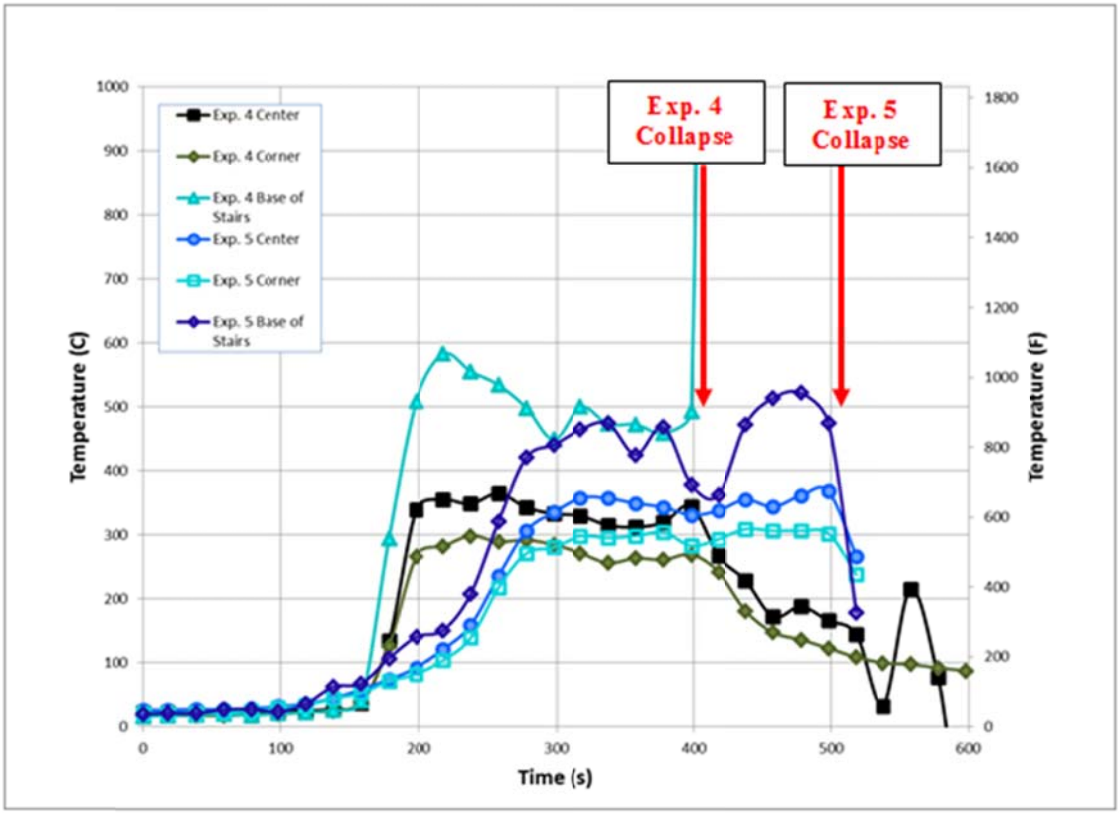

Figure 32. Basement temperatures at 6 ft. above the floor for Experiments 4 and 5

Table 18. Comparison of Basement Temperatures at 5 ft. above the floor

	Peak Temperature [Temperature 10 seconds Prior to Collapse] (^oC)		
Experiment	Center	Corner	Base of Stair
4	365 [350]	300 [280]	580 [490]
5	370 [370]	310 [300]	520 [480]

The second comparison was between Experiment A and Experiment B. All variables were the same with the exception of the fuel load. Experiment A had the standard fuel load consisting of the pallets and the cardboard boxes and Experiment B had no fuel load and was ignited with a propane plumber's torch. Figure 33 shows the basement temperatures at 6 ft. above the floor and the collapse times for Experiments A and B. In the graph time zero for Experiment B was when the floor system was ignited by the torch and sustained burning. Table 19 shows the peak temperatures and temperatures 10 seconds before collapse of each experiment. Temperatures at the corner location, remote from the fire are similar between experiments while Experiment A had higher center temperatures and Experiment B had higher base of stair temperatures. Fire development in both experiments was dictated by the burning of the floor system and not the fuel load in the basement. Comparing the time from floor system ignition to collapse in both experiments yields collapse times within 90 seconds of each other.

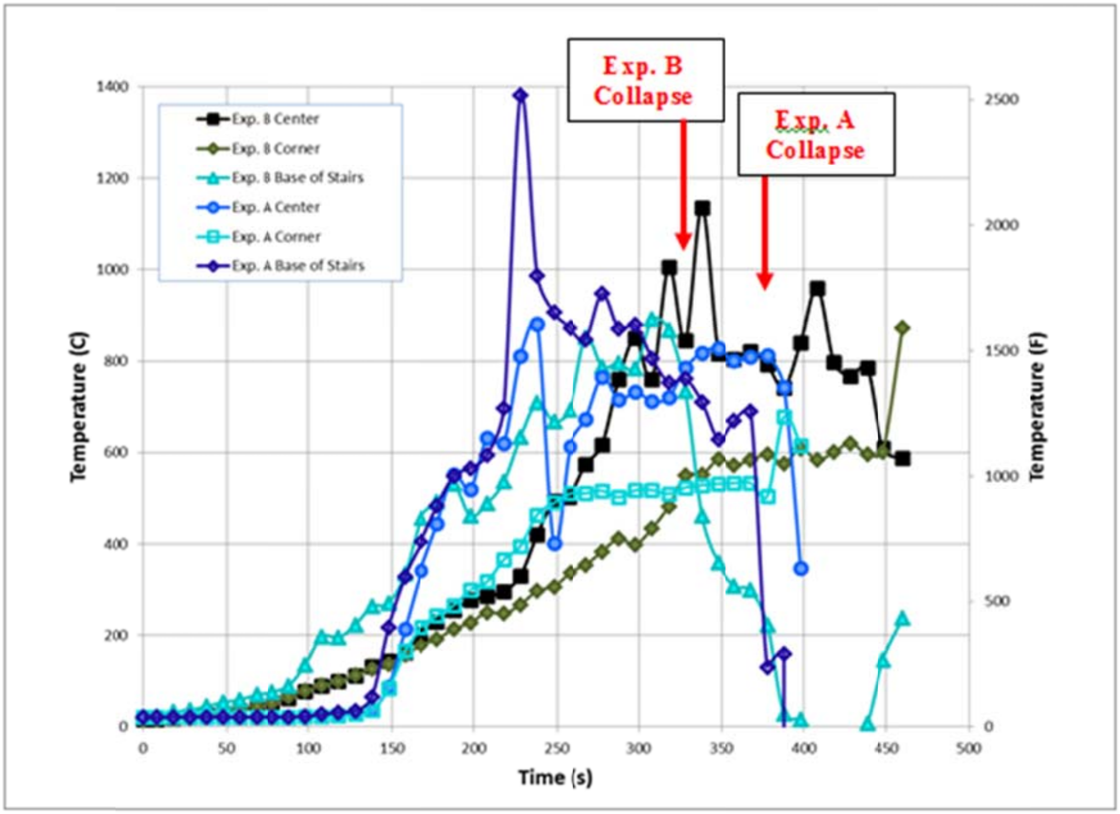

Figure 33. Basement temperatures at 6 ft. above the floor for Experiments A and B

Table 19. Comparison of Basement Temperatures at 5 ft. above the floor

	Peak Temperature [Temperature 10 seconds Prior to Collapse] (^oC)		
Experiment	Center	Corner	Base of Stair
A	1150 [800]	620 [550]	900 [700]
B	900 [900]	700 [550]	1380 [880]

Building on the concept developed above, that the floor system is the primary fuel source; it becomes possible to separate the fuel load causing the floor system to ignite from the time to achieve floor collapse. This can be accomplished by examining the time from floor system sustained ignition to collapse. This difference in time will be referred to as Δt. Comparing this time for the two sets of experiments above yields collapse times within 13% and 27% respectively (Table 20). It is also worth noting the differences in peak temperatures between Experiments 4 and 5 (No Ventilation) and Experiments A and B (Max Ventilation). The added availability of oxygen in the maximum ventilation cases to a fuel rich condition enabled an increased generation of heat which resulted in higher temperatures.

Table 20. Delta t calculations for fuel load comparison experiments

Experiment Number	Floor Support	Ventilation Description	Fire Spread to Floor	Collapse	Δt (min:sec)
4	Engineered Wood I-Joist (12 in.)	No Vent	2:43	6:49	4:06
5	Engineered Wood I-Joist (12 in.)	No Vent/No boxes	3:45	8:27	4:42
A	Engineered Wood I-Joist (12 in.)	Max Vent / Same as Exp. 3	2:20	6:20	4:00
B	Engineered Wood I-Joist (12 in.)	Max Vent / Torch ignition	25:55	31:25	5:30

Comparisons can be made to the temperatures that were generated to expose the floor systems in all of the series of experiments independent of the source of the fire. Dimensional lumber was chosen for this comparison because the experiments lasted longer than the other floor systems and these joists were tested in each of the types of experimentation. Comparing the temperatures in the dimensional lumber experiments for each series of experiments to the standard time temperature curve yields an assessment of fuel load. The standard time temperature curve provides a standard fire exposure for comparing relative fire performance of building construction assemblies. Figure 34 shows the average furnace temperatures for the component and floor furnace experiments, the temperatures in the basement, at the base of the stairs, 1 ft. below the floor assembly in the field experiment and the temperatures in the basement of the bungalow house 1 ft. below the ceiling versus the standard time temperature curve.

The component level furnace experiment was able to remain close to the standard curve for the duration of the experiment by balancing the fuel burned inside the furnace with the burning of the floor joist. The assembly level floor furnace experiment remained below the curve for the first 100 seconds and then exceeded the curve as the floor assembly ignited and contributed to the burning in the furnace. The maximum ventilation field experiment also remained below the standard curve for the first 120 seconds and then exceeded it until approximately 360 seconds before remaining at or below it until collapse. The house fire experiment also began below the curve for the first 100 seconds and then exceeded it until approximately 380 seconds before remaining near or below it until collapse. It is important to note that typically the standard time temperature curve is followed for hourly ratings, 30 minutes to 4 or more hours, while these experiments only lasted approximately 7 to 20 minutes after ignition before they failed.

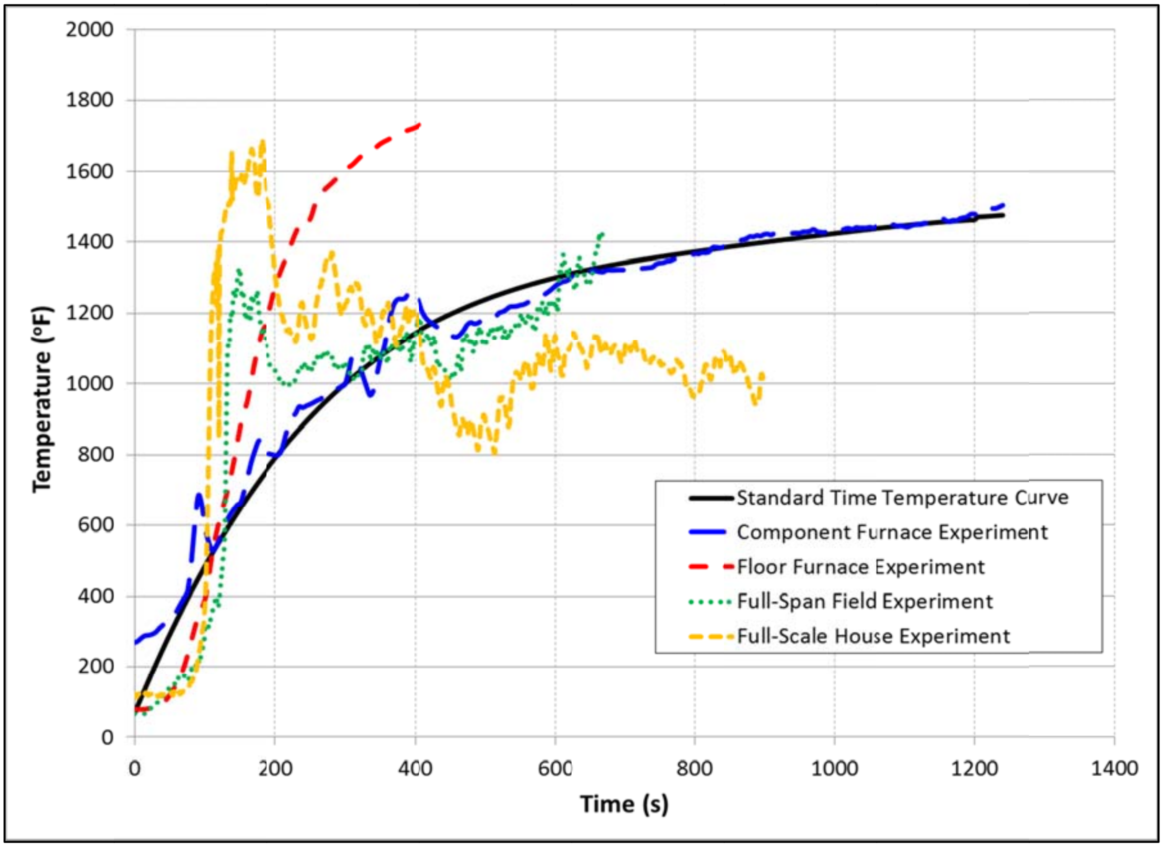

Figure 34. Comparison to the standard time temperature curve

6.6. Span

There was not an experimental comparison that only varied span however span can be compared between experimental series. An engineered I-joist experiment was conducted on the floor furnace with a span of 13 ft. 4 in. and a experiment with the same type of joists was conducted in the field experiments with a span of 20 ft. While the fuel load or source of fuel was varied the resulting failure time was similar. Examining the temperatures exposing both of those experiments shows very similar exposures between the furnace and field experiment (Figure 35). The temperatures compared are the average furnace temperature and the temperature 1 ft. below the ceiling adjacent to the fuel package ignited in the field experment. The comparison of failure times suggest that a span difference of 6 ft. 8 in. in this case did not cause a significant difference in failure time.

Table 21. Span Comparison

Experiment	Span	Spacing (i.o.c.)	Depth (in)	Load	Details	Failure Time
UL Floor Furnace	13 ft. 4 in.	24	11 7/8	Modified	Previous UL Research (Backstrom & et al., 2010)	6:00
Full-Span Field Experiment	20 ft.	24	11 7/8	Modified	Maximum Ventilation	6:49

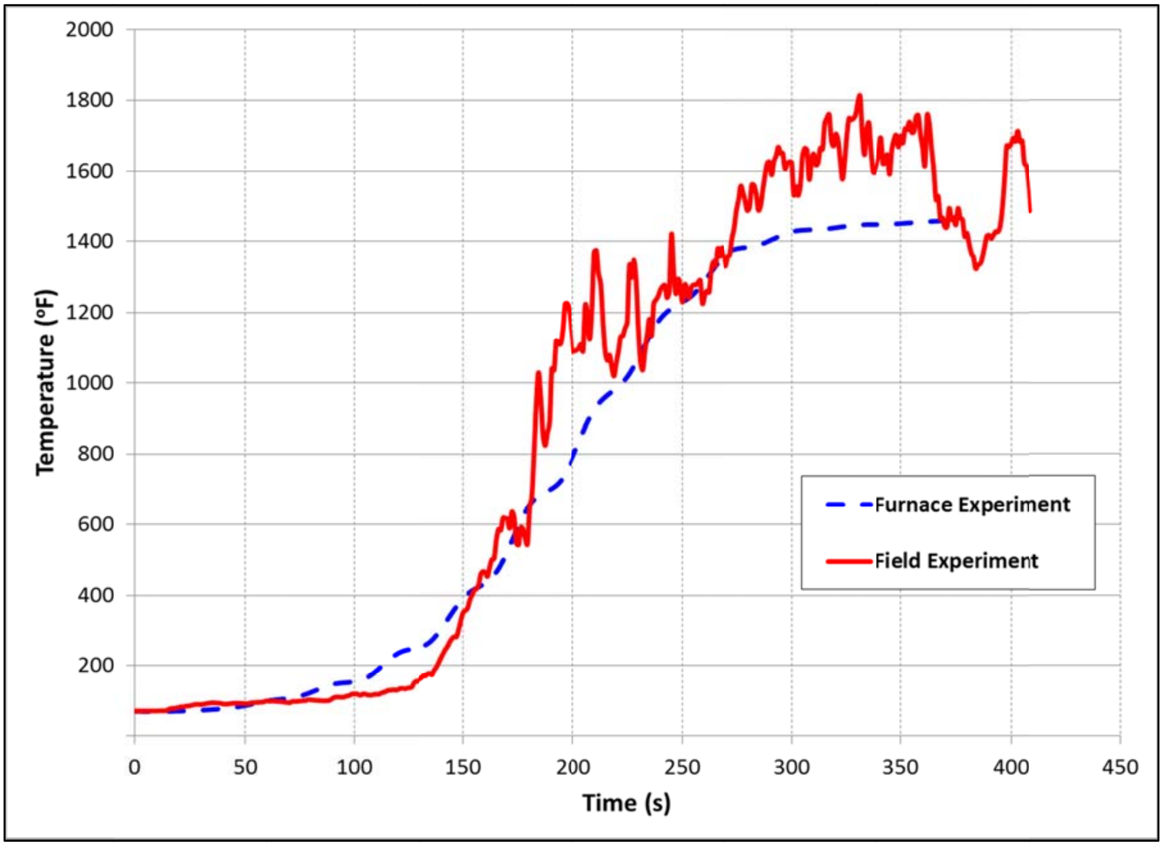

Figure 35. Temperature Comparison for Span Analysis of Engineered I-joist Experiments

6.7. Protection Methods

Previous UL floor furnace experiments examined gypsum wallboard as a protective barrier for wood floor systems. Since there are often many obstructions in a basement that make applying gypsum wallboard to the underside of joists difficult or time consuming, these experiments examined if there are any spray applied protection technologies that could provide protection to extend the time to floor system failure. Two potential technologies were identified, spray applied fire retardants and spray applied intumescent coatings.

The first technology tested was a spray applied fire retardant coating. This product is designed to be applied on wood to improve the flame spread properties of the wood product. It was applied to an engineered I-joist and tested in the floor furnace. This technology only provided minimal impact to extending the time to failure from 6:00 to 8:40 (Table 22).

The second technology tested for equivalence was a spray applied intumescent coating which was UL Classified for Fire Resistance for multiple applications when applied to steel sections. This product is currently not designed for use on wood. This technology increased the the time to failure by almost 200% , 6:00 to 17:50. Currently, this product is cost prohibitive when compared to the cost of gypsum wallboard and its compatibility with wood is unknown but thought to be degrading over time due to its chemical composition. Even with those caveats, it still did not achieve the comparative protection of ½ in. gypsum wallboard, 26:43 (Table 22).

Table 22. Engineer I-Joist Floor Assemblies with Protection Methods under the same modified loading conditions

Test Assembly	Supports	Time to failure
1	Engineered I-Joists – Unprotected (12 in.)	6:00
3	Engineered I-Joists w/ Fire Retardant Coating (12 in.)	8:40
4	Engineered I-Joists w/ Intumescent Coating (12 in.)	17:50
5	Engineered I-Joists w/ gypsum wallboard (1/2 in.)	26:43

Table 23. Dimensional Lumber Floor Assemblies with Protection Methods under the same modified loading conditions

Test Assembly	Supports	Time to failure
1	Dimensional Lumber (2 x 10) - Unprotected	18:35
2	Dimensional Lumber (2 x 10) – Gypsum Wallboard (1/2 in)	44:40
3	Dimensional Lumber (2 x 10) – Plaster and Lath	79:00
4	Dimensional Lumber (2 x 10) w/ 100% Loading	7:04
5	Old Dimensional Lumber (2 x 8) w/ 100% Loading	18:05

7. Tactical Considerations

Bringing together the results of these experiments or all experiments for the fire service, to understand how they may impact tactics on the fire ground is crucial to the safety of the fire service. All of the changes to the fire environment that have occurred over the past few decades make it essential for the fire service to reevaluate their tactics on a regular basis.

Note to Fire Service Readers: Before you read this section it is very important to understand this information and these considerations as they pertain to the types of structures used in these experiments. Another important factor to keep in your mind is the capabilities and resources available to your particular department. If your department has 3 person staffing on an engine and your mutual aid is 20 minutes away you may look at these considerations differently than if your department has 6 person staffing and you expect 4 engines and 2 trucks on the scene in 10 minutes. There are no two fires that are the same and not every fire has one answer that is correct every time, most of the time it depends on a number of variables. Even in these controlled experiments with the same structure and fuel load there are differences in how the fire develops. These tactical considerations are not meant to be rules but to be concepts to think about, and if they pertain to you by all means adapt them to your operations.

7.1. Operational Timeframe

Every fire department has a wide range of response times within their response area depending on factors such as distance from the fire station, type of fire department and time of day just to name a few. In an analysis done by the United States Fire Administration (USFA) in 2006 they conclude, “In most of the analyses done here, response times were less than 5 minutes nearly 50% of the time and less than 8 minutes about 75% of the time. Nationally, average response times were generally less than 8 minutes. The overall 90th percentile, a level often cited in the industry, was less than 11 minutes." (USFA, 2006)

These response times don't take into consideration the time between ignition and notification to the fire department to begin their response. It is important to note that the fire department rarely knows when the fire started. Conservatively for this discussion let's assume that it takes 4 minutes from the time of ignition, for the fire to be discovered, for the fire department to be notified and for the fire department to begin their response. Figure 36 shows the response times from the USFA study and how they compare with the minimum, maximum and average collapse times from all of the experiments with unprotected floor systems. It is clear that the fire department has to seriously consider collapse in their initial operations because regardless of the flooring type, ventilation configurations, fuel load or mechanical load collapse could occur before their arrival or within their operational timeframe.

All of these experiments were started with a flaming ignition. The average collapse times of all of the engineered floor systems were prior to the arrival of the fire service with the 50th percentile response time of 5 minutes (9 minutes total including 4 minutes to begin the response). All of the engineered floor system experiments, including the maximum times to collapse occurred prior to the arrival of the 90th percentile response time of 11 minutes (15 minutes total including 4 minutes to begin the response). The average collapse time of the dimensional lumber floor system experiments also occurred at the time of the arrival of the fire service with the 90th percentile response which emphasizes the importance of protecting all types of flooring systems, including dimensional lumber. Regardless of the unprotected floor system type no factor of safety can be assumed, doubling the average collapse time of all of these experiments still results in a collapse time that could occur within the operational timeframe of any fire department with any response time. It is important to note that these times are when the fire service would arrive to begin their operations, not the time it takes to mitigate the incident.

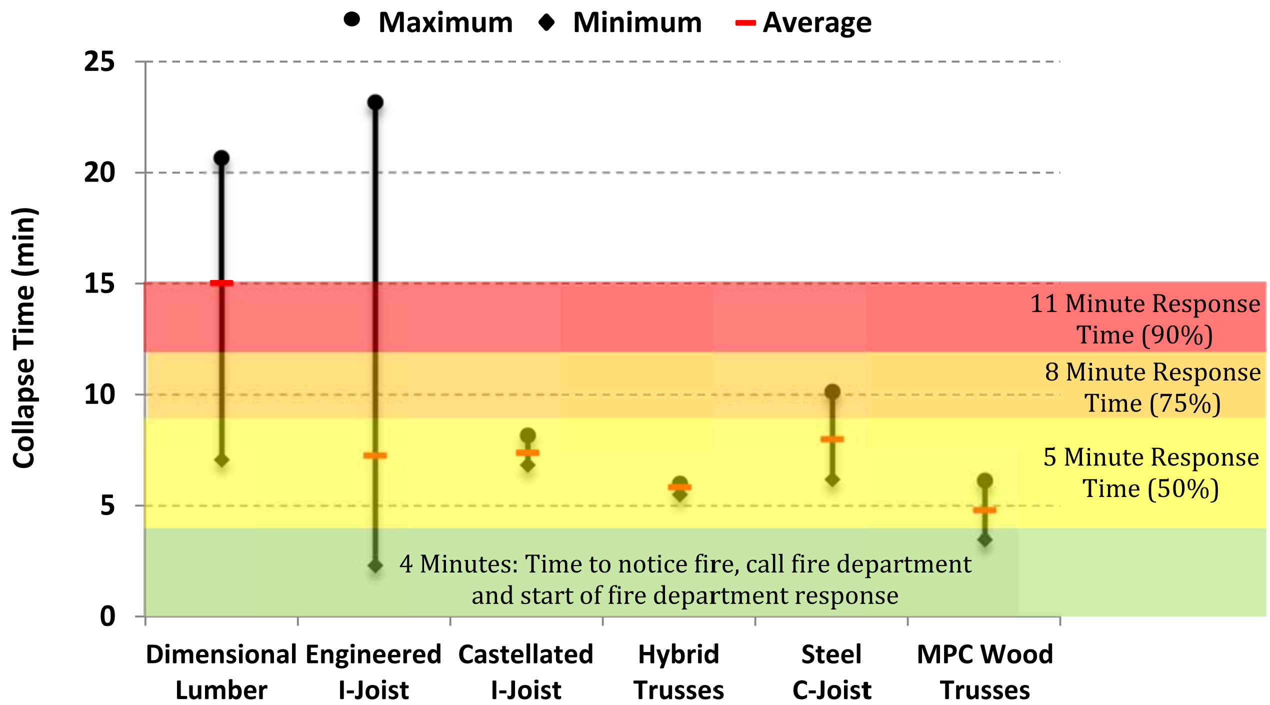

Figure 36. Collapse times versus fire department response times

7.2. Size up

For all of the structure experiments conducted during this study the floor section over the top of the initial fire was the section to collapse first. Second, the amount of ventilation provided to the fire allowed the floor system to collapse faster. While there are few if any reliable interior clues as to when the floor system was going to collapse, for example floor sag may not be noticeable or temperatures may not be predictive. Size up is one task that could go a long way in increasing firefighter safety at basement fires. It is very important to locate the fire floor in the structure and to determine the amount of current ventilation to the fire as well as the potential amount of ventilation based on windows or doors that are still intact prior to fire fighters making entry to the structure. While there are many important factors to observe on the fire ground, operating over a well-ventilated basement fire, these are two factors that can lead to firefighters falling through the floor into a fully developed basement fire.

7.3. Basement Fire Attack

When attempting to extinguish a basement fire it is possible for firefighters to be positioned at or near the top of the basement stairs. Depending on conditions they may attempt to descend the stairs to extinguish the fire. Firefighters in the crawling position would be exposed to temperatures that are 3 ft. above the floor. Figure 37 shows the temperatures at the top of the stairs in the field experiments, 3 ft. above the floor, up until collapse of the floor system. The horizontal dashed line indicates 250 °C (500 °F) as the tenability threshold for firefighters. This is the temperature turnout gear is tested to and the point at which a short duration exposure will not be easily tolerated by a firefighter. All of the ventilated field experiments have temperatures in excess of the threshold indicating that if the hot gases from the fire are able to flow up the stairs then the tenability for firefighters is low in that area and the probability of making it down the steps without injury is minimal.

Figure 38 shows the temperatures at the bottom of the stairs up through the time of floor system collapse. It also demonstrates that if the fire is ventilated then the temperatures at the bottom of the stairs are also not tenable for firefighters. The thought that if it is hot at the top of the stairs during a basement fire then relief may be found at the bottom of the stairs is not supported by the data from these experiments. Furthermore when basement fire conditions reach the severity to create these conditions, unprotected basement structural elements are being rapidly damaged by the fire.

Both figures show that temperatures are lower for the unventilated experiments however once ventilation openings are made such as in experiment 2, conditions change quickly. Temperatures at the top of the stairs change from less than 200 °C (390 °F) to over 400 °C (750 °F) in less than 30 seconds, exceeding firefighter tenability limits. Ventilating the basement while firefighters are attempting to descend the stairs or ventilating while firefighters are at the top of the stairs could be very dangerous.

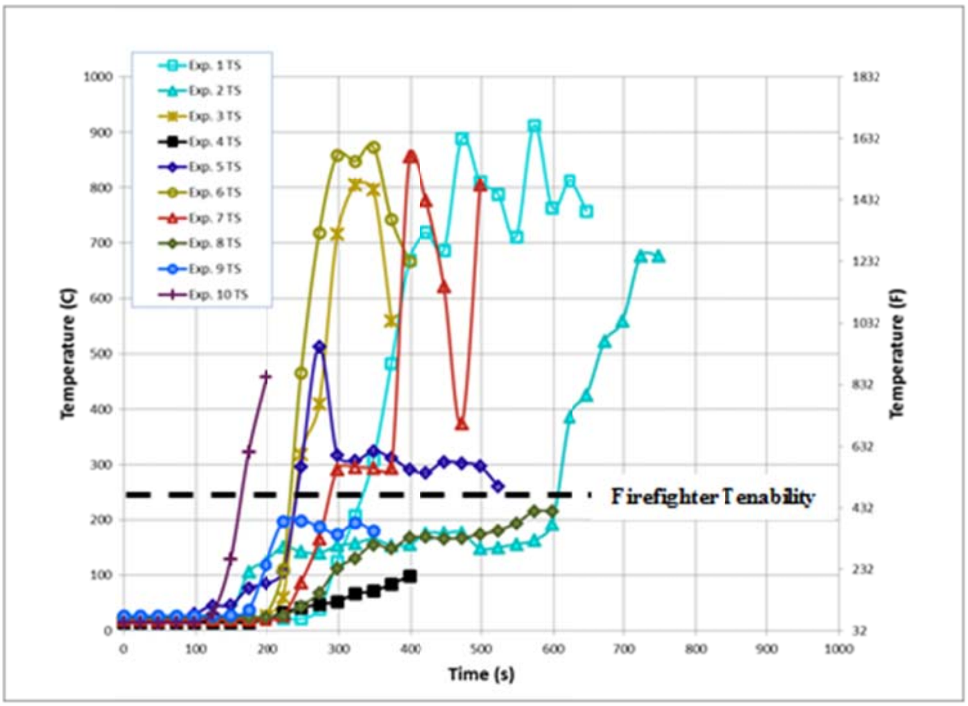

Figure 37. Field Exp. Temperatures 3 ft. above the floor at the top of the stairs

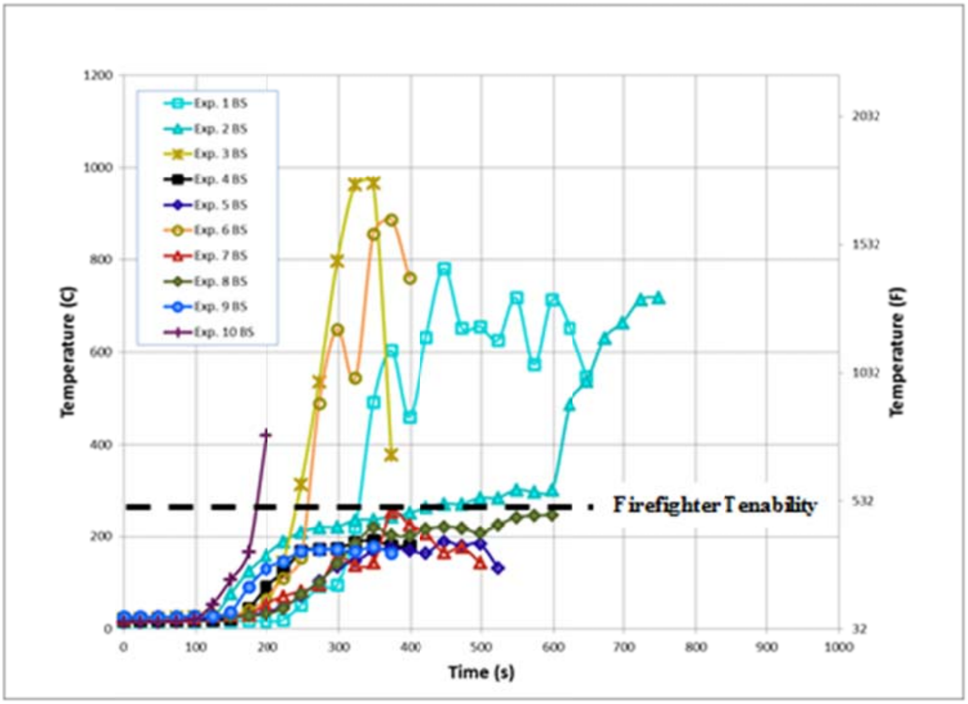

Figure 38. Field Exp. Temperatures 3 ft. above the floor at the bottom of the stairs

7.4. Ventilation

The field experiments demonstrate the importance of coordinated ventilation. While most of the floor systems in the field experiments collapsed prior to "the start of fire department intervention with sequenced ventilation", the dimensional lumber supported floor system in experiment 2 did not and it highlights the importance of flow paths. As the ventilation openings in the basement were made, a flow path was created from the basement to the front door on the first floor of the structure. Anyone in this path would have to move quickly to survive. Figure 39 shows the impact of making ventilation openings on the temperatures in the structure, 3 ft. above the floor. Opening the front door had little impact on the temperatures and even lowered the temperatures on the first floor slightly. However, once the basement ventilation openings were created, a flow path from the basement to the front door was created and the temperatures increased dramatically throughout the structure. Figure 40 shows the velocities of the gases traveling up the basement stairs. Average velocities increase from 3 m/s (7 mph) to 6 m/s (13 mph) once the basement door was opened. Since the ventilation of the basement is not being done by the crew on the first floor it becomes paramount for the crew that wishes to ventilate the basement to be in communication with the crew on the first floor and to coordinate the action.

It is also important to note, that the flow path requires an inlet and an exhaust in order for the flow of gases to occur. Closing a door at the top of the stairs will decrease the hazard from the hot gases and enable the first floor crew an opportunity to move to a safer location while the fire is controlled from below.

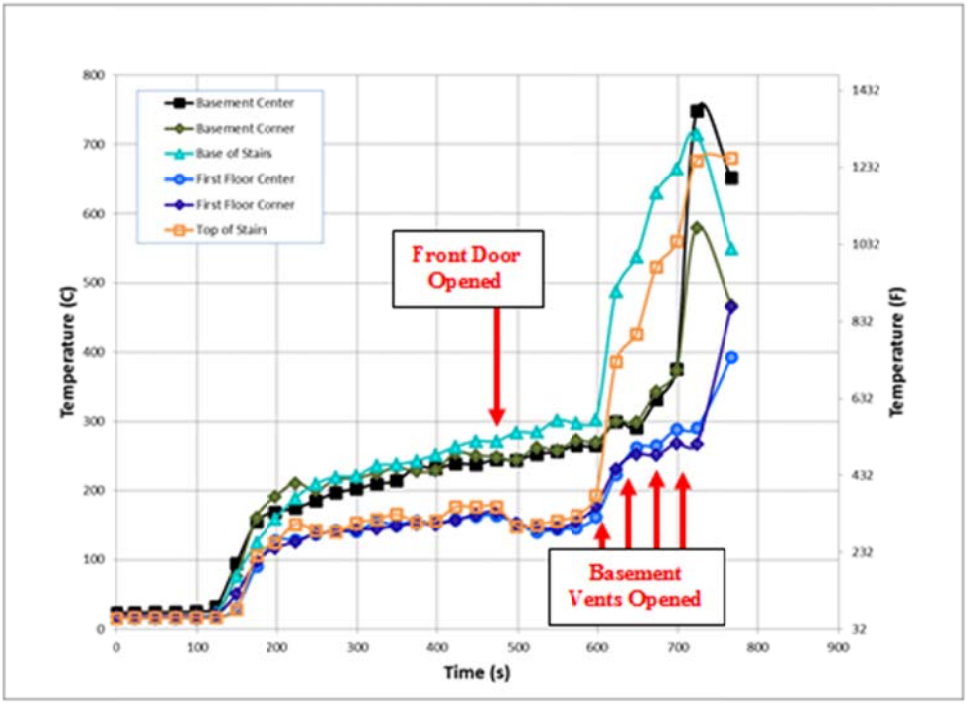

Figure 39. Field Experiment 2 Temperatures at 3 ft. above the floor

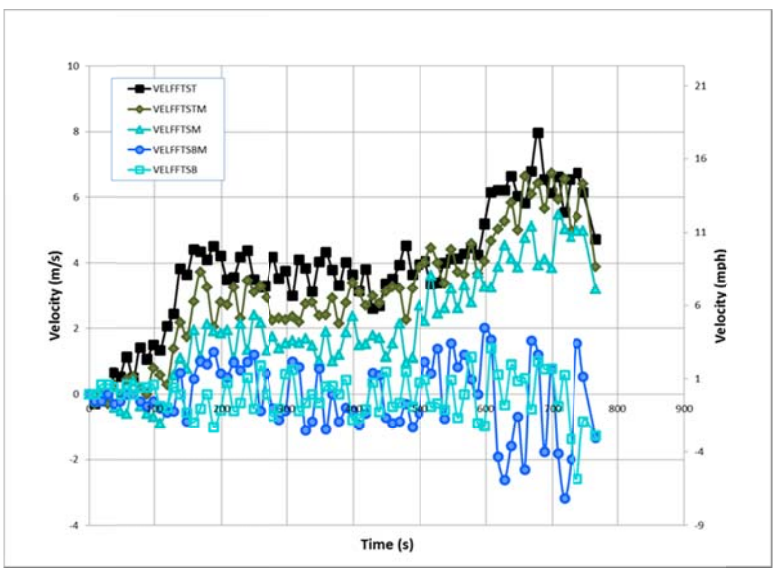

Figure 40. Field Experiment 2 Velocities at the top of the stairs

7.5. Floor Sag as a Collapse Indicator

Firefighters operating within a structure often attempt to determine the strength and stability of their area of operation from above the structure supporting their weight, in some situations operating above a fire. When possible the stability of the floor or roof system should be evaluated from below the area of operation to allow for the inspection of potential damage to the structural elements.

The results of this research have shown that the potential for a well involved, ventilated fire to significantly damage the combustible structural elements is high. Furthermore even under ventilated fires compromised the structural stability of the floor systems tested. The collapse in some cases occurred very rapidly and without significant warning. It is imperative for the fire service to understand that any perceived weakness of the structure in the area of operation may in fact be a late indicator of the damage that has already occurred. In order for a perceived weakness to be present the floor system's stability and/or strength has already been compromised. In these situations firefighters must make every attempt to conduct a controlled evaluation of the structure from below prior to continued operations.

On a span of 16 to 20 feet, just as the ones used in these experiments, it can be difficult to detect the sag of the floor as you crawl on top of it. Firefighters are often looking for warning signs that collapse is about to happen. Table 24 details the deflection 5 seconds prior to collapse for each of the 4 floor systems. The dimensional lumber floor (16 ft. span) deflected the least prior to collapse and the steel C-joist floor (20 ft. span) deflected the most prior to ultimate collapse. Figure 41 gives a relative depiction of what a 20 ft. floor span would look like from the side if it were deflected 6 and 12 inches from flat.

Table 24. Deflection Prior to Collapse

Floor System	Deflection 5 seconds prior to collapse (in.)			
Dimensional Lumber (2 x12)	5.1		5.2	
Engineered Wood I-Joist (12 in.)	10.7	10.9	12.0	12.8
Steel C-Joist (12 in.)	14 +*		14 +*	
Parallel Chord MPCWT	13.6		10.4	

* NOTE: Instrument maximum was 14 in

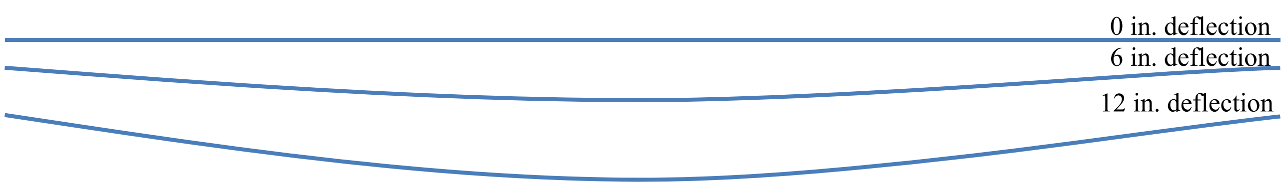

Figure 41. Relative depiction of 0, 6 and 12 in. deflections on a 20 ft. span

7.6. Temperatures on first floor prior to collapse

Temperature may not be an important factor in determining the safety of the firefighters operating on the floor above a basement fire. The layout of the first floor indicating the temperature measurement locations as well as the section of the floor that collapsed first in every experiment (shaded in orange) is shown in Figure 42. Firefighters operating near the top of the stairs would feel the highest temperatures and elevated temperatures would be felt on the remainder of the first floor at the 3 ft. elevation (Figure 43 through Figure 45). Most experiments remained tenable for firefighters operating on the first floor as long as it was for a short period of time. Temperatures above 250 °C (500 °F) would not be bearable for a period of time much beyond a couple minutes. There did not appear to be a repeated temperature spike in the corner location, above the collapse area prior to the time of collapse that could be used as a predictor.

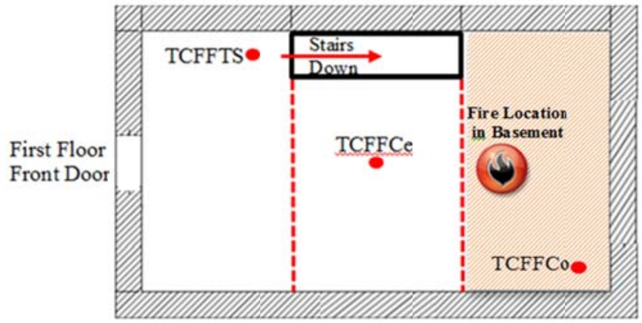

Figure 42. First floor temperature locations and collapse zone

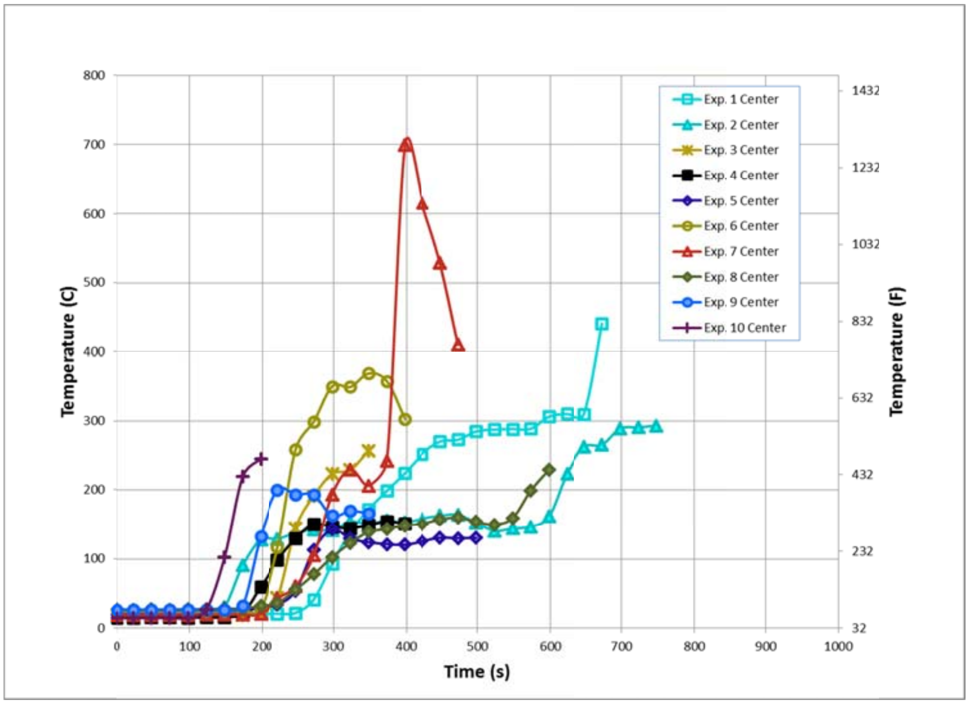

Figure 43. First floor center temperatures 3 ft. above the floor

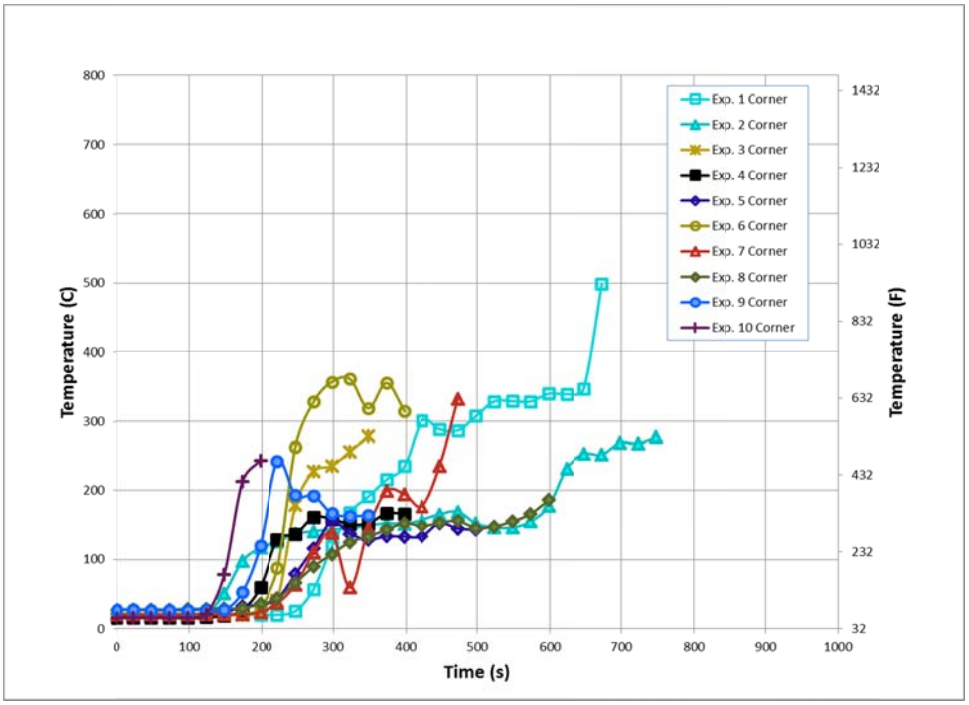

Figure 44. First floor corner temperatures 3 ft. above the floor

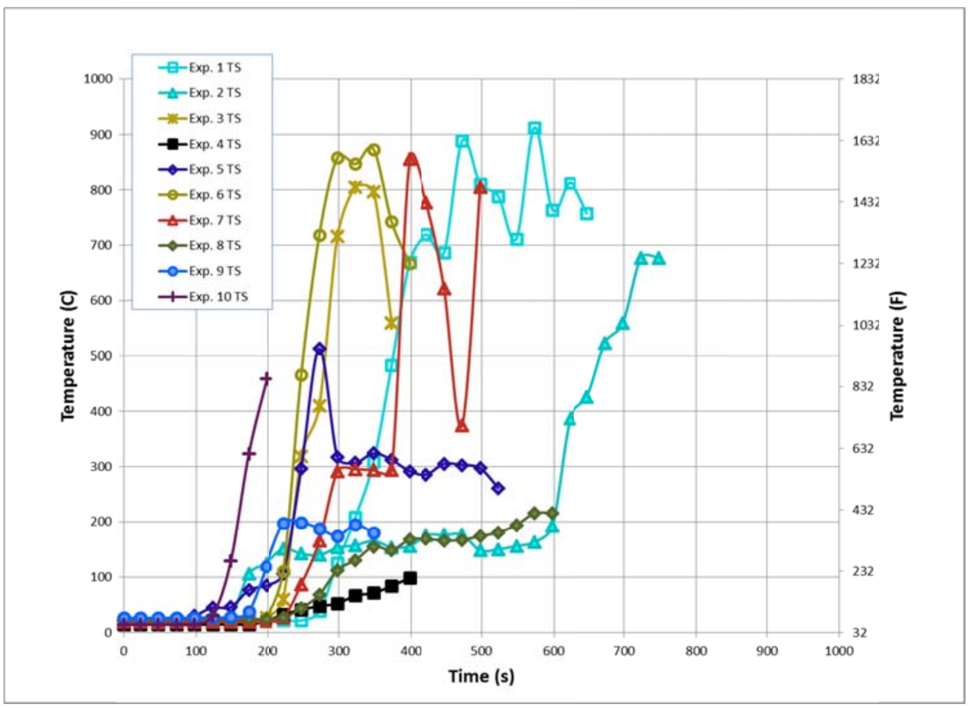

Figure 45. First floor stair temperatures 3 ft. above the floor

7.7. Visual Inspection of Damaged Floor Systems

Whenever possible firefighters should attempt to visually assess the structural stability of the floor system from below, prior to committing to operations above a damaged floor system. Once the type of floor structure is identified firefighters should inspect for failure mechanisms common to the structural element encounter. Figure 46 through Figure 53 show common failure mechanisms respective of the floor framing systems. Noticing any of these elements during inspection should trigger communication of the hazard to all other personnel operating on the scene of the incident.

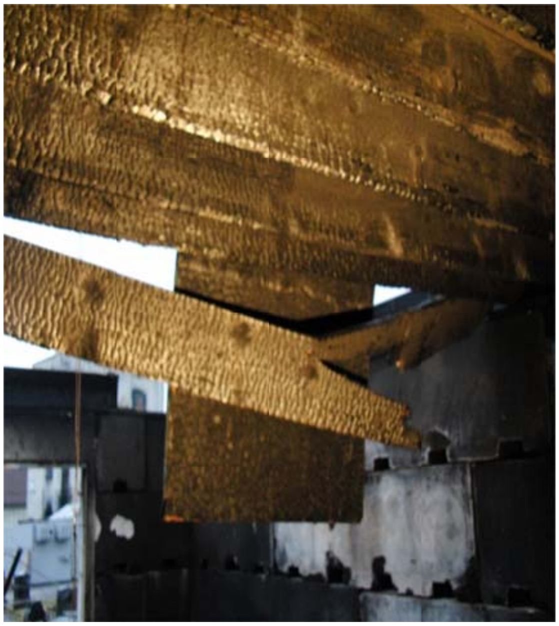

Figure 46. Dimensional Lumber Joist Fracture

Figure 47. Dimensional Lumber Complete Joist Burn Through

Figure 48. Engineered I-joist Web Burn Through

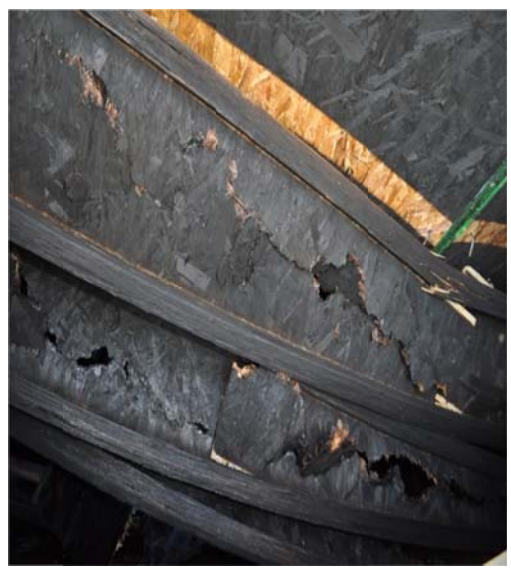

Figure 49. Engineered I-joist Web Failure and Sheathing Separation

Figure 50. MPCWT Steel to wood panel point connection failure

Figure 51. MPCWT Detail of Connection Failure

Figure 52. Steel C-joist Loss of strength inducing progressive joist deformations, sheathing connection failure, joist bracing and lateral bracing strap failure

Figure 53. Steel C-joist deformation detail

7.8. Sounding the Floor

A common fire service practice to determine the structural soundness of a floor before working on it is to sound or strike the floor with a tool such as a haligan bar or an ax to see if sponginess or softness can be felt. In every furnace experiment except for one, the old dimensional lumber, the OSB floor decking remained in place and did not burn through. When burn through did occur it was over 17 minutes into the experiment. All of the other unprotected floor systems failed well before this time and therefore striking the floor would result in hitting solid OSB floor decking although the joists below the floor may be compromised. This would be masked even further if there was a finish floor such as carpet, hardwood or tile on top of the sub flooring. Striking the floor should not be used as a reliable indicator that the floor is safe to operate on top of.

7.9. Thermal Imagers

It was highlighted in the previous 2008 UL study and 2010 NIST study that thermal imagers cannot be used to determine structural integrity of a floor system. The data from the floor furnace series of experiments supports both of those studies. Table 25 shows the temperatures on the exposed and unexposed sides of the floor system moments prior to collapse. The only exception was the legacy lumber floor (Floor Furnace Experiment 7) because it had burned through prior to collapse resulting in high exposed side temperatures. These temperatures are on the subfloor and would be further masked by the finish floor like carpet or hardwood. Thermal imagers can be a great tool for determining if there is a basement fire but should not be used to determine structural integrity of a floor system. There were no signs seen by the thermal imager during these experiments that could be considered a predictive indicator of pending collapse.

Table 25. Floor Furnace Experiment Temperatures on either side of the subfloor

Assembly	Average temperature of exposed side of subfloor (°F)	Average temperature of unexposed surface of floor (°F)
1. Engineered I Joists with Openings	1418	164
2. Engineered Wood and Metal Hybrid Trusses	1431	147
3. Engineered I Joists w/ Intumescent Coating	556	185
4. Engineered I Joists (100% Load)	1195	73
5. Engineered I Joists w/ Fire Retardant Coating	859	149
6. Nominal 2 in by 10 in Dimensional Lumber (100% Load)	1649	188
7. Legacy Nominal 2 in by 8 in Dimensional Lumber (100% Load)	1362	613

7.10. Overhaul

In Full-span Laboratory Experiment C a fire was ignited in the void space of the floor system with a ½ in gypsum board ceiling. This fire grew but became ventilation limited and began to smother itself. The fire was not able to self-sustain. In order to examine the fire damage a pike pole was used to open up the floor where the fire was ignited. An approximate 2 ft. by 3 ft. hole was opened just inside the basement doorway (Figure 54). The resulting fire grew differently with the available oxygen, eventually leading to collapse. Figure 55 shows the temperatures in the area of the hole opened up by the firefighters increased and sustained up until the time of collapse. Due to the impact in the fire behavior after the hole was opened, a hoseline should be in place before making an opening to a basement floor void space to limit the impact of adding ventilation to the ventilation limited space.

The temperatures in the basement never exceeded 60 °C (140 °F) for the entire experiment leading up to collapse even though the temperatures in the void space exceeded 700 °C (1300 °F). The fire did burn up through the OSB floor decking well into the experiment. This could ignite a fire on the first floor which could mask the fact that the fire is in the floor system. The crew checking the basement could experience cool temperatures in the basement but should still inspect the floor system by making an opening, with a hoseline available to extinguish any fire they encounter.

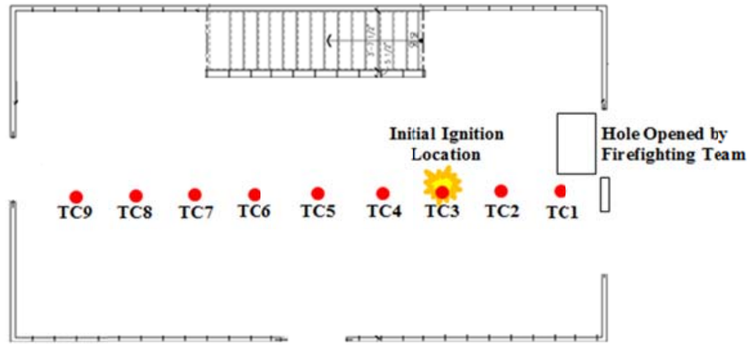

Figure 54. Experiment C Void Thermocouple and Hole Location

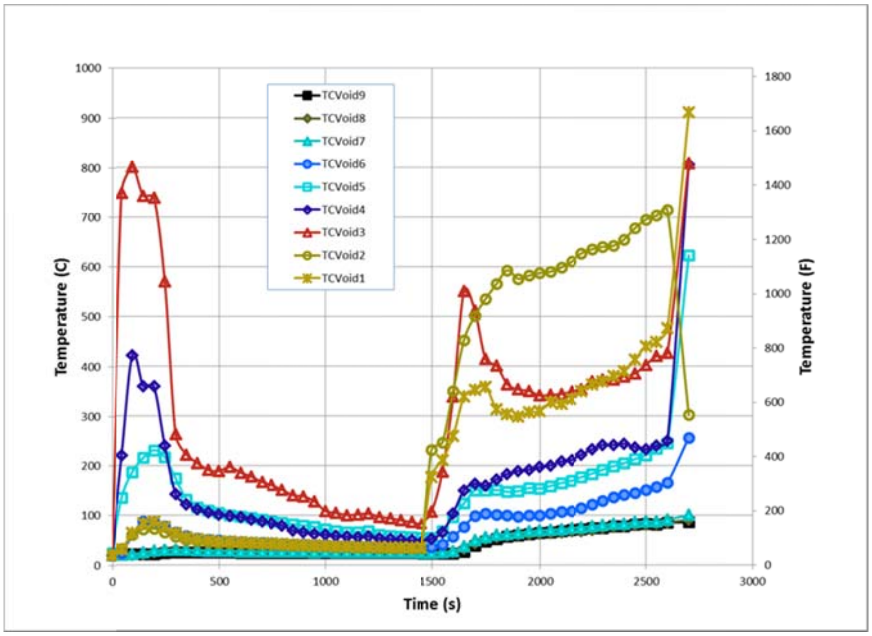

Figure 55. Experiment C void space temperatures.

8. Code Implications

Based on some previous research by UL and others as well as concerns from the fire service a code change is pending that was the result of compromises made between all of the parties that worked to develop the final proposal. The following is the code language that has been adopted for inclusion in the 2012 edition of the International Residential Code.

R501.3 Fire protection of floors. Floor assemblies, not required elsewhere in this code to be fire resistance rated, shall be provided with a ½ inch gypsum wallboard membrane, 5/8 inch wood structural panel membrane, or equivalent on the underside of the floor framing member.

Exceptions:

1. *Floor assemblies located directly over a space protected by an automatic sprinkler system in accordance with Section P2904, NFPA13D, or other approved equivalent sprinkler system.*
2. *Floor assemblies located directly over a crawl space not intended for storage or fuel-fired appliances.*
3. *Portions of floor assemblies can be unprotected when complying with the following:*
   3.1 The aggregate area of the unprotected portions shall not exceed 80 square feet per story.

3.2 Fire blocking in accordance with Section R302.11.1 shall be installed along the perimeter of the unprotected portion to separate the unprotected portion from the remainder of the floor assembly.

4. Wood floor assemblies using dimension lumber or structural composite lumber equal to or greater than 2-inch by 10-inch nominal dimension, or other approved floor assemblies demonstrating equivalent fire performance.

Much like other new code language there are some areas that are left up to interpretation as a result of several compromises. Some of the experiments were conducted to examine the impact of the code change on structural collapse hazards to the fire service.

8.1. Exception 4

This study can begin to address Exception 4 of the proposed change. First it allows 2-inch by 10-inch nominal dimensional lumber or larger to be unprotected. This sets the benchmark for other floor assemblies. The floor furnace and the full-span field experiments can help to define this benchmark. The dimensional lumber floor furnace experiment with a modified load failed at 18:43 and the dimensional lumber floor with 100% of the design load failed at 7:00.

The full-span field experiments with dimensional lumber collapsed at 11:09 and 12:45 after ignition of the fuel load respectively. The first experiment assumes having sufficient ventilation to allow the fuel load and floor system to burn at near optimal levels which could be considered the worst case scenario. The second simulated operations of the fire department that began at 8 minutes after ignition.

Conservatively, taking the slowest time to collapse (18:43), it can argued that this is not an acceptable level of performance because 18:43 can be justified as being within the fire services operation timeframe as described in the previous section, which provides little to no factor of safety. The intent of the code states "The purpose of this code is to establish the minimum requirements to safeguard the public health, safety and general welfare through structural strength, means of egress facilities, stability, sanitation, adequate light and ventilation, energy conservation, and safety to life and property from fire and other hazards attributed to the built environment and to provide safety to fire fighters and emergency responders during emergency operations [IBC Chapter 1, Part 1, Section 101.3 & IRC Chapter 1, Part 1, Section R101.3]. Based on the collapse times from these experiments there is little to no safe operating time for firefighters in a structure with an unprotected dimensional lumber floor system.

The final floor furnace experiment with old dimensional lumber raises the question as to whether all dimensional lumber can be adequately described by its nominal dimensions. The older reclaimed dimensional lumber didn't reach failure until 160% longer than the modern dimensional lumber even though its dimensions were actually smaller. While the fire service suggests that the factor of safety provided by older dimensional lumber was acceptable the experimental results show that new dimensional lumber is significantly different in terms of performance under fire conditions. Protecting the dimensional lumber as well as engineered lumber floor systems in future code requirements would eliminate this fire performance change in dimensional lumber and provide a more reasonable factor of safety for the fire service.

8.2. Equivalence

Another code implication is the definition of "equivalent" as used in the following section, "*Floor assemblies, not required elsewhere in this code to be fire resistance rated, shall be provided with a ½ inch gypsum wallboard membrane, 5/8 inch wood structural panel membrane, or equivalent on the underside of the floor framing member.*" Two different products, utilizing two different technologies, were tested to see if they provide equivalent protection to an engineered floor system with ½ in. gypsum wallboard. The benchmark for this equivalency is interpreted to be approximately 26:45 which is the approximate performance of the three engineered floor systems experimented with ½ in. gypsum board protection (Table 26).

The first technology tested for equivalence was a spray applied fire retardant coating. This product is designed to be applied on wood to improve the flame spread properties of the wood product. This technology only provided minimal impact to extending the time to structural collapse, and it did not come close to providing "equivalent" protection to gypsum wallboard (Table 26).

The second technology tested for equivalence was a spray applied intumescent coating which was UL Classified for Fire Resistance for multiple applications when applied to steel sections. This product is currently not designed for use on wood. While this technology extended the collapse time by almost 200% it did not reach the protection level of gypsum wallboard. Currently, this product is cost prohibitive when compared to the cost of gypsum wallboard and its compatibility with wood is unknown but thought to be degrading over time due to its chemical composition.

Table 26. Collapse times of engineered floor systems with protection technologies

Assembly	Protection	Collapse Time
Engineered I joist (12 inch deep)	None	6:00
Engineered I joist (12 inch deep)	1/2 inch regular gypsum wallboard	26:45
Parallel chord truss with steel gusset plate connections (14 inch deep)	1/2 inch regular gypsum wallboard	29:15
Parallel chord truss with glued connections (14 inch deep)	1/2 inch regular gypsum wallboard	26:45
Engineered I joist (12 inch deep)	Spray applied fire retardant coating	8:40
Engineered I joist (12 inch deep)	Spray applied intumescent coating	17:50

When determining equivalence it is important to select the appropriate test method. Coatings that improve the flame spread properties of wood do not necessarily improve the structural integrity of the floor system when exposed to fire. A common test method for flame spread is the Steiner Tunnel, ASTM E84. A common test method for structural integrity is the floor furnace, ASTM E119. Structural integrity is the purpose of this section of the code therefore any determination of equivalence should use a test method such as ASTM E119.

In the full-scale field experiments the dimensional lumber outperformed all of the lightweight alternatives however they did not resist collapse for a period of time that could be seen as providing an acceptable level of safety for the responding firefighters. The two floor systems with 2-inch by 10-inch nominal flooring members collapsed at 11:09 and 12:45 respectively. The first experiment assumes having sufficient ventilation to allow the fuel load and floor system to burn at near optimal levels which could be considered the worst case scenario. The second simulated operations of the fire department that began at 8 minutes after ignition. This could be interpreted to mean that the fire department would need to eliminate the hazard in less than 5 minutes to avoid the collapse. This assumes that the fire is witnessed, called into the fire department, the fire department is dispatched, the fire department arrives and the fire department begins their firefighting operation in 8 minutes. While possible, this is not the case for the majority of fires that occur across the United States. This emphasizes the importance of protecting all types of flooring systems, including dimensional lumber.

8.3. Exception 3

The exception in Section 3.1 of the code allows for an aggregate area of 80 ft^2 of unprotected floor per story. Experiment D was conducted in the laboratory to examine the potential impact of this exposed floor area. This experiment had a 9 ft. 10 in. wide by 7 ft. 9 in. deep exposed truss area that was fire blocked with ½ in. gypsum wallboard on all of the sides (Figure 56 and Figure 57). The exposed area was located on the centerline of the room toward the back of the stairwell location. The fire was ignited at the end of the basement near the doorway as shown in

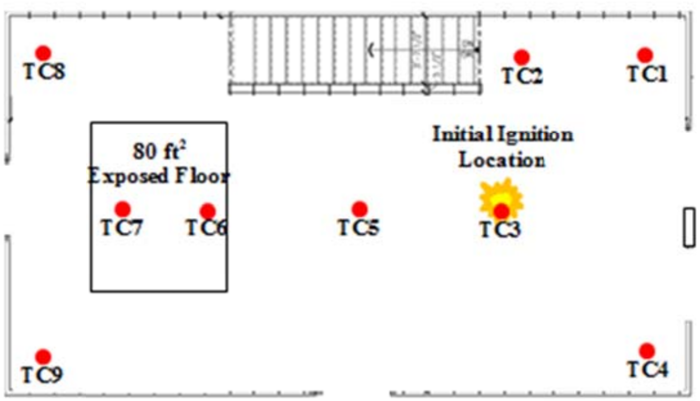

Figure 58. At 13:10 the section of floor above the fire source collapsed. At 15:36 a secondary collapsed occurred that included the center/shorter span next to the stairwell and the span with the unprotected floor area. The three joists that were protected beyond the unprotected area remained intact.

The results of this experiment demonstrate that having an exposed section of flooring remote from the source of the fire doesn't mean that the floor will collapse in that area first. In this case the unprotected area collapsed 2:26 after the protected area over the fire collapsed. Adding gypsum board to a majority of the floor system increased the collapse time of the MPCWT from 3:28 in Experiment 10 to 13:10 in Experiment D. The worst case scenario would be to place the exposed floor area over the fire location however it can be expected that the results would be similar to those of Experiment 10 because the center span of the truss deteriorating over the fire would cause truss failure as the wood was burned away.

Limiting the fuel load in relation to the exposed floor area or placing the exposed floor area in a separate room from the finished section of the basement would increase the safety when the floor area must be exposed. The fire blocking was also successful in limiting the exposure to the remained of the floor.

Figure 56. Close view of exposed trusses

Figure 57. Detailed image showing draft stopping of the exposed trusses

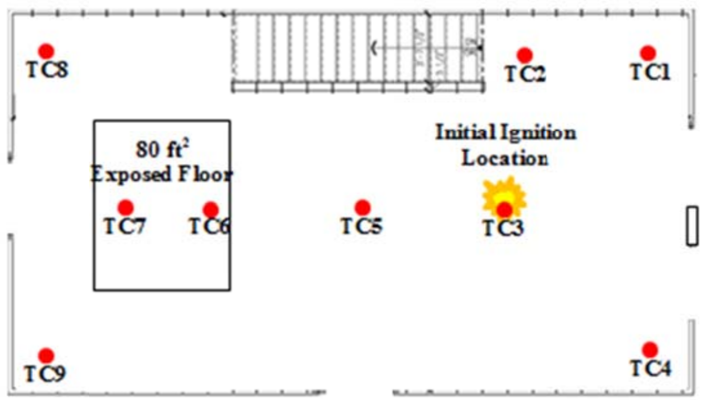

Figure 58. Experiment D Void Thermocouple and Exposed Floor Location

9. Summary of Findings:

Basement fires are challenging and dangerous. Firefighters can be in a position where they are operating above the fire and in some cases without knowing it. When above a basement fire with an unprotected wood floor assembly a number of challenges exist. Often the fire service has no idea how long the fire has been burning, no information on the type of floor system and no means of assessing the structural integrity of the floor system. There are little if any warning signs of collapse so it is very important to understand the hazards associated with a basement fire because the consequences of falling through a floor into a basement fire are pinnacle. To increase fire fighter safety UL accomplished several objectives with this research project.

Improving firefighter safety by further educating them of the hazards associated with engineered flooring systems.

UL conducted several series of experiments to examine basement fires and collapse hazards posed to the fire service. There are several tactical considerations that result from this research that firefighters can use immediately if applicable to them.

- Collapse times of all unprotected wood floor systems are within the operational time frame of the fire service regardless of response time.
- Size-up should include the location of the basement fire as well as the amount of ventilation. Collapse always originated above the fire and the more ventilation available the faster the time to floor collapse.
- When possible the floor should be inspected from below prior to operating on top of it. Signs of collapse vary by floor system; Dimensional lumber should be inspected for joist rupture or complete burn through, Engineered I-joists should be inspected for web burn through and separation from subflooring, Parallel Chord Trusses should be inspected for connection failure, and Metal C-joists should be inspected for deformation and subfloor connection failure.
- Sounding the floor for stability is not reliable and therefore should be combined with other tactics to increase safety.
- Thermal imagers may help indicate there is a basement fire but can't be used to assess structural integrity from above.
- Quickly descending the stairs to find relief at the bottom was not possible, temperatures at the bottom of the basement stairs where often worse than the temperatures at the top of the stairs.
- Coordinating ventilation is extremely important. Ventilating the basement created a flow path up the stairs and out through the front door of the structure, almost doubling the speed of the hot gases and increasing temperatures dramatically.
- Floor sag is a poor indicator of floor collapse.
- First floor gas temperatures can be a poor indicator of conditions below, especially when remote from the top of the stairs.
- Hoselines should be available when opening up void spaces to expose wood floor systems.

Understanding the impact of span, fuel load, ventilation and fire location to system failure.

These variables were assessed through several different types of experiments as well as within the experimental series. Span was varied between 12 ft. in the component furnace experiments to 20 ft. in the full span field and laboratory experiments. Fuel load was varied from a fuel load representative of what could be found in a basement to a standard furnace exposure to igniting just the floor system itself. Ventilation was varied from a door and 3 open windows to all ventilation openings closed. Fire location was varied between in the basement and above a protective ceiling. The analysis of all of these variables was conducted with respect to system failure times and mechanisms.

Examine different fire protection methods and develop data to assess their effectiveness and working with the engineered products manufacturers design products to meet fire performance and mechanical performance standards.

Three technologies were utilized to try to improve the fire performance of engineered floor systems, gypsum board, fire retardant coating and intumescent coating. Gypsum board applied to the bottom chord of an engineered I-joist floor system extended the collapse time from 6:00 to 26:45. The next technology tested was a spray applied fire retardant coating. This product is designed to be applied on wood to improve the flame spread properties of the wood product. This technology only provided minimal impact to extending the time to structural collapse, and it did not come close to providing "equivalent" protection to gypsum wallboard.

The third technology tested for equivalence was a spray applied intumescent coating which was UL Classified for Fire Resistance for multiple applications when applied to steel sections. This product is currently not designed for use on wood. While this technology extended the collapse time by almost 200% it did not reach the protection level of gypsum wallboard. Currently, this product is cost prohibitive when compared to the cost of gypsum wallboard and its compatibility with wood is unknown but thought to be degrading over time due to its chemical composition. This technology has the potential to provide adequate protection but further research needs to be conducted to understand its impact on wood over time and the cost needs to be brought down considerably to make it a cost effective option.

Improve occupant safety by allowing for longer egress times.

By applying a protective layer of gypsum board to unprotected floor systems, not only does it extend the time to collapse but it also separates the large fuel load that is the floor system from the fuel load in the room. When unprotected the combustible floor system is in the ideal location above the fire to quickly spread and grow the fire when sufficient air is available. This separation or protection allows for slower fire growth and longer times for occupant egress.

Provide data to substantiate code changes related to fire rated engineered floor systems to result in improved building fire safety.

Based on some previous research by UL and others as well as concerns from the fire service a code change to the 2012 International Residential Code has gone into effect that was the result of compromises made between all of the parties that worked to develop the final proposal. This change requires gypsum wallboard protection, or equivalent, of engineered lumber floor systems in new homes. This research project examined what "equivalent" could mean and if there were technologies that could meet this definition. Intumescent coating technology showed promise however it did not provide equivalent protection as tested. There are several exceptions in the code language that where examined in this research project. One exception is that there is no protection required for dimensional lumber floor systems. This research study provides data to substantiate the need to protect dimensional lumber floor systems to improve firefighter safety. The second exception examined was the allowance of an exposed 80 ft^2 exposed area. Limiting the fuel load in relation to the exposed floor area or placing the exposed floor area in a separate room from the finished section of the basement would increase the safety when the floor area must be exposed.

Effectively model the impact of fire insult on engineered flooring systems and provide a valuable test database to the fire community for validation of computer-aided engineering models.

Modeling was completed utilizing two models, a computational fluid dynamics model, Fire Dynamic Simulator (FDS) and a finite element model, ANSYS. Fire behavior of a basement fire experiment was modeled utilizing FDS and the structural performance of wood beams and a floor system were simulated utilizing the finite element model. The reports included in the appendix provide a test data database for the fire community to validate computer-aided engineering models.

10. Future Research Needs:

To date residential floor systems have been a subject that has been very thoroughly tested. Future research would be needed to make sure that the fire service is receiving the proper message from the research and that they are implementing the results. Another fire service research project should be to examine the effect of applying water through an exterior basement opening on the conditions as they pertain to tenability at the top of the stairs and the rest of the structure. Since operating on top of a wood floor system involved in fire is dangerous there should be an analysis done on alternative suppression strategies to increase firefighter safety. Many fire departments would flow water in through a basement window or doorway to begin to suppress the fire however other departments refuse to do so claiming that the conditions inside the structure would be made untenable for any occupants inside.

Additional research should be conducted to further understand how dimensional lumber has changed over time in regards to structural stability. Newer lumber growth methods impact on fire performance should be further investigated.

11. Acknowledgements:

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Appendix A. Fire Resistance Tests on Wood and Composite Wood Beams

Accessible from the UL fire service web site, www.ul.com/fireservice

Appendix B. Fire Service Collapse Hazard Floor Furnace Experiments

Accessible from the UL fire service web site, www.ul.com/fireservice

Appendix C. Full-Scale Floor System Field and Laboratory Fire Experiments

Accessible from the UL fire service web site, www.ul.com/fireservice

Appendix D. Basement Fire Growth Experiments in Residential Structures

Accessible from the UL fire service web site, www.ul.com/fireservice

Appendix E. Modeling the Thermal and Structural Behavior of Wood Beams in a Fire Environment

Accessible from the UL fire service web site, www.ul.com/fireservice

Appendix F. Fire Modeling of Basement with Wood Ceiling

Accessible from the UL fire service web site, www.ul.com/fireservice