Full-Scale Floor System Field and Laboratory Fire Experiments

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January 2012

Document Information

Release Type	ntial) ☑ External (Public)
UL Distribution	
External Distribution	National Institute of Standards and Technology

Date: January 2012

Keywords: Structural Collapse, Engineered Lumber, Firefighting, Ventilation, Fire Behavior, Modern, Legacy

Title: Full-Scale Floor System Field and Laboratory Fire Experiments

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EXECUTIVE SUMMARY

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 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.

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

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 floor system itself was a significant contributor to fire growth and flashover conditions. 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 or all ventilation locations open 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 metal plate connected wood truss 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.

Operational Timeframe: A well ventilated basement fire that has involved the floor system is inherently dangerous to operate on top of. This holds true regardless of the construction method or members involved. The longest time to collapse of an unprotected floor system during this series of experiments was 12:45 after ignition. Since the fire department does not typically know when the fire started there is no guaranteed safe operational timeframe to be operating on top of a basement fire.

Size-up: Size-up is an important factor when it comes to assessing risk versus benefit for the fire service. When faced with a basement fire, the location of the fire and the amount of ventilation the fire is receiving are important factors that could indicate the chance and area of floor collapse.

Basement Fire Attack: A ventilated basement fire that has involved the floor system creates high risk conditions in the area of the stairwell. These conditions become even worse when a flow path exists from a ventilation opening in the basement to a ventilation opening on the first floor. If an interior attack is deemed appropriate, the fire service wants to avoid creating this flow path and being in or near this flow path as temperatures can increase very quickly and without warning. Coordination between interior crews and outside ventilation crews needs to be communicated. Ventilating the basement while firefighters are attempting to descend the stairs or ventilating while firefighters are at the top of the stairs increases the risk to the interior attack crew.

Ventilation: 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 is in coordination and communication with the crew on the first floor. Any firefighter that gets caught in the flow path between the ventilation location in the basement and the ventilation location on the first floor could be in danger once the fire responds to the air provided by the ventilation actions of the fire service.

Floor Sag as Collapse Indicator: Every floor system sagged prior to collapse however over the span it could be difficult to notice. The dimensional lumber floor had the least amount of sag of less than 6 inches prior to collapse and the metal C-joist floor had the most sag of over 14 inches. These test results did not support the use of floor sag as a reliable collapse predictor.

Temperatures on the First Floor Prior to Collapse: 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.

Visual Inspection of Damaged Floor Systems: During size-up if it was determined that there are benefits to committing personnel for an interior attack, firefighters should visually assess the structural stability of the floor system from below, prior to committing to operations above a fire exposed and therefore damaged floor system. Once the type of floor structure is identified firefighters should inspect for failure mechanisms common to the structural element encountered, such as joist rupture for dimensional lumber floor systems or web burn through for engineered I-joist floor systems.

Overhaul: Due to the impact in the fire behavior after the hole was opened in the void space above the basement ceiling, 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 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.

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1. Project Overview

These experiments are part of a project titled, “Improving Fire Safety by Enhancing the Fire Performance of Engineered Floor Systems and Providing the Fire Service with Information for Tactical Decision Making.” This project was funded by the National Institute of Standards and Technology through the American Recovery and Reinvestment Act. A comprehensive technical approach was developed to examine all of the necessary variables to address the concerns of the fire service and to meet the objectives laid out below.

The objectives of this project include:

- Improving firefighter safety by further educating them of the hazards associated with engineered flooring systems.
- Understanding the impact of span, fuel load, ventilation and fire location to system failure.
- Examine different fire protection methods and develop data to assess their effectiveness.
- Improve occupant safety by allowing for longer egress times.
- Provide data to substantiate code changes related to fire rated engineered floor systems to result in improved building fire safety.
- Advance the practice of measurement science in keeping with the programs' intention and NIST mission.
- Provide a science basis for code improvements to limit occupant and first responder injury and loss of life as well as the tax loss and other fire related liabilities of local, state and federal governments.

Three related series of experiments are documented in this report.

- Fuel Characterization Calorimeter Experiments: These experiments were conducted to measure the heat release rates of the fuel load selected for the field and laboratory experiments. Three replicate experiments were conducted for each combination of pallets and boxes filled with expanded polystyrene foam trays.

- Full-Span Field Experiments: Ten experiments were conducted in outdoor free standing structures to examine four different residential flooring systems while varying, ventilation parameters, fuel load and floor loading.

- Full-Span Laboratory Experiments: Four experiments were conducted in a free standing structure in a large laboratory to factor out weather conditions from the previous experiments and to examine additional variables such as ignition scenario, protection features and code implications.

The technical plan for this project is shown in Figure 1. The tasks covered in this report are highlighted in red. A literature review is also included in this report for material that pertained to these three series of experiments. For results from other tasks in this project or to see the summary report visit www.ul.com/fireservice.

Figure 1. Project Flow Chart

2. Introduction

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. Basement fires can be one of the most dangerous and challenging fires for the fire service. The fire service often operates above the fire which is arguably the most dangerous place to be. Changes in building construction practices have made extinguishing basement fires even more dangerous. Unprotected wood floor assemblies and engineered floor assemblies have reduced the time to safely operate on top of these floor systems. Previous research by various organizations, including UL (Underwriters Laboratories, Inc., 2008), NIST (Harman, 2007), NFPA (FPRF, 1992) and National Research Council Canada (Sultan, Séguin, & Leroux, 2008), provided evidence of the greater risk in structural failure of engineered floor systems in fire events. This previous research work was limited to validating the problem in a single scenario (single floor span length, single fire location, limited fuel load and limited engineered lumber products). This research project assesses other typical scenarios including: longer floor span lengths, more realistic fire loads, different ignition locations, more realistic ventilation scenarios, additional engineered floor system products, code change implications and most importantly the impact of firefighter operations on floor system failure times and mechanisms.

Three series of experiments were conducted to examine the variables described above. The first was a series of three heat release rate experiments to define a realistic and conservative fuel load for the subsequent experiments. The second series consisted of ten field experiments conducted on a simulated basement. Variables altered included fuel load, ventilation scenarios and sequences, applied load and type of floor system. The field experiments were followed by four laboratory experiments at the same scale as the field experiments where variables such as fire ignition scenario, fire ignition location, floor protection methods and ventilation were examined. This report describes the background that leads to this research, examines the experiments and their results in detail, discusses the similarities and differences with previous research results, examines the potential code implications, examines the impact on firefighter operations and concludes with recommendations and considerations for the fire service.

There are many potential contributing factors that influence outcomes during fireground 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. Fahy further states, "Anecdotally, there is a growing concern in the fire service related to whether firefighters and fire officers receive the degree of training and experience necessary to properly assess the risks on the fireground. If the number of structure fires is decreasing, how in fact do firefighters and fire officers gain the experience 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 fireground experience due to a continuing reduction in structure fires.

3. Background

The drive towards engineered floor systems provides economic and productivity benefits to the construction industry and provides architectural options desired by home owners. However, under fire conditions, these engineered floor systems can lead to structural failure in a shorter time as a consequence of the reduced cross-sectional dimensions of the engineered products as compared to traditional 2-by dimensional lumber floor systems. So, despite the structural performance of these new products to traditional lumber construction under 'normal' conditions, the trend reverses in a fire environment. As a result of a 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 highlighting the risks of injury and death that can occur during fire-fighting operations involving engineered floor truss systems. (NIOSH, Preventing Injuries and Deaths of Fire Fighters Due to Truss System Failures, NIOSH Publication No. 2005-132, 2005), (NIOSH, 2006), (NIOSH, 2007)

Recent research by various organizations, including UL, NIST, NFPA and National Research Council Canada, provided evidence of structural failure times of residential 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 up to 20 ft. or more. However, spanning longer distances and holding all other specifications the same can potentially reduce the time to failure when exposed to fire conditions.

The construction industry is continually introducing new engineered products to meet customer demands, such as, better structural stability, faster construction time, efficient use of resources and cost effectiveness. 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. (PRNewswire, 2007) 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 modern building construction.

These new engineered floor designs tend to incorporate even further engineered floor products that use less material than those which were evaluated in previous research. As an example, Figure 2 shows the engineered lumber product tested in UL research, while Figure 3 shows a different engineered lumber product that incorporates a low-density design with significantly less mass per linear foot than the first product. Some of these products include trusses and I-beams with cut-outs for ease of installing duct work and hybrid trusses that incorporate engineered lumber and steel members as shown in Figure 4. With the prevalence of engineered floor systems driven by environmental and economic pressures in the construction industry, it is necessary to ensure that fire safety is not compromised when these products are used in building construction today.

Figure 2. Engineered wood I-beam

Figure 3. Engineered wood I-beam with cut-outs

Figure 4. Wood/ Steel hybrid trusses

4. Literature Review

The following sections discuss the various, formal and informal, 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 referenced during the development of the various research parametrics 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 (FPRF) in October of 1992 (Grundahl, 1992), a complete review of the literature cited in the FPRF 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.

The NELCFRP 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 in the NELCFRP included: 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.

Subsequent internet searches used Google and site-specific search engines to find articles, reports, proceedings, presentations, and other documents related to the topic. The technical publication search included electronic databases of periodicals, books, proceedings, etc. The Illinois Fire Services Institute utilized the University of Illinois library resources to obtain copies of documents not electronically available and any other documents that may have added to the search. Additionally, after a review of the documents, relevant references were specifically added to the search.

Lightweight construction, a term utilized by the fire service, should be considered interchangeable with the products categorized as engineered lumber components and assemblies for the purposes of this literature section.

4.1. Firefighter Injuries and Deaths Due to Structural Collapse

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 100,00, 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).

4.1.1. Residential Collapse Trends of NIOSH Firefighter Fatality Investigation Program

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. Table 1outlines the incidents, the involved structural system, and the type of assembly (floor or roof) involved in the structural collapse. For additional information regarding specific details for each of the NIOSH investigated incidents visit http://www.cdc.gov/niosh/fire/.

Table 1. Incidents of Structural Collapse Referencing the NIOSH Firefighter Fatality Investigation Program

NIOSH Firefighter Fatality	Structural Framing System	Type of Assembly	Occupancy
FACE 9704	Dimensional Lumber	1st Floor Assembly	One-story single family residence
FACE 9817	Dimensional Lumber	2nd Floor Assembly	Three-story multi-family residential/commercial structure
FACE 200232	Dimensional Lumber	1st Floor Assembly	Three-story residential duplex
FACE 200240	Dimensional Lumber	Roof Assembly	2.5 Story single family residence
FACE 200405	Dimensional Lumber	1st Floor Assembly	Two-story townhome
FACE 200509	Dimensional Lumber	Roof Assembly	Vacant one-story residence
FACE 200809	Dimensional Lumber	1st Floor Assembly	Two-story single family residence
FACE 200826	Dimensional Lumber	1st Floor Assembly	Two-story single family residence
FACE 200837	Dimensional Lumber	Roof Assembly	Vacant two-story single family residence

FACE 200923	Dimensional Lumber	1st Floor Assembly	Two-story mixed commercial/residential structure
FACE 200026	Engineered Lumber / Wood Trusses	1st Floor Assembly	One-story single family residence
FACE 200116	Engineered Lumber / Wood Trusses	1st Floor Assembly	One-story single family residence
FACE 200127	Engineered Lumber / Wood Trusses	Roof Assembly	One-story single family residence
FACE 200206	Engineered Lumber / Wood Trusses	1st Floor Assembly	Two-story single family residence
FACE 200211	Dimensional Lumber	1st Floor Assembly	One-story single family residence
FACE 200624	Engineered Lumber / I-Joist	1st Floor Assembly	One-story single family residence
FACE 200626	Engineered Lumber / I-Joist and Wood Trusses	1st Floor Assembly	Two-story single family residence
FACE 200707	Engineered Lumber / I-Joist	1st Floor Assembly	Two-story single family residence

Generally the majority of the NIOSH Firefighter Fatality Investigations addressing structural collapse determine the fires ability to weaken or compromise areas within the occupancy that are not protected by active or passive fire protection methods. This fact highlights two distinct areas within frame or ordinary constructed buildings where a fire has the ability to burn and weaken exposed structural elements, i.e. the attic area under the roof assembly or the basement area under the first floor assembly. Figure 5 defines the percentage of fire events with respect to floor or roof assemblies.

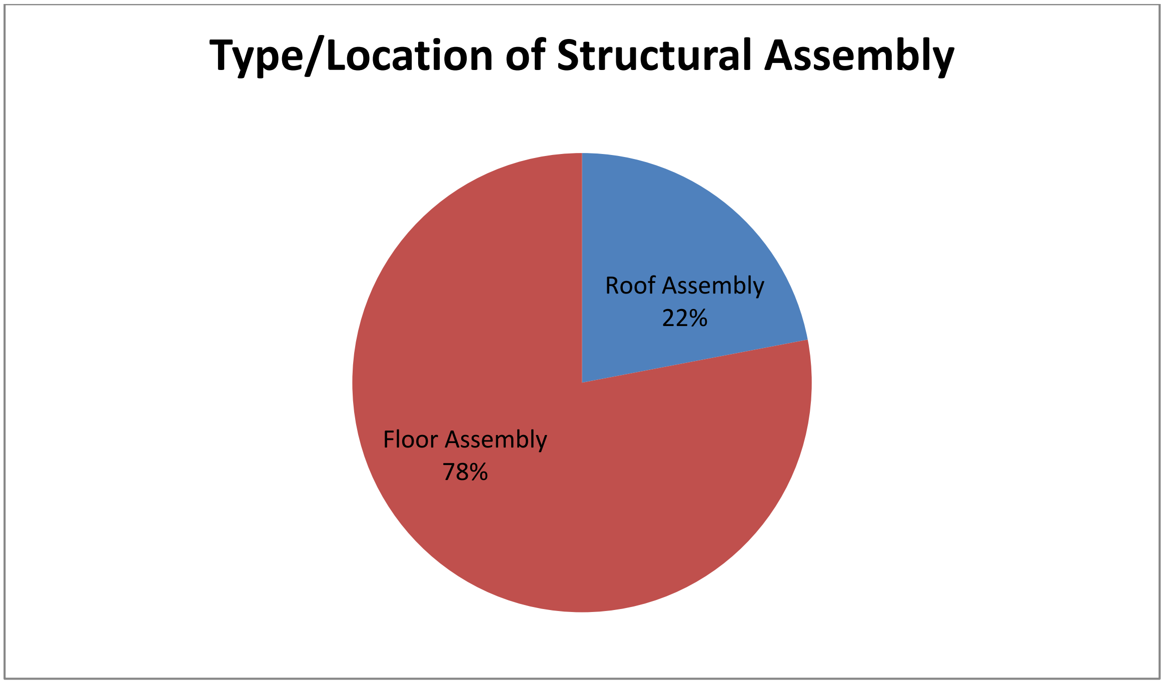

Figure 5. Structural Assembly Analysis of NIOSH Firefighter Fatality Investigations

Fires within these distinct areas then burn and weaken the structural elements surrounding the involved fire area. Figure 6 defines the percentage of fire events with respect to framing systems that collapsed during fire ground operations.

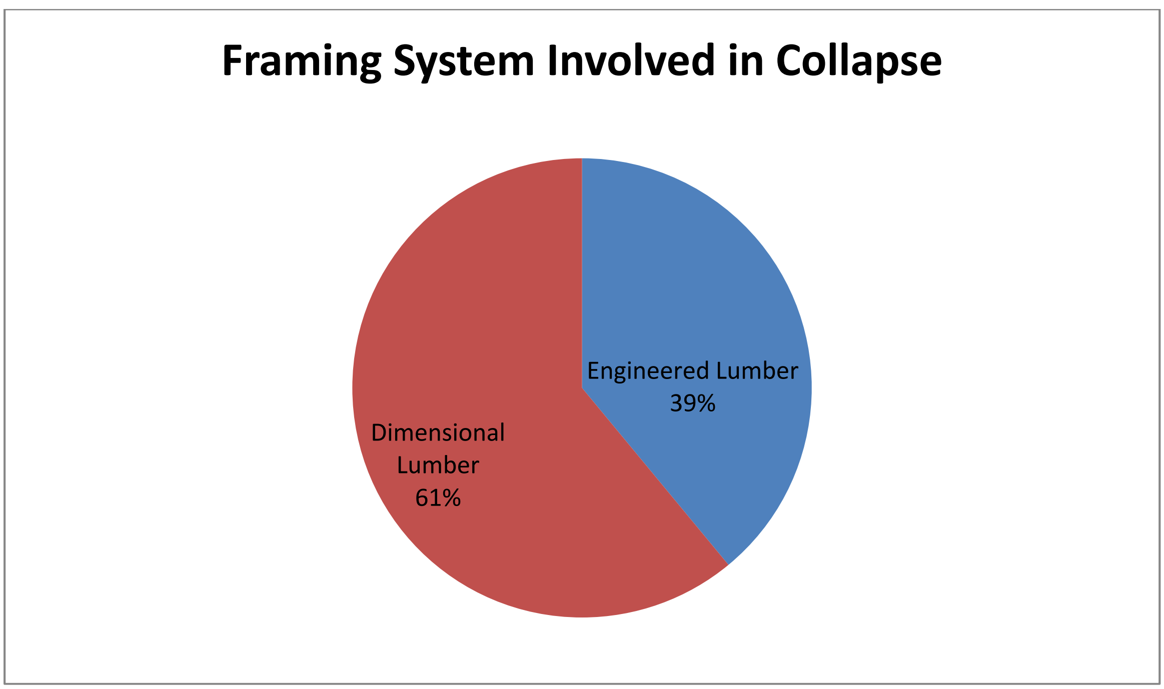

Figure 6. Framing System Analysis of NIOSH Firefighter Fatality Investigations

4.1.2. Residential Collapse Trends of IAFC Firefighter Near Miss Reporting System

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)

4.1.3. Residential Collapse Trends Discussion

There is a distinct trend of structural collapse incidents that have resulted in both firefighter injuries and deaths, specific to residential construction. These incidents highlight that at these events firefighters and incident commanders were not able to recognize imminent collapse due to fire performance issues of both unprotected dimensional and unprotected engineered lumber within floor and roof assemblies. As the accuracy of the documentation of the post fire investigations increases, additional photographic forensic evidence has become available to document incident specific failures. The fire community will continue to use this information to improve construction methods and practices, and for occupant and firefighter educational tools.

4.2. Fire Endurance Performance of Unprotected Assemblies – Non-Standardized Demonstrative Testing

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. The following is a review of selected examples of documented demonstrative testing.

4.2.1. Demonstrative Testing Conducted by the Los Angeles City Fire Department, 1982.

Conducting Agency: One of the first documented demonstrative fire service tests was conducted by John Mittendorf of the Los Angeles City Fire Department in 1981 (Mittendorf, 1982). Mittendorf cites a need for the tests due to a lack of available information on the performance of lightweight constructed systems.

Test Series: This test series evaluated and recorded the behavioral characteristics of roof systems under fire conditions. This project tested: metal plate connected (MPC) trusses, engineered wooden I-beams (also known as wooden I-joists), open pin-end connected steel web (PECSW) truss construction, and panelized construction were subjected to fire conditions. The test specimens were constructed to represent actual field conditions. Trusses used the correct on center spacing; 1/2 in., 3/8 in. or 3/4 in. CDX plywood decking; and were hung or supported as they would be in normal installations. The span of the construction was limited to the size of the donated products. The source fire for each test was fueled from four gallons of paint thinner and sawn pallets. The fire exposure for each test was believed to be approximately equal. No live load was imposed on any of the tested assemblies. The test time began at ignition of the thinner and pallets. A time limit of 6 min. per test was used.

Test Results: The collapse times ranged from 1 minute and 20 seconds for a metal plate connected truss spaced 16" O.C. with a 3/4" CDX plywood sheathing spanning 30 feet to 5 minutes for an open web truss spaced 24" O.C. with 1/2" CDX plywood spanning 20 feet.

Table 2. Non-Standardized Test Results (Mittendorf, 1982).

Structural Member	Span (ft.)	Spacing (in. o.c.)	Sheathing Material	Loading (psf)	Failure Time (min:sec)
Wood I-beams	12	32	1/2" CDX ply.	Dead Ld. - Self Weight	1:20
PECSW construction	20	24	1/2" CDX ply.	Dead Ld. - Self Weight	3:20
MPC Truss floor system*	30	16	3/4" CDX ply.	Dead Ld. - Self Weight	5:00
MPC Truss roof system*	Unknown	32	1/2" & 5/8" CDX ply.	Dead Ld. - Self Weight	6:00
8 x 8' panel. sys., 2x4 joists	8	24	1/2" CDX ply. &1 x 6" sheath.	Dead Ld. - Self Weight	No failure

* Penetration depth of gusset plate connector = 3/8 in.

Review and Comment: This test series demonstrates a significant reduction in work time for firefighters operating on a building constructed with a lightweight roof systems exposed to fire conditions. However this series makes a comparative performance analysis difficult due to parameter variability. Although the products were tested with respect to their allowable spans, the depths of the tested members were not documented. These tests did not apply a structural live load to the assemblies, therefore the internal member stresses for the tested components is also unknown. The characterization of the fuel load for the fire was not analyzed and the environmental, ventilation, and conditions from test to test added a degree of variability.

4.2.2. Demonstrative Testing Conducted by the Illinois Fire Service Institute, 1986.

Conducting Agency: The Illinois Fire Service Institute (IFSI) in 1986 conducted a similar demonstrative study of lightweight constructed floor systems citing similar fire performance concerns (Straseske, 1988). The ISFI test series sets out to, "help determine the time available for firefighters to suppress a fire within a structure utilizing types of lightweight construction." The IFSI report states, "There is a lot of speculation on what specific floor systems might due under fire conditions, but very little gathered data."

Test Series: The following floor systems were tested: conventional 2 x 10 joists on 16 in. centers, wood I-beams on 24 in. centers, open-web trusses with wood members and gusset plates on 24 in. centers, open-web trusses with a stamped out steel webs on 24 in. centers, and open-webbed trusses with a wooden top and bottom chord and pipe web members on 24 in. centers. All floor systems were constructed with a 3/4" oriented strand board (OSB) subfloor and loaded similarly with an applied load of 31 pounds per square foot. In order to provide some uniformity all decks were 8'x16' and were supported on 24" high concrete masonry unit wall. The perimeter was enclosed with 3/4" plywood on three sides. The fuel load was 4 gallons of diesel fuel and 1 gallon of gas in a cut off 55 gallon barrel approximately 12" high.

Test Results: The 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.

Table 3. Non-Standardized Test Results (Straseske, 1988).

Structural Member	Spacing	Assemb. Rating (min:sec)	Structural Failure (min:sec)	Loading (psf)
2 x 10	16 in. o.c.	9:00[1]	> 13:00	31.0
I-joist	24 in. o.c.	4:40[1]	4:40	31.0
MPCT[2]	24 in. o.c.	9:00[1]	15:45	31.0
MPSWT[2]	24 in. o.c.	7:30[1]	N/A	31.0
TJL	24 in. o.c.	6:50[1]	9:45	31.0

[1] Assembly rating is due to deck burn through.

[2] MPCT = Metal Plate Connected Truss; MPSWT = Metal Plate Steel Web Truss; TJL = Trus Joist L-Series Truss; TPSB = Truss Plate Spliced Beam; F_b = fiber bending stress.

Review and Comment: This test series demonstrates a limited work time for firefighters operating in a building constructed with an unprotected wood floor system exposed to fire conditions. However this series makes a comparative performance analysis difficult due to parameter variability. The products were tested without respect to their spacing, allowable spans and the applied load created variability for the internal member stresses. The characterization of the fuel load for the fire was not analyzed and the ventilation conditions, although partially controlled, added a degree of variability. A review of the video for this test series was conducted and these video images suggest a degree of variability in the fire development which may have additionally influenced the time to failure for the tested assemblies. A summary of these tests results is shown in Table 3.

4.2.3. Demonstrative Testing Conducted by the Dutchess Community College Fire Science Program, 2009.

Conducting Agency: In 2009 the Fire Science Program at Dutchess Community College conducted a demonstrative burn test of engineered wooden I-Joists, the result of these were posted in a online power point presentation (Dutchess Community College, 2009).

Test Series: The test assembly was comprised of a series of four engineered I-Joists spanning 16 ft. with a ½" plywood subfloor. The floor was weighed by one 300 lb. plastic barrel filled with water. The floor was supported by 6 ft. high 2x4 finished walls, a rear wall was also constructed for fire containment. The assembly burn compartment reached a flashover condition at approximately 2 minutes with a structural collapse following at 4 minutes. Additionally the Dutchess program also conducted two roof construction comparison burns in 2010. The results of these tests were posted in a 4 minute video segment. The test assembly compared the performance of a stick built pitched roof assembly with nailed 2x6 members and a 1/2 in. plywood roof sheathing to a 2x4 pitched chord metal plate connected wood trusses with a 1/2 in. plywood roof sheathing. Both roofs were loaded by equally distributing a 300 lbs. load across the roof surface. The fuel load was comprised of wood pallets and hay. The trusses were supported at the perimeter by 55 gallon barrels and were in an open air configuration.

Test Results: The 2x4 pitched chord truss assembly reached a fully developed fire condition at approximately 90 seconds and the assembly collapsed at 5 minutes. The stick built pitched roof assembly reached a fully developed fire condition at approximately 90 seconds, the fire video then shows that the fire has reduced in size and separated into two distinct locations, one on the roof structure and one concentrated on the fireload, at the 10 minute mark. Prior to 10 minute mark there appears to have been burn through of the roof sheathing as the applied roof loads no longer are visible atop the roof sheathing. The fire continues to burn in limited fashion until the collapse of the assembly at 21 minutes.

Table 4. Non-Standardized Test Results (Dutchess Community College, 2009).

Structural Member	Span (ft.)	Sheathing Material	Failure Time (min:sec)	Loading
Engineered Wood I-beams	16	1/2" CDX ply.	4:00	300 lb. conc. load
MPC Truss roof system*	16	5/8" CDX ply.	5:00	300 lb. distributed
2x6 pitched roof assembly	16	5/8" CDX ply.	21:00	300 lb. distributed

* Penetration depth of gusset plate teeth = 3/8 in.

Review and Comment: This test series demonstrates a reduction in work time for firefighters operating in a building constructed with a lightweight constructed floor and roof systems exposed to fire conditions. However this series makes a comparative performance analysis difficult due to parameter variability. The products were tested without respect to their allowable spans. In the case of the floor test the internal member stresses varied due to the use of a singular concentrated load. While the roof loading was distributed, the geometry and member framing sizes varied from 2x4 to 2x6 members creating variability for the internal member stresses. The characterization of the fuel load for the fire was not analyzed and the uncontrolled ventilation conditions added a degree of variability. A review of the video for this test series was conducted and these images suggest that the fire burned in the decay stage for some time during the 2x6 pitched roof assembly test. This size of this decayed fire potentially extended the time to failure for the 2x6 pitched roof assembly test. A summary of these tests results is shown in Table 4.

4.3. Fire Endurance Performance of Unprotected Assemblies – Non- Standardized ASTM E-119 Furnace Testing

There are only 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. Numerous agencies have conducted Non-Standardized tests with modified loading conditions, i.e. loading less than 100 % of the design load.

4.3.1. National Engineered Lightweight Construction Fire Research Project Report: Literature Search and Technical Analysis – National Fire Protection Research Foundation, 1992.

Conducting Agency: In October of 1992 the National Fire Protection Research Foundation published, "National Engineered Lightweight Construction Fire Research Project Report: Literature Search and Technical Analysis" (Grundahl, 1992). The overall objective of the Fire Protection Research Foundation (FPRF) National Engineered Lightweight Construction Fire Research Project was to define the actual fire performance characteristics of engineered components.

Report Series: 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. The following is a list of the testing citing for Non-Standardized ASTM E-119 furnace testing conducted with modified loading conditions respective of the structural elements being examined for this research project.

Report Results: The results are summarized in Table 5.

Table 5. 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 8; ½ in. ply. w/blk	16 in. o.c.	11:38	21.0[1] (40%)
FPL	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.

Review and Comment: The FPRF report and the source literature were reviewed for testing conducted prior to 1992. Non-standardized ASTM E-119 furnace testing provides a comparative analysis to standardized ASTM E-119 furnace testing with one exception, a reduced applied loading. This modified loading conduction results in a reduction in the member design stress. The majority of the tests conducted were of unprotected dimensional lumber floor assemblies. A summary of these tests results is shown in Table 4.

4.3.2. Underwriters Laboratories Inc. "Structural Stability of Engineered Lumber in Fire Conditions", Project Number 07CA42520, File Number NC9140, September 2008

Conducting Agency: The project, conducted by Underwriters Laboratories Inc. in September of 2008, provides fire resistive performance of nine assemblies tested 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.

Test Series: Nine fire tests were conducted. Seven of the samples represented floor–ceiling constructions and two samples represented roof-ceiling constructions. A goal of the project was to develop comparable fire performance data among assemblies. All assemblies were intended to represent typical residential construction. Some assemblies included construction features such as 2 by 10 floor joists and 2 by 6 roof rafters that the fire service expressed satisfactory knowledge of their structural performance based upon their experience. Other assemblies included lighter weight wood structural members such as "I" joists and trusses. Two of the assemblies did not include a ceiling (unprotected wood), six of the assemblies included a ceiling, protecting the wood flooring assembly, consisting of 1/2-inch thick regular gypsum board and one assembly included a 3/4-inch thick plaster ceiling.

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. For the two samples that represented roof-ceiling assemblies, the two mannequins were the only live load applied on the test sample.

The construction details of the nine samples are summarized in Table 6.

Table 6. Summary of Test Samples (Underwriters Laboratories, Inc., 2008)

Test Assembly No.	Supports	Ceiling	Floor or Roof
1	2 by 10s @ 16 inch centers	None	1 by 6 subfloor & 1 by 4 finish floor
2	12 inch deep "I" joist @ 24 inch centers	None	23/32 inch OSB subfloor, carpet padding & carpet
3	2 by 10s @ 16 inch centers	1/2 inch regular gypsum wallboard	1 by 6 subfloor & 1 by 4 finish floor
4	12 inch deep "I" joist @ 24 inch centers	1/2 inch regular gypsum wallboard	23/32 inch OSB subfloor, carpet padding & carpet
5	Parallel chord truss with steel gusset plate connections, 14 inch deep @ 24 inch centers	1/2 inch regular gypsum wallboard	23/32 inch OSB subfloor, carpet padding & carpet
6	Parallel chord truss with glued connections, 14	1/2 inch regular gypsum wallboard	23/32 inch OSB subfloor, carpet padding & carpet

Test Assembly No.	Supports	Ceiling	Floor or Roof
	inch deep @ 24 inch centers		
7	2 by 6s @ 16 inch centers with 2/12 pitch	1/2 inch regular gypsum wallboard	1 by 6 roof deck covered with asphalt shingles
8	2 by 10s @ 16 inch centers	3/4 inch plaster	1 by 6 subfloor & 1 by 4 finish floor
9	Roof truss with steel gusset plate connections @ 24 inch centers with 2/12 pitch	1/2 inch regular gypsum wallboard	7/16 inch OSB covered with asphalt shingles

Test Results: The results of the ASTM E119 fire tests are expressed in terms of hours such as 1/2 hour, 1 hour or 2 hour rated assemblies. These time ratings are not intended to convey the actual time a specific structure will withstand a fire. All fires are different. Variations result from room size, combustible content and ventilation conditions. The ASTM E119 test method does provide a benchmark that enables a comparison of fire performance between test samples.

For unrestrained floor-ceiling assemblies and unrestrained roof-ceiling assemblies such as the tested samples, ASTM E119 includes the following Conditions of Acceptance:

1. The sample shall support the applied load without developing conditions that would result in flaming of cotton waste place on the floor or roof surface.

2. Any temperature measured on the surface of the floor or roof shall not increase more than 325 ºF. The average temperature measured on the surface of the floor or roof shall not increase more than 250 ºF.

The results of the nine fire tests in terms of the ASTM E119 Conditions of Acceptance are summarized in Table 7.

Table 7. Summary of Test Results ASTM E119 (Underwriters Laboratories, Inc., 2008)

Test Assembly No.	Time of 250ºF avg. temperature rise on surface of floor / roof (min:sec)	Time of 325ºF max. temperature rise on surface of floor / roof (min:sec)	Flame passage through floor / roof (min:sec)	Collapse (min:sec)	Fire resistance rating (min)
1	*	*	18:30	18:45	19
2	*	*	06:00	06:03	6
3	*	*	44:15	44:45	44
4	*	*	*	26:45	27
5	*	29:15	28:40	29:15	29

6	*	24:15	26:00	26:45	24
7	39:45	38:30	26:00	40:00	26
8	*	*	*	79:45	51**
9	*	*	*	23:15	23

* - This condition was not achieved during the fire test.
** - Plaster ceiling in contact with furnace thermocouples at 51 minutes. The test method requires that the junction of the thermocouples in the furnace be placed 12 inches away from the ceiling surface at the beginning of the test and shall not touch the sample as a result of deflection.

In addition to the fire resistance rating determined by the Conditions of Acceptance in ASTM E119, a finish rating is typically published for fire resistive assemblies with combustible supports such as the tested as samples. The finished rating is defined as the time when the first occurrence of either: (1) a temperature measured on the face of the combustible supports nearest to the fire increases more than 325 ºF or (2) the average temperature measured on the face of the combustible supports nearest the fire increases more than 250 ºF.

Several fire test standards similar to ASTM E119 such as ISO 834:1 Fire-resistance tests – Elements of building construction – Part 1: General requirements define load bearing capacity as the elapsed time that a test sample is able to maintain its ability to support the applied load during the fire test. The ability to support the applied load is detailed in the report (Table 8).

Table 8. Summary of Significant Events in Addition to ASTM E119 Conditions of Acceptance (Underwriters Laboratories, Inc., 2008)

Test Assembly No.	Initial falling of ceiling material (More than 1 ft^2) (min:sec)	Average temperature on unexposed surface of ceiling at initial falling (ºF)	Finish rating (min:sec)	Loadbearing capacity (min)
1	No ceiling	No ceiling	00:45	18
2	No ceiling	No ceiling	00:30	4
3	23:30	605	15:30	45
4	17:15	531	7:45	25
5	16:30	519	10:45	24
6	16:00	559	12:15	25
7	15:45	253	15:15	40
8	74:00**	1109	74:00**	80
9	13:45	730	14:45	24

Notes:** - plaster ceiling in contact with furnace thermocouples at 51 minutes

Review and Comment:

- The overall objective of the Structural Stability of Engineered Lumber in Fire Conditions project was to develop comparable fire performance data for unfinished and finished assemblies constructed with dimensional and engineered lumber components.

- Nine fire tests were conducted. Seven of the samples represented floor–ceiling constructions and two samples represented roof-ceiling constructions. All assemblies were intended to represent typical residential construction. Some assemblies included construction features such as 2 by 10 floor joists and 2 by 6 roof. Other assemblies included lighter weight wood structural members such as "I" joists and trusses. Two of the assemblies did not include a ceiling, six of the assemblies included a ceiling consisting of 1/2-inch thick regular gypsum board and one assembly included a 3/4-inch thick plaster ceiling.
- The fire containment performance of a combustible floor-ceiling assembly representing typical legacy construction without a ceiling was 18 minutes. The time duration was based upon the performance of the assembly when exposed to the time-temperature curve defined in Standard ASTM E119. This performance was defined as the bench mark performance for comparison purposes.
- The fire containment performance of a combustible floor-ceiling assembly supported by engineered I joists was 14 minutes less than the bench mark performance.
- The fire containment performance of the combustible floor-ceiling assembly supported by engineered I joists with a ½ inch thick regular gypsum board ceiling exceeded the bench mark performance by 7 minutes.
- The fire containment performance of a combustible floor-ceiling assembly supported by either: (1) engineered I joists, (2) parallel chord trusses with steel gusset plate connections or (3) parallel chord trusses with glued connections were approximately equal when a ceiling consisting of ½ inch thick regular gypsum wallboard was provided.
- Unprotected wood assemblies, both dimensional and engineered components, upon combustion contributed significant fuel loads to the experimental fires raising corresponding temperatures above the standardized ASTM E119 time temperature curve.

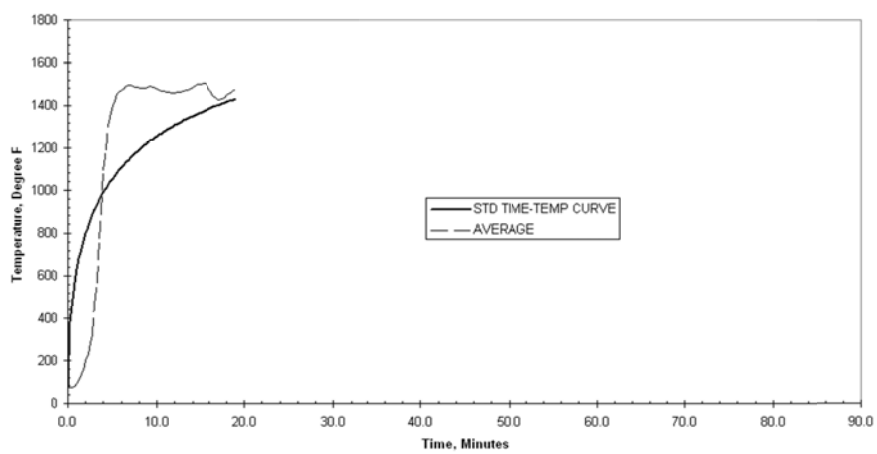

Figure 7 - UL263 Standard Time Temperature Curve and Average Furnace Temperature vs. Time for Assembly No. 1

- Unprotected Lightweight assemblies with minimal mass to stiffness ratios exhibited dynamic vibrations prior to structural collapse indicting that the assemblies were significantly weakened far before the end of the collapse time, or end of test.
- Unprotected Lightweight assemblies exhibit a reduced load bearing capacity when significantly weakened by fire as evident in a comparative analysis comparing test standards

similar to ASTM E119 with standards such as the ISO 834:1 Fire-resistance tests – Elements of building construction.

4.3.3. Underwriters Laboratories Inc. "Structural Stability of Engineered Lumber in Fire Conditions", Project Number 08CA33476, File Number NC10412, Submitted to Chicago Fire Department - September 2009

Conducting Agency: The project, conducted by Underwriters Laboratories Inc. in September of 2009, provides fire resistive performance of three alternate assemblies tested in addition to the 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. A total of three fire tests were conducted on test assemblies representing floor–ceiling constructions so as to develop comparable fire performance data among assemblies. All the test assemblies were intended to represent typical residential construction.

Test Series: The first assembly was constructed with parallel chord trusses with metal gusset connections as the structural components with a regular 1/2" gypsum board ceiling and included the following unique features: Recessed lighting fixture penetrations in the ceiling, HVAC supply and return penetrations in the ceiling, HVAC duct work in the interstitial space above the ceiling, Metal gusset connection on the bottom cord and AFG grant sponsored test # 5 was similarly constructed without the unique features noted above.

The second assembly was constructed with parallel chord truss with glued connections as the structural components. This assembly was similar to the AFG grant sponsored test # 6 with the exception that this test did not include a ceiling.

The third assembly was constructed with parallel chord truss with metal gusset connections as the structural components and included simulated stairwell framing.

The construction details of the three test assemblies are summarized in Table 9and detailed in Test Records 1 through 3.

Table 9. Summary of Test Samples (Underwriters Laboratories, Inc., 2009)

Test Assembly No.	Supports	Ceiling	Floor or Roof
1	Parallel chord truss with steel gusset plate connections, 14 inch deep @ 24 inch centers with bottom chord splices, can lights and duct work	1/2 inch regular gypsum wallboard	23/32 inch OSB subfloor, carpet padding & carpet
2	Parallel chord truss with glued connections, 14 inch deep @ 24 inch centers	None	23/32 inch OSB subfloor, carpet padding & carpet

Test Assembly No.	Supports	Ceiling	Floor or Roof
3	Parallel chord truss with steel gusset plate connections, 14 inch deep @ 24 inch centers with simulated staircase and bottom chord splices	None	23/32 inch OSB subfloor, carpet padding & carpet

The three 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 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 described in this report, the load placed on the samples was intended to represent typical conditions during a 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.

Standard ASTM E119, Fire Tests of Building and Construction Materials, describes a fire test method that establishes benchmark fire resistance performance between different types of building assemblies. For floor-ceiling assemblies, the standard requires a minimum 180 square foot sample prohibit the passage of flame through the sample and limit the temperature rise at specific locations as the sample while the sample supports a load and is exposed to a standardized fire. The standardized fire represents a fully developed fire within a residential or commercial structure with temperatures reaching 1000 ºF at 5 minutes and 1700 ºF at 60 minutes.

Test Results: The results of the ASTM E119 fire tests are expressed in terms of hours such as 1/2 hour, 1 hour or 2 hour rated assemblies. These time ratings are not intended to convey the actual time a specific structure will withstand an actual fire event due to differences in building configuration and construction, fuel load, and ventilation. However, the results from ASTM E119 test method enable a useful benchmark to compare the fire resistance performance of test assemblies.

For unrestrained floor-ceiling assemblies such as the tested assemblies, ASTM E119 includes the following Conditions of Acceptance:

1. The sample shall support the applied load without developing conditions that would result in flaming of cotton waste place on the floor surface.
2. Any temperature measured on the surface of the floor shall not increase more than 325 ºF and the average temperature measured on the surface of the floor shall not increase more than 250 °F.

The results of the three fire tests in terms of the ASTM E119 Conditions of Acceptance are summarized in Table 10.

Table 10. Summary of Test Results ASTM E119 (Underwriters Laboratories, Inc., 2009)

Test Assembly No.	Time of 250ºF avg. temperature rise on surface of floor (min:sec)	Time of 325ºF max. temperature rise on surface of floor (min:sec)	Flame passage through floor (min:sec)	Collapse (min:sec)	Fire resistance rating (min)
1	*	*	26:00	30:08	26
2	12:30	11:15	11:45	13:06	11
3	10:45	5:00	11:30	13:20	5

Notes:
* - This condition was not achieved during the fire test.

Other significant data obtained during the fire tests included observation of the conditions of the ceiling and floor surfaces, temperatures in the concealed space above the ceiling membrane and deflections of the floor and roof surfaces.

The finish rating and the load bearing capacity of Benchmark assemblies from the UL project and the three tested assemblies are summarized in Table 11.

Table 11. Summary of Significant Events in Addition to ASTM E119 Conditions of Acceptance (Underwriters Laboratories, Inc., 2009)

Test Assembly No.	Initial falling of ceiling material (More than 1 ft^2) (min:sec)	Average temperature on unexposed surface of ceiling at initial falling (ºF)	Finish rating (min:sec)	Load bearing Capacity (min)
Benchmark1 [1]	No ceiling	No Ceiling	00:45	18
Benchmark2 [2]	16:00	559	12:15	25
Benchmark3 [3]	16:30	519	10:45	24
Benchmark4 [4]	23:30	605	15:30	45
Benchmark5 [5]	74:00**	1109	74:00**	80
1	17:15	646	13:00	24
2	No ceiling	No ceiling	00:15	10
3	No ceiling	No ceiling	00:30	5

** - plaster ceiling in contact with furnace thermocouples at 51 minutes

Notes:

1 – Benchmark 1 data represents a combustible floor-ceiling assembly of typical unprotected legacy construction (2 x 10) without a ceiling

2 – Benchmark 2 data represents a combustible floor-ceiling assembly of typical modern construction of parallel chord truss with glued connections with a ½ thick regular gypsum board ceiling

3 – Benchmark 3 data represents a combustible floor-ceiling assembly of typical modern construction of parallel chord truss with steel gusset connections with a ½ thick regular gypsum board ceiling
4 – Benchmark 4 data represents a combustible floor-ceiling assembly of typical protected legacy construction (2 x 10) with a ½ inch regular gypsum board ceiling
5 – Benchmark 5 data represents a combustible floor-ceiling assembly of typical protected legacy construction (2 x 10) with a ¾ inch metal lath and plaster ceiling

Review and Comment: From the previous 2008 UL project, it was determined that the load bearing capacity of an unprotected combustible floor-ceiling assembly representing typical unprotected legacy construction (2 x 10) without a ceiling was 18 minutes. The time duration was based upon the performance of the assembly when exposed to the time-temperature curve defined in Standard ASTM E119. This was defined as the benchmark (Benchmark 1) fire resistance performance of traditional exposed lumber construction typically found in lowest floor above basement or crawl spaces.

- The fire containment performance of Test Assembly 1 representing modern steel gusset truss construction with a ceiling with penetrations was 6 minutes more than the benchmark performance
- The fire containment performance of Assembly 2 representing unprotected modern glued truss construction was 8 minutes less than the benchmark performance.
- The fire containment performance of Assembly 3 representing unprotected modern steel gusset construction with stairwell framing was 13 minutes less than the benchmark performance.
- Similar to previous results, unprotected wood assemblies exhibited a reduced load bearing capacity when significantly weakened by fire. The unprotected engineered wood assemblies upon combustion contributed significant fuel loads to the experimental fires raising corresponding temperatures above the standardized ASTM E119 time temperature curve.
- Unprotected engineered assemblies exhibit a reduced load bearing capacity when significantly weakened by fire as evident in a comparative analysis comparing test standards similar to ASTM E119 with standards such as the ISO 834:1 Fire-resistance tests – Elements of building construction.

4.4. Fire Endurance Performance of Unprotected Assemblies – Standardized ASTM E-119 Furnace Testing

4.4.1. National Engineered Lightweight Construction Fire Research Project Report: Literature Search and Technical Analysis –Fire Protection Research Foundation, 1992.

Conducting Agency: In October of 1992 the National Fire Protection Research Foundation published, "National Engineered Lightweight Construction Fire Research Project Report: Literature Search and Technical Analysis" (Grundahl, 1992). The overall objective of the Fire Protection Research Foundation (FPRF) National Engineered Lightweight Construction Fire Research Project was to define the actual fire performance characteristics of engineered components.

Report Series: 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. The following is a list of the testing citing for Standardized ASTM E-119 furnace testing conducted with modified loading conditions respective of the structural elements being examined for this research project.

Table 12. . 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%)

Review and Comment: The FPRF report and the source literature were reviewed for testing conducted prior to 1992. The majority of the tests conducted were of unprotected dimensional lumber floor assemblies. A summary of these tests results is shown in Table 12.

4.5. Fire Endurance Performance of Unrated Full Scale Assembly Testing

4.5.1. Fire Performance of Selected Residential Floor Construction Under Room Burnout Conditions - National Bureau of Standards, 1980.

Conducting Agency: 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 J. , 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.

Test Series: 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. These tests examined the performance of: conventional 2 x 8 spaced at 16 in. and 24 in. centers, 7-1/4 in. deep C-shaped galvanized steel joists spaced at 24 in. and 32 in. centers, and one 12 in. deep metal plate connected truss spaced at 24 in. on center. The floor framing was covered with one layer of 23/32-in plywood subfloor with a finished carpet. The fuel load for each experiment was common to a typical recreation room of the period and included a sofa, an upholstered chair, an ottoman, an end table, a bookcase and a coffee table.

Table 13. 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.

Review and Comment: The fire resistance periods based on flame-through of the floor assembly and structural failure of floor joists varied from 10 – 12 minutes for floors with unprotected wood joists and was 4 minutes or less for floors with unprotected steel joists/ The addition of a 1/2 in. thick gypsum board ceiling as a protective layer increased the fire resistance time of the steel joist floor assembly approximately 12 minutes. A summary of these tests results is shown in Table 13.

4.5.2. Structural Collapse Fire Tests: Single Story, Wood Frame Structures - National Institute of Standards and Technology (NIST), 2004.

Conducting Agency: In March of 2004 NIST conducted NISTIR 7094, "Structural Collapse Fire Tests: Single Story, Wood Frame Structures" (Stroup, 2004). A series of fire tests was conducted in Phoenix, Arizona to collect data for a project examining the feasibility of predicting structural collapse. The fire test scenario was selected as part of a training video being prepared by the Phoenix, Arizona Fire Department.

Test Series: Multiple fires were started in each structure to facilitate collapse; the fires were not intended to test the fire endurance of the structures. Four structures with different roof constructions were used for the fire tests. The roof structure was built with manufactured trusses on 2 ft. centers. These structures were identical except for the roof construction. One structure had a roof consisting of asphalt shingles on ½ in five-ply plywood while a second structure had asphalt shingles on ½ in oriented strand board (OSB). Both structures had a layer of 15 lb. felt paper between the asphalt shingles and the plywood or OSB. The other two structures used tile over either plywood or OSB as the roof construction. The cementatious tile roofs had two layers of 30 lb. felt over the plywood or OSB and nominally 1 in by 2 in boards to hold the tile in place.

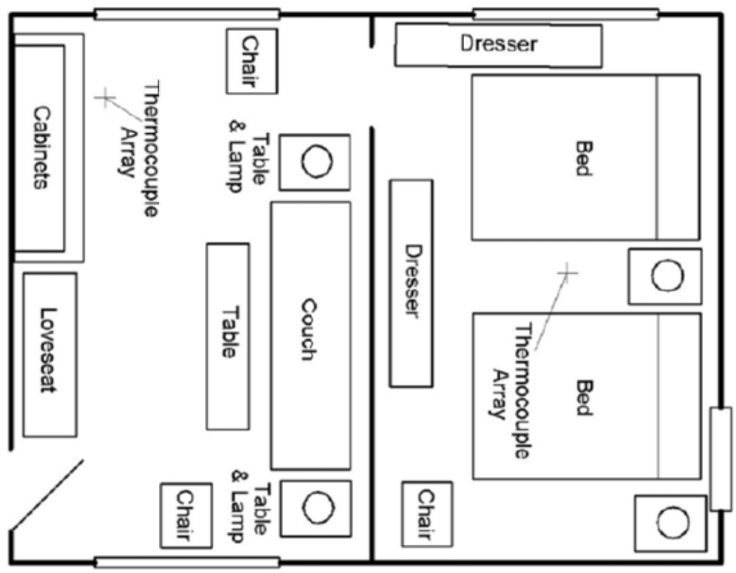

Figure 8. Plan view of generic test structure showing approximate placement of furniture and other items with the structure (not to scale).

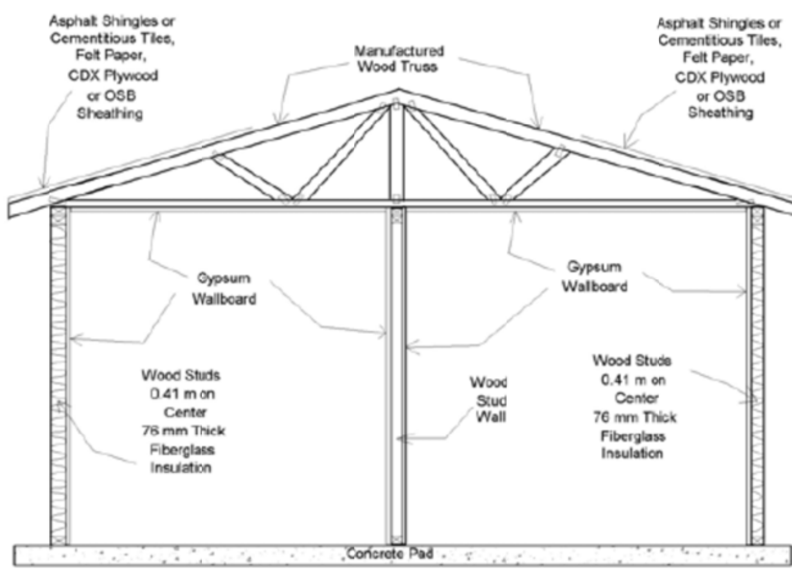

Figure 9. Diagram showing typical construction of the structure.

Temperatures were measured as a function of time in four locations within each structure. Furniture items were placed in the front and back of each structure to simulate living room and bedroom areas. The living room contained a couch, a love seat, and two chairs consisting of wood frames with polyurethane foam cushioning material. Two wood end tables, a wood coffee table, and two table lamps were also placed in the living room. The bedroom contained two sets of foam mattresses and box springs on metal frames. Wood bed tables were placed adjacent to each bed. Two wood dressers were located in the room. One dresser was located along the wall opposite the ends of the two beds while the second dresser was adjacent to the side of the second bed. Finally, a chair with polyurethane padding on a wood frame was positioned in the bedroom diagonally opposite the end corner of the first bed. Table lamps were placed on top of the two bed tables. Both rooms in each structure had nylon wall-to-wall carpet laid on the floor over 3 lb. pad.

The living room and bedroom areas of each structure were ignited simultaneously using electric matches. Peak temperatures obtained during the tests ranged from approximately 1500 °F to 1800 °F. The roof of each structure collapsed approximately 17 minutes after ignition. This limited set of burn tests indicated that infrared cameras may not be a viable tool for predicting structural collapse in residential structures. The thermal signature of the fire coming through the roof is washed out by radiation from smoke or fire plumes or was obscured by water spray or rain. Since one typically expects hot smoke or fire plumes as well as water sprays to be present at residential fire scenes, thermal images do not appear to be an adequate indicator of pending structural collapse. A summary of these tests results is shown in Table 14.

Table 14. Non-Standardized Test Results (Stroup, 2004).

Structural Member	Spacing (in.)	Sheathing Material	Failure Time (min:sec)	Loading
2x6 pitched roof MPC Truss roof system	24	1/2" CDX ply. w/ 15 lb. felt and asphalt shingles	17:30*	(3) 300 lb. concentrated loads
2x6 pitched roof MPC Truss roof system	24	1/2" OSB ply. w/ 15 lb. felt and asphalt shingles	17:00*	(3) 300 lb. concentrated loads
2x6 pitched roof MPC Truss roof system	24	1/2" CDX ply. w/ (2) layers of 30 lb. felt and cement tiles	16:00*	(3) 300 lb. concentrated loads
2x6 pitched roof MPC Truss roof system	24	1/2" OSB ply. w/ (2) layers of 30 lb. felt and cement tiles	17:10*	(3) 300 lb. concentrated loads

* Partial collapse occurred local to the firefighter mannequins.

Review and Comment: This test series makes a comparative roof performance analysis with a ventilated "realistic equivalent fire load". Fuel packages for this project were characterized using cone calorimeter experiments. The roof trusses were equivalent but not tested with respect to their maximum allowable spans. The study subjected the roof systems to three concentrated live loads consisting of two 300 pound mannequins and a 300 roof top mechanical unit. The documented collapse times were recorded when the mannequins fell through the roof assemblies. Structural collapse was determined based on mannequins fall through but deflections were not monitored for the roof structure, it is therefore difficult to ascertain if the documented collapse times were due to sheathing failures or by the collapse of the structural elements. This limited set of burn tests indicated that infrared cameras may not be a viable tool for predicting structural collapse in residential structures. This project did not provide a forensic analysis of the failures mechanisms of the structural elements.

4.5.3. The Performance of Composite Wood Joists Under Realistic Fire Conditions – Tyco International, 2008.

Conducting Agency: In July of 2008 the Fire Suppression and Building Products Division of Tyco International conducted a series of five comparative demonstrative tests at Underwriters Laboratories (UL) in Northbrook Illinois. 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.

Test Series: The furniture was comprised of synthetic material (i.e. furniture, carpet, etc.). The floor was covered in a Berber type carpet. The fuel package consisted of a couch and loveseat, a coffee table with plastic children's toys, two end tables with lamps, a picture on the wall and an empty entertainment center arrangement. 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 ignition scenario included a small wastebasket filled with a ½ lb. of shredded 20 lb. copy paper and a polyester blanket draped over the arm of the couch. 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/ft_2. 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.

A summary of these tests results is shown in Table 15.

Table 15. Non-Standardized Test Results.

Structural Member	Spacing (in.)	Sheathing and Finish Material	Failure Time (min:sec)	Loading	Sprinkler
11-7/8" Engineered Wood I-beams.	24	7/8" CDX ply. w/ carpet pad and Berber Carpeting	N/A - Fire Controlled at 2:55	(2) 300 lb. conc. loads with uniformly dist. of 5 lbs./ft.	Yes – Residential Horizontal Sidewall
11-7/8" Engineered Wood I-beams.	24	7/8" CDX ply. w/ carpet pad and Berber Carpeting	N/A - Fire Controlled at 3:00	(2) 300 lb. conc. loads with uniformly dist. of 5 lbs./ft.	Yes – Residential Pendant (13 gpm)
11-7/8" Engineered Wood I-beams	24	7/8" CDX ply. w/ carpet pad and Berber Carpeting	N/A - Fire Controlled at 4:15	(2) 300 lb. conc. loads with uniformly dist. of 5 lbs./ft.	Yes – Residential Pendant (22 gpm)
11-7/8" Engineered Wood I-beams	24	7/8" CDX ply. w/ carpet pad and Berber Carpeting	11:10	(2) 300 lb. conc. loads with uniformly dist. of 5 lbs./ft.	None
11-7/8" Engineered Wood I-beams	24	7/8" CDX ply. w/ carpet pad and Berber Carpeting	8:34	(2) 300 lb. conc. loads with uniformly dist. of 5 lbs./ft.	None

Review and Comment: The Tyco test series clearly demonstrates the advantages of active fire suppression systems. It also consistently demonstrates a significant reduction in work time for a firefighters operating in a building constructed with an unsprinklered and unfinished engineered I-Joist floor systems exposed to fire conditions. This test series makes progress towards a comparative performance analysis. The products were tested with respect to their allowable spans and the applied load, although atypical, was consistent. The characterization of the fuel load for the fire was considered equivalent to a modern synthetic fuel load and the environmental conditions were controlled as the testing was conducted in a large research facility.

4.5.4. Fire Performance of Houses. Phase I Study of Unprotected Floor Assemblies in Basement Fire Scenario, 2009.

Conducting Agency: In December of 2009 J. Z. Su of 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.

Test Series: 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.

A simple fuel package was developed for use in Phase 1 full-scale experiments to create a repeatable fire that simulated a basement living area fire. This fuel package consisted of a mock-up sofa constructed with exposed polyurethane foam and wood cribs. Combined with different ventilation conditions, the fuel package provided two relatively severe basement fire scenarios with a reproducible fire exposure (above 800°C) to the unprotected floor-ceiling assemblies.

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 an uniform imposed live load of 20 psf.. A summary of these tests results is shown in Table 16.

Table 16. 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.

Review and Comment: In all of the NRC-IRC experiments, structural failure of the test floor assemblies occurred. The moment of floor failure was characterized by a sharp increase in floor deflection and usually accompanied by heavy flame penetration through the test assemblies as well as by a sharp increase in compartment temperature above the test floor assemblies. With the relatively severe fire scenarios used in the experiments, the times to reach structural failure for the wood I-joist, steel C-joist, metal plate and metal web wood truss assemblies were 35-60% shorter than that for the solid wood joist assembly.

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). There was structural deflection of all of the floor assemblies prior to their structural failure. The steel C-joist floor assembly produced the highest deflection rate, followed by metal-web and metal-plate wood trusses. The solid wood joist assemblies produced the lowest deflection rate. There were three distinct patterns for structural failure of the test assemblies. For the solid wood joist assemblies, the structure failure occurred after deflection of the floor, mainly in the form of OSB subfloor failure (burn through). For all other floor assemblies, after deflection of the floor, the structure failure occurred either in the form of complete collapse into the basement or in the form of a "V" shaped collapse due to joist or truss failure. The main mode of structural failure for the solid wood joist assemblies after they structurally deflected was by flame penetration through the OSB subfloor, with most of the wood joists significantly charred but still in place at the end of the tests. Whereas for all other floor assemblies, after they structurally deflected, failed by complete structural collapse due to joist or truss failure.

4.5.5 Performance of Protected Ceiling/Floor Assemblies and Impact on Tenability with a Basement Fire Scenario, 2011.

Conducting Agency: In May of 2011 J. Z. Su of 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.

Test Series: 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 17 shows a matrix for the full-scale fire experiments. The study focused on the impact of the protection measures on the life safety of occupants from the perspective of tenability for occupants and integrity of structural elements as egress routes.

Table 17. Matrix of Full-Scale Fire Experiments.

Test Assembly	Gypsum board ceiling only	Suspended ceiling only	Sprinklered only
Wood I-joist	X	X	X
Metal web wood truss	X		X
Steel C-joist	X		
Solid wood joist	X		

The experiment tested the fire performance of the protected floor/ceiling systems, tenability conditions in the floor areas above the fire, and timeline for fire initiation, smoke alarm activation, onset of untenable conditions, and structural failure.

Four experiments were conducted respectively using a wood I-joist assembly, steel C-joist assembly and metal web wood truss assembly, as well as, solid wood joist assembly with regular gypsum board on the basement side of the test assembly (i.e. gypsum board ceiling in the fire room). The experiments conducted using the gypsum board protected assemblies exhibited the same chronological sequence of fire events — fire initiation, smoke alarm activation, onset of untenable conditions, and finally structural failure of the test floor assemblies. The smoke alarms in the basement fire compartment took 30 s to activate consistently. Smoke obscuration was the first hazard to arise. The smoke obscuration limit was reached at around 190 s in these experiments. Untenable (incapacitation) conditions were reached shortly after smoke obscuration. Heat exposure reached the incapacitation doses on the first story after 240-300 s; CO exposure reached the incapacitation doses on the second story after 300-400 s. Compared to the experiments conducted in the previous study using the same floor structures without gypsum board protection, tenability conditions were similar or improved slightly whilst the structural performance was improved significantly with the gypsum board protected floor assemblies. The times taken to reach structural failure for the gypsum board protected floor assemblies were extended beyond those with no protection. With gypsum board protection, all engineered test assemblies had the structural failure time similar to that of the solid wood joist assembly under the test fire scenario.

This project also conducted experiments utilizing a two-sprinkler layout in the basement fire room and a single pendant sprinkler system below the bottom of the exposed combustible floor assemblies. The two sprinkler system experienced activation of one sprinkler by heat and was able to control the fire quickly and keep the temperature in the fire room close to the ambient level. Tenability limits were not reached during the 1200-s experiment. There was no structural damage to the test floor assembly and no damage to the sprinkler piping system either. The single sprinkler system also effectively protected the structural integrity of the test floor assemblies and kept the conditions tenable in the test house during the experiments. The test floor assemblies had no structural damage and the tenability limits were not reached during the experiments.

Table 18 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.

Review and Comment: With the gypsum board protected floor assemblies, tenability conditions were similar or improved slightly, while the structural performance was improved significantly in the experiments, compared to the experiments conducted in the previous study using the same floor structures without gypsum board protection. With gypsum board protection, all engineered test assemblies had similar structural failure times, matching that of the solid wood joist assembly under the test fire scenario. The benefit of the suspended ceiling as a protection measure for the test assembly was marginal, compared to the same test assembly without a suspended ceiling. The residential sprinkler systems effectively protected the structural integrity of the test assemblies and there was no structural failure or damage to the test assemblies in the test scenario. The residential sprinkler systems also kept the conditions tenable in the test house during the experiments.

4.5.5. Lennon, T. "Large Scale Natural Fire Tests on Protected Engineered Timber Floor Systems". Fire Safety Journal, March 2010

Conducting Agency: As part of an ongoing research project to investigate the performance in fire of specific types of innovative construction products and techniques (ICPT), BRE Global have carried out large-scale fire tests to determine the response of different floor systems to a realistic fire scenario.

Test Series: The principal objective was to determine the mode of failure of different floor systems to provide information to key stakeholders (particularly the Fire and Rescue Service), which can be taken into account in the dynamic risk assessments that underpin fire fighting operations. The following presents the results and observations from those fire tests for three floor systems: (i) solid timber floor joists, (ii) I-section floor beams with solid timber top and bottom flanges and an oriented strand board (OSB) web, and (iii) a timber truss incorporating solid timber upper and lower chord members and a pressed steel web member. These reflect the two most common types of engineered floor systems used in the UK and allow for direct comparison with a more ‘‘traditional’’ form of construction.

Three tests were performed at BRE's North East test facility in a single story compartment formed from concrete blocks. The compartment was designed to dimensionally reflect a typical domestic dwelling with an associated design loading appropriate for this purpose. The compartment had internal dimensions of 13 ft. x 10 ft. with the joists spanning in the long direction. The floor-to-ceiling height of the compartment was 8 ft. The compartment had two ventilation openings, one on the short and one on the long sides, both measuring 2.5 ft. x 3.3 ft. Based on this layout, the size and spacing of the engineered floor joists of each type of floor was determined by the corresponding floor manufacturer.

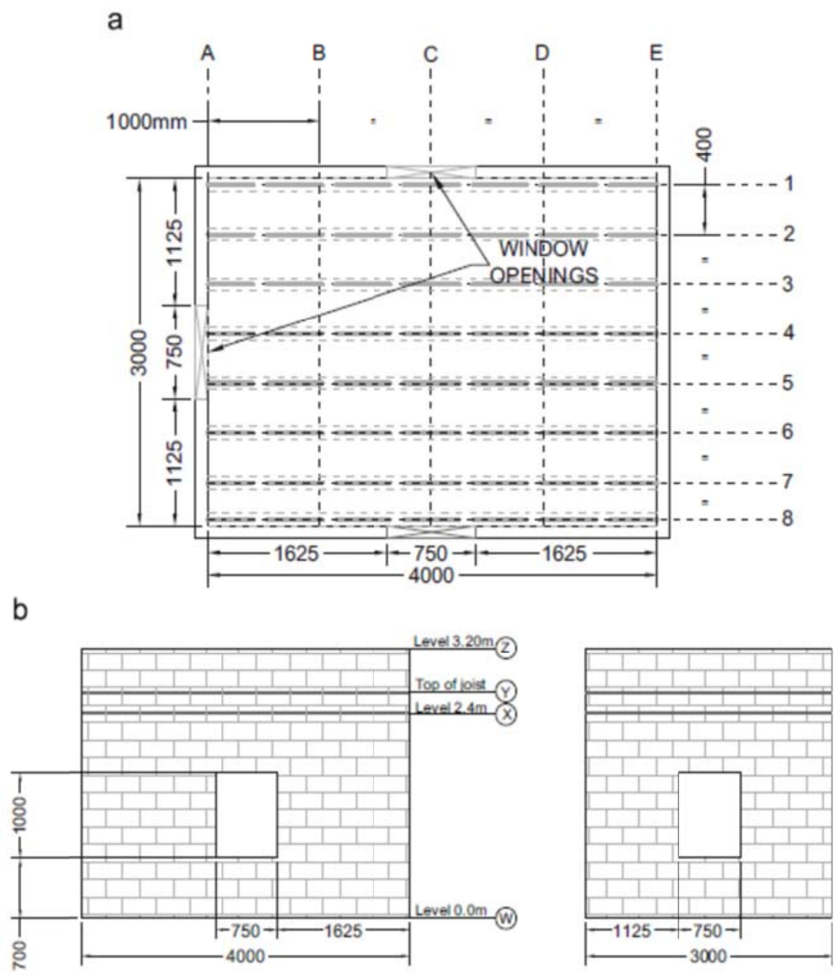

Figure 10. Experimental Compartment: (a) plan; (b) elevation (units in millimeters).

The resulting member sizes with centers at 16 inches are summarized in Table 19. The joists were connected to the supporting masonry walls using common joist hangers. The hangers were manufactured from cold-formed thin steel. These were embedded into the mortar between block work courses.

Table 19. Matrix of Full-Scale Fire Experiments.

Joist Details	Overall Dimensions (inches)	Web	Web to Flange Connection
Solid Timber Joist	1.75 x 8.65	N/A	N/A
Engineered I-section joist	1.75 x 8.65	.375	Phenol-formadehyde adhesive
Engineered Truss joist	2.85 x 8.65	Cold Formed Steel	Mechanical Nailing Plates

The purpose of the tests was to evaluate the response of the floor systems to a “realistic” fire scenario such as may occur in a room with in a modern apartment building. The dimensions and ventilation condition within the room of origin were consistent with a fire within the living area of an apartment building where the door is closed. They are also consistent with previous research into the performance of timber frame structures in fire. To provide a comparison with the results from standard fire tests and to evaluate the performance of the passive fire protection the fire load density was calculated such that the floor joists would be exposed to a natural fire of a severity equivalent to 60 min. of exposure in the standard fire test. The figure adopted of 450 MJ/m^2 is lower than codified design values but is in line with published average fire load densities and consistent with previous research into the performance of medium rise timber frame buildings in fire. The equivalent severity was calculated using the time equivalence method of BSEN1991-1-2 taking into account the number and size of openings and floor area. In addition, the predicted compartment time–temperature response was calculated according to the parametric approach detailed in annex A of BS EN 1991-1-2. The design fire load was provided by 12 cribs each with 25 kg of solid timber, giving a total fire load of 5400 MJ, for each test.

The floor system was designed for an imposed load of $1.5kN/m^2$, in addition to its self-weight, which is representative of a typical load in a residential building as per BS EN 1991-1-1 for category A buildings. At the fire limit state the structure will typically be designed for a combination of 50% of the imposed load and 100% of the dead load. This load combination is consistent with the guidance in the UK National Annex to BS EN 1991-1-2. Therefore, a uniformly distributed load of $0.75kN/m^2$ was applied to the floor system during testing using 36 sand bags (each 25 kg). The floor deflections due to the application of the imposed load were measured by taking readings prior and post application of the load. The difference between these two values was taken as the deflection due to loading. The maximum-recorded deflection was just over 3.5 mm.

Performance of the plasterboard lining

The three floor systems were designed by the manufacturers to achieve 60 min. fire resistance. For this purpose, the engineered I- section joists were protected by 2 x15 mm plasterboards while the solid timber and truss web joists were protected by 2 x 12.5 mm plasterboard. The 30 mm plasterboard specification for the I-section joists was extremely efficient in protecting the floor. The outer layer of the lining fell away during the test. However, the internal layer remained intact until the fire entered its decay phase. Comparatively 25mm of type F plasterboard was insufficient to protect the solid and truss web joists for 60 min in a fire. Both layers of the thinner boards fell away during the steady state phase of the fire resulting in significant damage to the joists above. The performance of the lining to the I-section joists meant that the test did not provide enough information to draw a conclusion about the failure behavior of the floor. Comparatively a large volume of new information has been collected for steel webbed engineered floor joists, and some observations have been made regarding the likely mechanisms, which cause failure and the associated rate of deflection, at the point of failure.

Comparison of the deflection behavior of different joist systems

Comparison of data for deflection and average temperature for the points of maximum observed deflection.shows the relationship between average joist temperature, deflection, and time for all three tests, at the point of maximum observed deflection. This provides an opportunity to compare the performance of the two engineered floor systems against solid joists.

Initially, the deflection of the solid timber joists remained insignificant for approximately 30 min. After this, the maximum deflection increased at an almost steady rate to reach a maximum value of about 29 mm after approximately 56 min of exposure. This is also the time at which the maximum average temperatures in all tests appears to have been reached. The initial deflections of the two engineered floor systems were of a comparable magnitude with both reaching a value of approximately 6mmafter48minofexposure.This is almost half the deflection reached by the solid timber joists after the same time of exposure. After this, the rate of increase of the deflection of the engineered I-section joists remained much lower than that of the solid timber joists. With a maximum deflection of nearly 8 mm reached at 56 min (and remained unchanged at 60 min). The fire protection provided by the 30 mm fire line plasterboard used in this test was effective. After the first 48 min of fire exposure, a sharp increase in the rate of deflection of the engineered truss joists started to take place. After 56min of fire exposure, the maximum deflection was nearly 70mm (75mm after 60min).

Once the fire was extinguished, the floor continued to deflect reaching a maximum value of 90 mm. To give a comparative picture of the maximum deflection of each floor system the deflections measured after 60 min. at different locations across the floor. Where the test was terminated prior to 60 min. the last measured deflection were provided. The deflections of the engineered truss joists are the most significant. In general, for approximately the same joist temperature, it can be seen that the engineered truss joists deflected almost three times more than the traditional solid timber joists, after approximately 60min of fire exposure.

Failure modes of fire damaged timber floor joists

The rate at which deflections develop, especially prior to failure, is particularly important as far as safety is concerned and gives a good indication of the type of failure observed, i.e. brittle, ductile ,etc. Since failure did not occur in all floors the maximum rate of deflection observed after an exposure to fire of 30 min. will be used for comparison. For the solid timber joists this rate of deflection was nearly 1.0 mm/min, and remained constant over a period of about 30 min. This is a typical behavior for this type of floor giving reasonable warning before final collapse. In general, collapse occurs when the depth of char is such that the residual solid timber section is insufficient to support the load applied to the floor. The rate of deflection of the engineered I-section joists was approximately 0.2 mm/min. This indicates that the floor was well protected from fire by the 30 mm plasterboard, as recommended by the floor manufacturers. However, this also meant the resistance of the floor to direct fire exposure could not be evaluated in this experiment. Tests on similar floors suggest that when the lining to the joists is breached then the OSB web of the I-joists may be ‘burned through’. This may result in a loss of connectivity between the top and bottom flanges, which would be extremely detrimental to the load bearing capacity of the joists and could lead to a very sudden failure of the floor system.

The rate of deflection of the engineered truss joists was approximately 6.4 mm/min. This was accompanied by large deflections which occurred quite suddenly over a short period of time. This indicates a more dangerous mode of failure compared to that of solid floor joists. In this test the elapsed time between the point at which deflections within the floor became noticeable and the floor suffering significant damage, was less than 10 min. At this stage a decision was made to terminate the test to prevent the floor from collapsing within the following few minutes. This is an undesirable mode of failure. In general, failure of the engineered truss joists is likely to occur due to loss of material caused by combustion of the solid timber flanges. In addition, charring of the chords can cause failure of the mechanical fixings joining the steel web to the chords. This may lead to a loss of connectivity between the flanges leading to collapse of the section. However, this mode of failure is likely to be a localized one. This is because the steel web of an engineered truss joist is manufactured with a number of small discrete web modules each connected with its own mechanical fixings to the top and bottom chords. It was apparent that only a number of these modules failed during the test which prevented immediate collapse of the entire floor. It should be noted that the similar mode of failure was also reported in work undertaken in Canada on similar joists tested in a furnace.

Review and Comment: Like many systems the performance of floors is currently evaluated via a standard furnace test of limited dimensions with unrealistic boundary conditions. The intention in this project was to investigate the performance of a floor system connected to load bearing walls through proprietary connections and subject to a typical value of imposed load and a fire scenario that included direct flame impingement. The experimental program under-taken involved testing three different floor systems for typical residential applications exposed to a realistic fire scenario under realistic conditions of load and restraint. In each case a system representing a separating/compartment floor was selected such as would be used to separate different occupancies within an apartment building. For this reason the floors required a notional 60 min. fire resistance period. Guidance on the appropriate level of fire protection was taken from manufacturer's information. The general conclusion that may be drawn from the results of this test program is that engineered floors may be able to offer the same fire resistance as that of solid timber joists floors provided that the engineered joists are properly protected, from fire, by adequate boarding and that a good quality of installation is maintained during construction. However, when exposed directly to fire, some engineered joists may fail in a more rapid manner when compared to solid timber joists. This was supported by the following observations:

- The performance of the engineered I-section joists shows that this type of floor may be capable of providing 60 min. fire resistance on natural fire scenarios provided that two layers of 5/8" fire resistant plasterboard are used, as recommended by the manufacturers. However, more tests are needed to assess the exact behavior of such joists if exposed directly to fire due, for example, due to failure of the lining boards.
- When exposed to fire directly, the behavior of engineered truss joist floors, similar to the one tested, result in a more rapid mechanism of failure. The test showed that under this condition this type of floor may develop large deflections, and continue to deflect at a high rate over a short period of time leading to a sudden failure of the floor system. This mode of failure was not observed in the solid timber joists test. In this case, the steel modules forming the web of the section were detached due to charring of the timber chords which caused the connecting plate to lose its bond.
- The chipboard flooring offers some contribution to the overall fire resistance of the floor system by delaying the spread of fire if the ceiling void is breached. It also may offer additional structural resistance by acting as a stress skin should some of the joists become damaged.
- The joist hangers have been shown to be capable of surviving 60 min. exposure to a natural compartment fire with little or no damage observed.
- The deflection of the engineered truss joists was almost three times that of the solid timber joists after 60 min. of fire exposure.

- This research compared the full scale performance of dimensional and engineered floor systems with passive protection while exposing the built assembly to a ventilated “realistic equivalent fire load”.
- The study subjected the floor systems to a live load equivalent to 50% of the live load required by the local building code and documented the structural performance and failure mechanisms of the floor elements relative to finished ceiling failures during the fire tests.
- Comparison of the data for deflection and average temperature for the points of maximum deflection provides a potentially useful comparison of temperature affects as they correlate to structural stability. This comparative method should be considered for future analysis of protected and unprotected assemblies.

4.5.6. Madrykowski, D. “Examination of the Thermal Conditions of a Wood Floor Assembly above a Compartment Fire”. NIST Technical Note 1709, August, 2011

Conducting Agency: 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. 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.

Test Series: 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.

The support for Experiment 1 was composed of wooden I-joists, 11.9 in tall with a laminated veneer lumber flange width 2.3 in and a height of 1.4 in. The web of the joist was made from OSB that was 0.43 in thick. These joists conformed to the APA standard PRI 40 series specifications. The joists were spaced 24 in apart on center. Experiment 1 used laminate flooring over OSB.

The support for Experiment 2 was similar to the support for the floor in this Experiment 1, wooden I-joists, 11.9 in tall with a laminated veneer lumber flange width of 2.3 in and a height of 1.4 in. The web of the joist was made from OSB that was 0.43 in thick. These joists conformed to the APA standard PRI 40 series specifications. The joists were spaced 24 in apart on center. Experiment 2 used carpeting and padding over OSB.

The support for Experiment 3 was composed of solid wood joists. The joists had a nominal “2 x 12” cross-section which measured 1.25 in by 11.25 in. The joists were spaced 16 in apart on center. They spanned the entire 16 ft width of the structure. Solid wood bridging was installed between the joists. As with experiment 2, carpet and padding partially covered the OSB sub-flooring in this experiment.

The support for Experiment 4 was similar to Experiment 1. The floor structure was composed of wooden I-joists, 11.9 in tall with a laminated veneer lumber flange width of 2.3 in and a height of 1.4 in. The web of the joist is made from OSB that is 0.43 in thick. These joists conformed to the APA standard PRI 40 series specifications. The joists were spaced 24 in apart on center. For this experiment a ceiling comprised of 0.5 in thick gypsum board was attached to the bottom of the joist to protect the floor assembly.

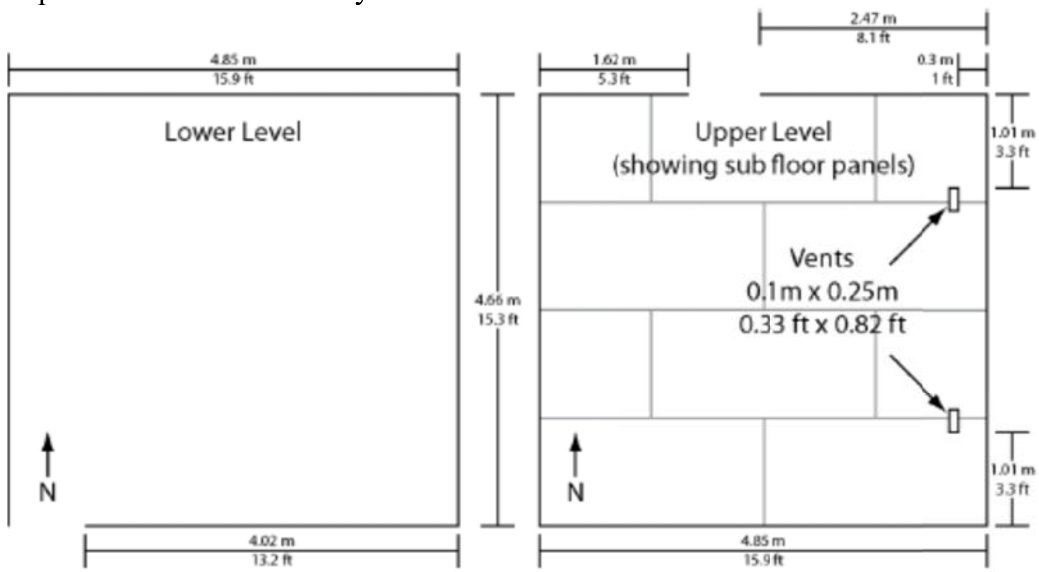

Figure 11. Floor plan of the upper and lower levels of the structures.

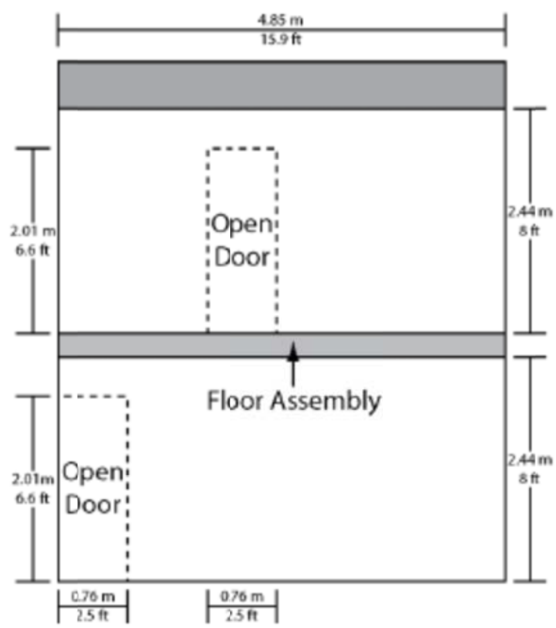

Figure 12. Elevation view of the structure, looking North, with dimensions.

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.

Test Results: All four experiments show that the combination of surface temperature and contrast of the joists past the flooring material as viewed with a thermal imager could be used as a reasonable indication of the existence of a fire, but very little could be determined qualitatively about the potential for floor collapse. The information available from a thermal imager, namely the variations and magnitude of infrared radiation from the flooring surface, is complicated by many factors. Consequently, it provides no straightforward indication of either severity of the fire below or its duration, which are better characterized indicators of potential collapse hazard. This set of experiments provides evidence of many of these complicating factors, and the effect they have on qualitative analysis using thermal imagers.

The collapse times for these experiments is given in Table 20. Matrix of Full-Scale Fire Experiments, no floor collapse occurred on the fourth experiment. In a real world scenario, differences in structural loading and fuel load could affect collapse time. In these experiments, the fuel loading was small compared to a furnished structure, and the loading on the upper level consisted only of the water-filled barrels in the center. In a more realistic scenario, fuel loading in the lower level could vary greatly from densely furnished to almost empty, and the structural loading would likely include, at a minimum, a full set of furniture. Firefighters inside the structure would likely be moving as well, providing significantly greater stress on the floor than the static load used in these experiments. Although collapse times are reported here, it should be noted that wood flooring systems were weakened prior to complete structural collapse.

Table 20. Matrix of Full-Scale Fire Experiments

Experiment	Collapse time after ignition sec (min:sec)
1	1470 (24:30)
2	1675 (27:55)
3	1485 (24:45)
4	No Collapse

4.6. 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. This trend should be continues and full-scale experiments should 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 should 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 should attempt to 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 should 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. Heat Release Rate Experiments

UL conducted a series of experiments to characterize the fuel load selected for the subsequent full-span experiments. Three experiments were conducted examining the burning characteristics of combinations of pallets and cardboard 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 based on four key criteria; representative of actual fuels, ability to create a representative and reproducible heat release rate and the ability to create ventilation limited conditions in the test structures. 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.

5.1. Facility and Instrumentation

The fuel was positioned in the nominal 50 by 50-ft. fire test cell (Figure 13) equipped with a 25-ft. diameter heat release rate measurement hood (Figure 14). Four inlet ducts provide make up air in the test facility and are located at the walls 5 ft. above the test floor to minimize any induced drafts during the fire tests.

The heat release calorimeter is equipped with convective and total heat release instrumentation. The convective instrumentation calculates the heat release rate from the energy rise of the products of combustion entering the calorimeter. The total heat release instrumentation calculates fire size using oxygen consumption techniques. The heat release calorimeter is calibrated up to a 10 MW fire size.

Figure 13. Fire Test Cell

Figure 14. Calorimeter Hood

5.2. Pallet/Box Experiments

The first fuel load was composed of two stacks of six pallets each topped with four cardboard boxes filled with expanded polystyrene trays centered below the calorimeter (Figure 15 through Figure 17). The two stacks were separated by 4 in (Figure 18). The hardwood pallets measured 42 in. on a side and had a height of 5 in. The average weight of the pallets was 49.5 lb. The cardboard boxes measured 21 in. on a side and were 20 1/8 in. tall. The average weight of the boxes filled with trays was 9.1 lb. The total average weight of the fuel package was approximately 667 lb. The moisture content of all of the pallets was measured in several locations and the pallets were selected if their moisture content was between 9 % and 11 %. The fire was ignited with two standard UL igniters made up of cotton gauze in a plastic bag, soaked in 8 ounces of gasoline (Figure 19). Each igniter weighed 0.5 lb., and they were placed in the separation of the pallets with one in each stack, on opposite sides (Figure 20). To light the igniters a torch was touched to them. The fire grew and was allowed to burn until the fuel load was diminished to a pile of flaming embers at which time it was extinguished. This configuration was conducted in triplicate to assess repeatability.

Figure 15. Double stack of fuel load

Figure 16. Fuel positioned in test cell

Figure 17. Polystyrene trays in box

Figure 18. 4 in. separation between stacks

Figure 19. UL Igniter

Figure 20. Igniter location

5.3. Experimental Results

The heat release rates for the duration of the 3 experiments as well as the average heat release rate are graphed in Figure 21. The third experiment developed a little slower than the first two but they all had an approximate peak heat release rate of 4.5 MW and sustained a minimum of 2 MW for approximately 13 minutes (780 s). The total heat released during each of the experiments and the average is shown in Figure 22. The average total heat released was 3,700 MJ. Images taken during Experiment 1 show the progression of the fire dynamics (Figure 23 through Figure 28). Each caption indicates the heat release rate at the time the images were recorded.

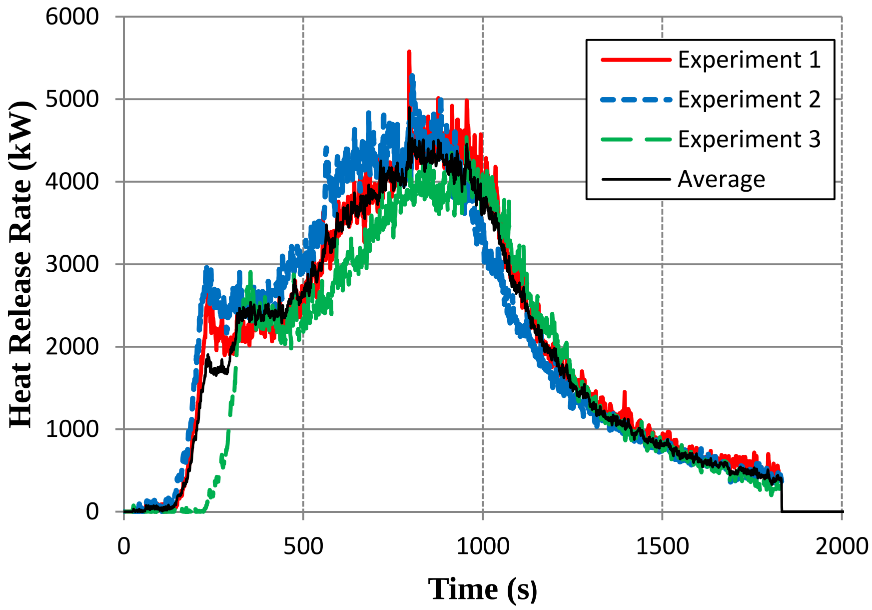

Figure 21. Pallet/Box Heat Release Rates

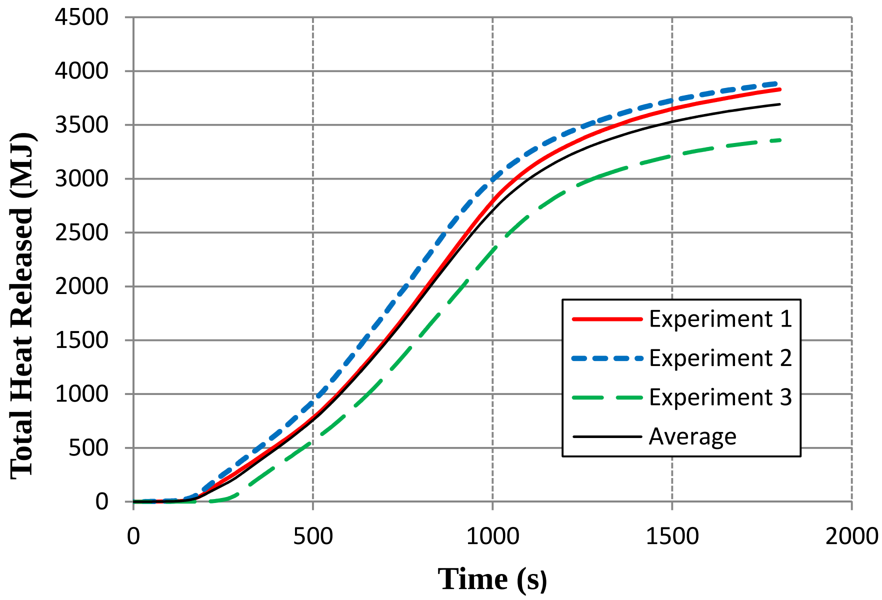

Figure 22. Pallet/Box Total Heat Released

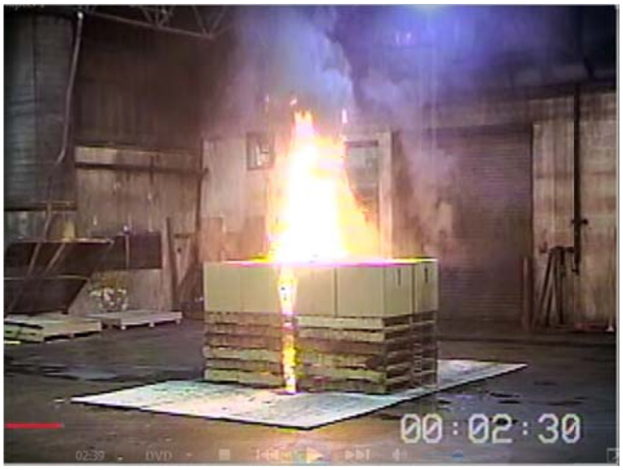

Figure 23. Conditions at 2:30 (150 s) – 400 kW

Figure 24. Conditions at 5:00 (300 s) – 2000 kW

Figure 25. Conditions at 7:30 (450 s) – 2400 kW

Figure 26. Conditions at 10:00 (600 s) – 3600 kW

Figure 27. Conditions at 15:00 (900 s) – 4700 kW

Figure 28. Conditions at 20:00 (1200 s) – 1700 kW

5.4. Discussion

The goal of the fuel load was to be repeatable due to the number of experiments being conducted, to be representative of actual fuel loads found in residential basements and to be reasonable and conservative in regards to energy production. The fuel load was also expected to create ventilation limited conditions with the ventilation openings closed and flashover conditions with the ventilation openings open. Figure 21 shows that the heat release of the fuel package is repeatable. Examining the repeatability of the total heat released shows that all three experiments are within 9% of the average total heat released (Figure 22).

Two previous studies examined the fuel loads found in basements. The first by the National Research Council of Canada (NRCC) (Bwalya, 2004) surveyed households and concluded that there was an average loading of 360 MJ/m^2 for a basement living room in homes with an average room size of 23 m^2. The second study was conducted by the National Bureau of Standards (now NIST) (Fang & Breese, 1980). This study also surveyed homes. The survey identified the mean fuel load of 28.3 kg/m^2 for a basement recreational room, 13.7 kg/m^2 for utility rooms and 15.6 kg/m^2 for other basement rooms. Overall, the average of movable fuel load in the basement of the 200 homes was 24 kg/m^2 with an average basement size of 32 m^2. The approximate composition of the fuel was 83% wood or paper, 16% plastic or fabric and 1% other. Their survey was followed up by experimental testing which concluded that a range of 5,400 MJ to 14,000 MJ total available heat was in the fuel loads.

The amount of energy produced during the heat release rate experiment was calculated by integrating the area under the curve of the heat release rate versus time plot of the average of the three experiments. This value was 3,700 MJ over the 30 minute experiment. Utilizing the NRCC loading of 360 MJ/m^2 and multiplying by the area of the basement used in the subsequent experiments of 63 m^2 yields 22,680 MJ. Assuming only one half of the basement can be considered a living room yields 11,340 MJ fuel loading. This value falls within the NBS study range of 5,400 MJ to 14,000 MJ. In order to remain conservative the total fuel load used in most of the full-scale experiments was selected to be two of the experimental pallet/box configurations. Each has available heat production of 3,700 MJ for a total of 7,400 MJ.

Comparing the selected fuel load to the composition found in the NBS study demonstrates a similar fuel composition. Pallets (wood) compose 89% of the selected fuel load and expanded polystyrene (plastic) composes 11% as compared to the 83% wood/paper and 16% plastic/fabric composition in the NBS study. This demonstrates that the selected fuel load of pallets/boxes is representative of fuel loads found in actual basements both in terms of heat content and composition.

Another point of comparison that is relevant to this discussion is the total energy released during a living room fire. Recently UL completed a study that involved modern living room fires (Kerber, 2010). A heat release rate experiment was conducted burning a living room arrangement of two sofas, a chair, coffee table, end table, television stand, television and carpeted floor and the total heat released was 3,650 MJ which is comparative to the 3,700 MJ released by the pallet/box fuel load. The main difference is the time at which the heat is released and the peak heat release rate. The living room's peak heat release rate was 11 MW and the fire lasted 19 minutes versus the 4.5 MW peak and a burn time of 30 minutes for the fuel package selected for these experiments. Since the experimental basement is simulated to have storage and a living room the fuel package selected for these experiments can be considered conservative as compared to the living room fire exposure.

To assess the ability to generate ventilation limited fire scenarios the amount of available oxygen can be combined with the theoretical total energy release can be compared to the actual energy release from the heat release rate experiments. The total internal volume of the subsequent experimental structures is 12,260 ft^3 including the basement and first floor. That value multiplied by 21 % oxygen available yields 2,575 ft^3 of oxygen. This volume of oxygen can be converted to mass to determine the mass of oxygen initially available in each structure assuming a standard temperature and pressure condition (40.46 g/ft^3). Multiplying by the theoretical value of 13.1 kJ (Huggett, 1980) of energy per gram of oxygen gives the theoretical maximum energy able to be produced in the closed experimental structure if all oxygen is able to burn.

Theoretical maximum energy = 104185 g O_2 x 13.1 kJ/g O_2
Theoretical maximum energy = 1,364,817 kJ = 1,365 MJ

The single fuel package of pallets and boxes selected for these experiments produces 3,700 MJ which is greater than the 1,365 MJ necessary to consume all of the oxygen in the experimental structure. This meets the final criteria of the fuel package which is to create ventilation limited conditions during the experiments. Additional fuel provided by the second fuel package or the burning of the floor system itself will speed up the time to ventilation limited conditions.

Examining ventilation limited conditions by assessing available oxygen when the structure is closed is one scenario that will be explored in the full-scale experiments but another scenario will be to have all of the ventilation (door and 3 windows) open during some of the experiments. In this scenario it is desired to transition to flashover to replicate real world scenarios observed in many basement fires. To find the minimum heat release rate needed for flashover to occur in the experimental structure Thomas's Flashover Correlation (Thomas, 1981) equation for heat release rate can be solved.

$$Q_{fo} = 7.8\ A_{room} + 378\ (A_{vent}\ H_{vent}^{1/2})$$

Where: Q_{fo} = Heat release rate necessary for flashover (kW)
A_{room} = Area of all surfaces within the room, exclusive of the vent area (m^2)
A_{vent} = Area of the total of all vents (m^2)
H_{vent} = The difference between the elevation of the highest point of all the vents and the lowest point of all the vents (m)

Solving this equation yields a minimum heat release rate to achieve flashover of 5.4 MW. This is slightly above the average peak heat release rate of the single fuel package of 4.5 MW. For this reason a second fuel package will be included as target fuel in the experimental basement and the contribution of the combustible floor system, regardless of the type, will be expected to contribute enough to transition the basement fire experiment to flashover.

6. Field Experiment Description

A series of ten experiments was conducted to examine four different residential flooring systems while varying, ventilation parameters, fuel load and floor loading (Table 21). The purpose was to test flooring 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.

Table 21. Experimental Series

Experiment	Floor Framing System	Ventilation Description
1	Dimensional Lumber (2 x12)*	Maximum Ventilation
2	Dimensional Lumber (2 x12)*	Sequenced Ventilation
3	Engineered I-Joist (12 in.)*	Maximum Ventilation
4	Engineered I-Joist (12 in.)*	Sequenced Ventilation
5	Engineered I-Joist (12 in.)*	Sequenced Ventilation/No boxes on pallets
6	Engineered I-Joist (12 in.)*	Maximum Ventilation /Modified Load
7	Metal Steel C-Joist (12 in.)*	Maximum Ventilation
8	Metal Steel C-Joist (12 in.)*	Sequenced Ventilation
9	Parallel Chord Metal Plate Connected Wood Truss (14 in.)*	Sequenced Ventilation
10	Parallel Chord Metal Plate Connected Wood Truss (14 in.)*	Maximum Ventilation

*Size denotes nominal size.

6.1. Facility

This series of field experiments was conducted at the Delaware County Emergency Services Training Center in Sharon Hill, PA. Two identical concrete structures were built on a concrete slab (Figure 29). They were designed to simulate residential basements. A top structure was placed on the concrete structures to create a simulated first floor. The steel framed top structure was moved by crane from structure to structure depending on which structure was being used for the experiment.

Figure 29. Concrete structures and top structure

6.1.1. Structure

The basement level of each structure was built from 2 ft. wide by 2 ft. tall by 4 ft. long interlocking concrete blocks. The interior dimensions were 20 ft. wide by 36 ft. long by 8 ft. tall (Figure 30). The floor systems were built on top of a wood sill plate that was attached to the top edge of the block walls. All of the joints in the block walls were stuffed with high-temperature insulation (Figure 31). There was an interior stairwell that connected the basement to the first floor (Figure 32 and Figure 33). A moveable top structure that had the same interior dimensions as the basement was placed onto the block walls to create a simulated first floor (Figure 34). Both structures were identical and were used alternately to speed up the time to complete the experimental series.

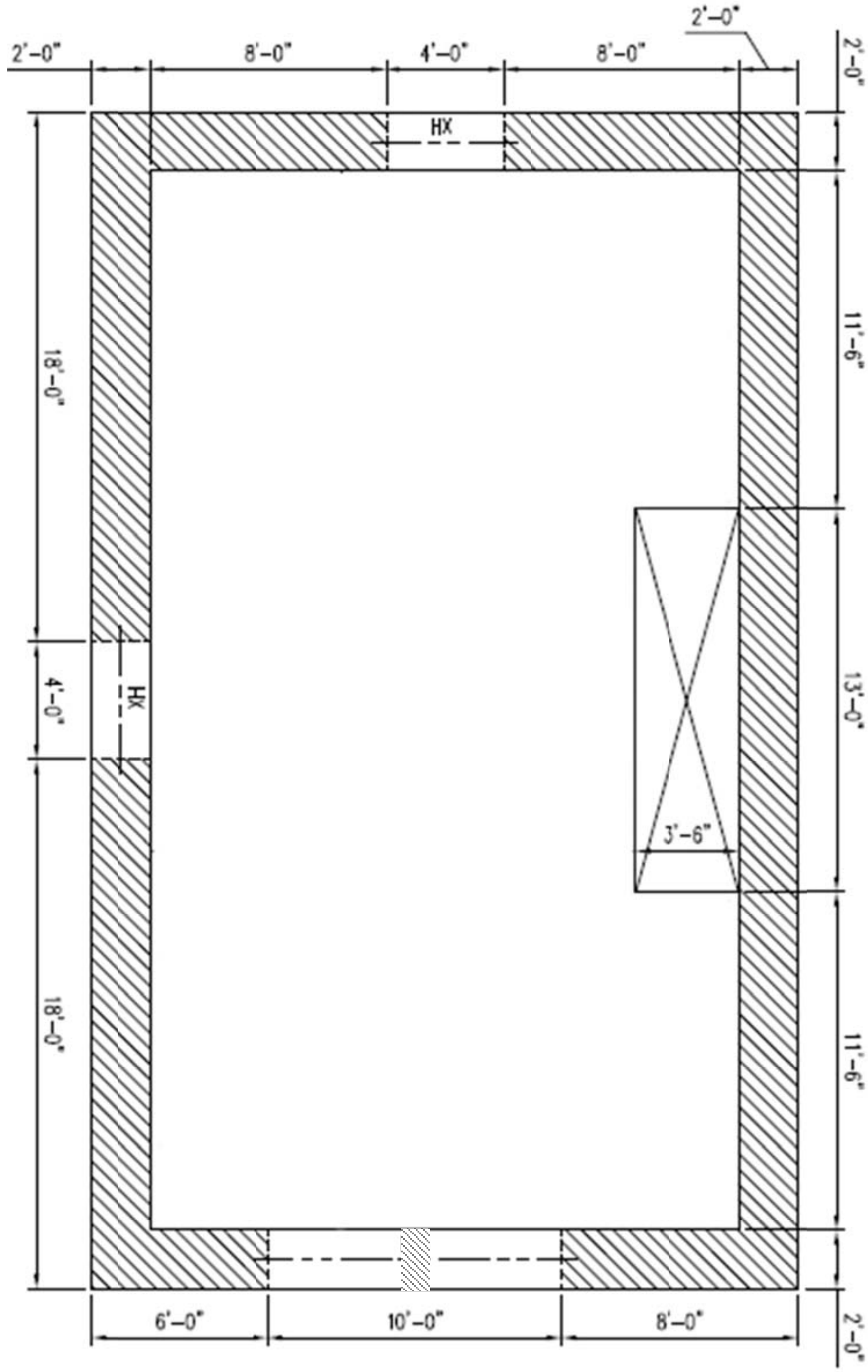

Figure 30. Structure Floor Plan, Basement Level

Figure 31. Experimental Structure

Figure 32. Interior stairwell

Figure 33. Top of stairwell and first floor

Figure 34. Movable top structure

6.1.2. Floor Systems

Four different floor systems were examined during these experiments.

1. Dimensional Lumber (Width 1 1/2 in., Depth 11 1/4 in.) [Figure 35]
2. Engineered I Joist (Depth 11 7/8 in, Flange Thickness 1 ½ in., Flange Width 2 ½ in., Web Depth 8 7/8 in., Web Width 3/8 in.) [Figure 36]
3. Steel C Joist (Depth 11 7/8 in., Width 1 ½ in., 1200S162-54 AISI section)[Figure 37]
4. Parallel Chord Metal Plate Connected Wood Truss (MPCWT) (Depth 14 in., Width 3 ½ in.) [Figure 38]

The floor systems were chosen based on their prevalence in residential construction, linkage to previous experiments and they were designed to optimize their span capabilities. The designs were developed in conjunction with the trade association that represents the manufacturers of each type of joist (Dimensional Lumber - American Wood Council, Engineered I Joist – American Wood Council, Steel C Joist – American Iron and Steel Institute and MPCWT –

Structural Building Components Association). Framing details for each floor system is located in Appendix A. Each floor system utilized 23/32 in. tongue and groove oriented strand board (OSB) decking (Figure 40).


Figure 35. Dimensional Lumber Floor System


Figure 36. Engineered Wood I Joist Floor System


Figure 37. Metal C Joist Floor System


Figure 38. MPCWT Floor System


Figure 39. End View of Joists


Figure 40. View of OSB decking from the basement

6.1.3. Instrumentation and Uncertainty

The measurements taken during the experiments included gas temperature, gas velocity, deflection and video recording. Measurement locations can be found in Figure 41. The figure also includes the labels that are used in the data plots and video captures that are in the Experimental Results Section. Gas temperature was measured with bare-bead, Chromel-Alumel (type K) thermocouples, with a 0.5 mm (0.02 in) nominal diameter. Thermocouple arrays were located in 3 locations on each level of the structure. All of the thermocouple locations had an array of thermocouples with measurement locations of 0.03 m, 0.3 m, 0.6 m, 0.9 m, 1.2 m,1.5 m, 1.8 m and 2.1 m (1 in, 1 ft, 2 ft, 3 ft, 4 ft, 5 ft, 6 ft and 7 ft) below the decking in the basement and ceiling on the first floor (Figure 42). The standard uncertainty in temperature of the thermocouple wire itself is ± 2.2 °C at 277 °C and increases to ± 9.5 °C at 871 °C as determined by the wire manufacturer (Omega Engineering Inc., 2011).

Gas velocity was measured utilizing differential pressure transducers connected to bidirectional velocity probes (Figure 43). These probes were located in the basement doorway, doorway at the top of the stairs and each of the three windows. There were five probes on the vertical centerline of each doorway located at 0.3 m (1 ft) from the top of the doorway, the center of the doorway, 0.3 m (1 ft) from the bottom of the doorway and two equally spaced between these probes. There were three probes on the vertical centerline of the windows located 0.15 m (6 in) from the top of the window, the center of the window and 0.15 m (6 in) from the bottom of the window. Thermocouples were co-located with the bidirectional probes to complete the gas velocity measurement. Positive measurements are flows out of the structure while negative velocity measurements are into the structure. The transducers were factory calibrated and documented to have an accuracy of ± 1 % (Setra, 2002).

Deflection of the floor system was measured in three locations along the centerline of the long dimension of the structure using linear deflection gauges. The first location was in the center of the long span floor section prior to the wall enclosing the stairwell. The second location was in the center of the shorter span adjacent to the stairwell opening and the third was centered in the long span section beyond the stairwell. The gauges were set to measure maximums of 5 in. of upward deflection and 20 in. of downward deflection (Figure 44). The gauges have an accuracy of 0.15% of the full-scale measurement with a repeatability of 0.015% of the full-scale measurement (Unimeasure Inc., 2011).

Video cameras were placed inside and outside the structure to monitor both smoke and fire conditions throughout each experiment (Figure 45). Eight video camera views were recorded during each experiment. The views recorded are detailed in Table 22 and shown in Figure 46 and Figure 47.

All readings from instrumentation that were impacted by collapse or suppression are assumed to provide data that is not reliable.

Table 22. Video camera views

View Description	View Label (Figure 46 and Figure 47)
Inside front basement corner	Front Basement
Inside rear basement corner	Back Basement
Inside first floor doorway	First Floor
Outside back overall	Back
Outside back close-up	Back Close
Outside front close-up Thermal Imaging	Back IR
Outside front	Front
Outside side	Side

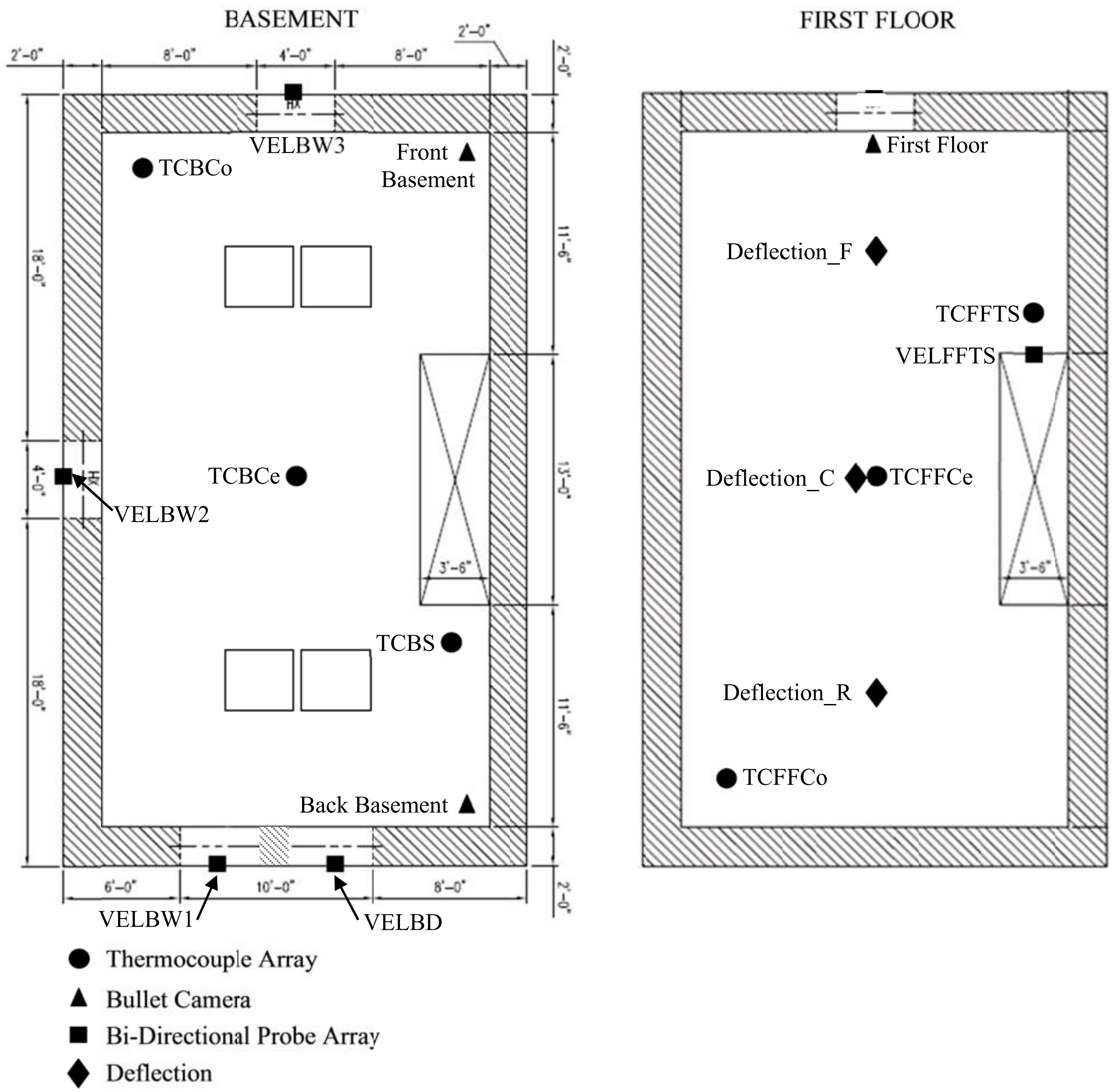

Figure 41. Measurement Locations and Labels

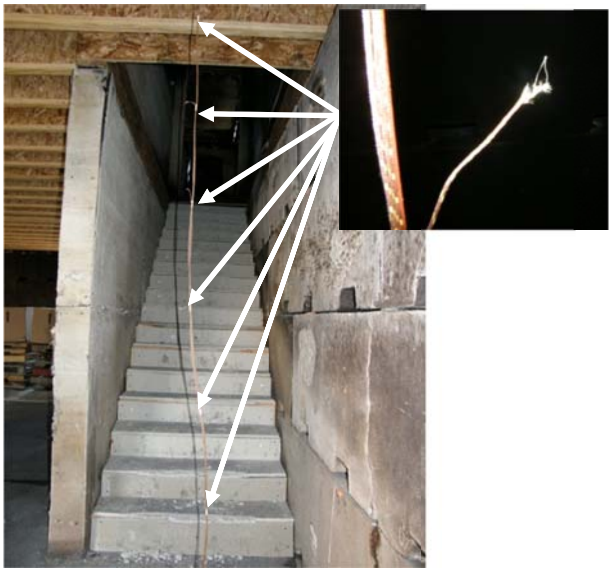

Figure 42. Thermocouple array with detail

Figure 43. Velocity probe locations in doorway and window with detail

Figure 44. Deflection Gauge

Figure 45. Bullet camera

Figure 46. Quad Video 1

Figure 47. Quad Video 2

6.2. Fuel Load

The fuel load was based on the heat release rate experiments described in Section 4. Each stack of pallets contained six pallets with a weight range of 210 lb to 240 lb. per stack. Two stacks made up each fuel package for a combined average weight of 450 lb. This was less than the 667 lb. of the fuel packages in the heat release rate experiments.

The fuel packages were located in the center of the front quarter of the structure and the back quarter of the structure. The squares in Figure 41 show the locations of the fuel packages. The center of the fuel package was located 9 ft from the end walls and 10 ft from the side walls. The fire was ignited the same way as the heat release experiments with two UL igniters. The igniters were lit remotely with a thin wire wrapped around a pack of matches that was electrically charged until the heat from the wire ignited the matches and in turn ignited the igniters. Only the fuel package located closest to the basement doorway was ignited. The second fuel package only contributed to the fire if ignited by flame and heat propagation during the experiment.

Experiment 5 had a modified fuel load in which the boxes of expanded polystyrene trays were removed and just the wood pallets remained.

Figure 48. Fuel package locations

Figure 49. Remote ignition

6.3. Structural Load

The loading of the floor systems was provided by water filled steel barrels positioned on top of the floor. The position of the barrels, the number of barrels and the amount of water in each barrel depended on the calculated load for each system. The load was consistent across the floor system technologies and was targeted to be 65% of the allowable design load for the floor assembly . Two different criteria were used to determine the allowable load for each test assembly: Bending stress/Moment capacity criteria or Code minimum (L/360) live load deflection criteria. The lower load from either criterion was used as the allowable design load. Table 23 summarizes the percentage of the allowable load applied to the test assembly under both criteria. Each barrel was filled to the appropriate mass of water and positioned to provide the calculated load. Detailed calculations and details of barrel placement are located in Appendix B.

Experiment 6 had a non-uniform load distribution where the total load was substantially less than the load used for the other experiments. It consisted of barrels loaded to 40 lb/ft^2 along the back and side walls to simulate furniture and two barrels filled to 300 lb to simulate two firefighters in the center of the floor. This load was consistent with the load used in previous research done by UL (Underwriters Laboratories, Inc., 2008) and the furnace experiments conducted as part of this research project.

6.4. Ventilation Parameters

The ventilation openings were sized based on the 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.

Three different ventilation parameters were used during these experiments.

1. Maximum Ventilation – All ventilation openings open
2. No Ventilation – All ventilation openings closed
3. Sequenced Ventilation – Ventilation openings opened to simulate fire department operations.

Ventilation or the amount of air available to the fire does play 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 and a simulated realistic scenario could be considered somewhere in the middle (Figure 50). This simulated realistic scenario or sequenced ventilation had the first floor door (or front door) opened at 8 minutes after ignition (Figure 51). This simulates the entry of a firefighting crew. At 10 minutes the basement door (or back door) was opened to simulate a firefighting crew gaining entry or ventilating the basement (Figure 52). At 10:30 the window next to the basement door was opened, at 11:00 the side window was opened (Figure 53) and at 11:30 the front window was opened.

Modern building codes, however, require air-tight building envelopes for houses where air infiltration from outside of the building envelope is required to be strictly controlled[1]. The tests and the results reported in this report did not comply with these modern requirements. The phrase "no ventilation" is thus used in this report somewhat loosely and represent restricted ventilation in comparison to the other ventilation scenarios described.

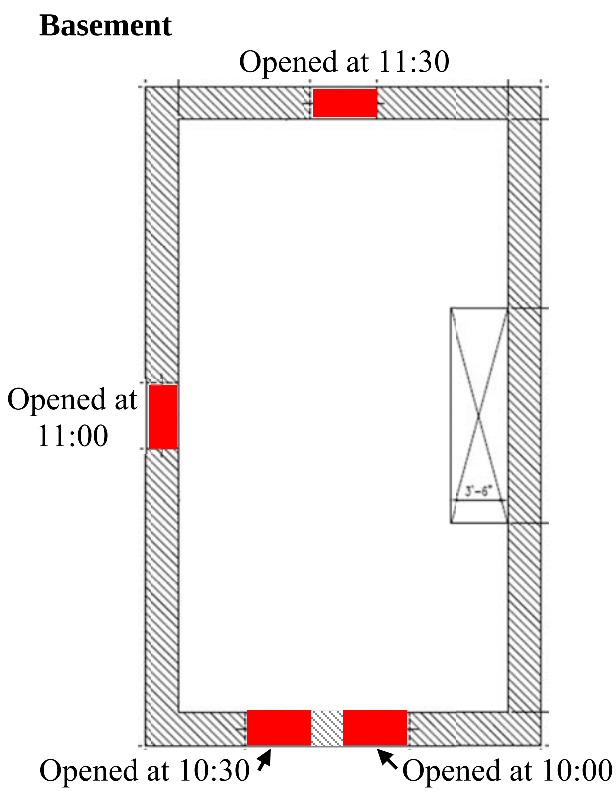

Figure 50. Sequenced Ventilation Details

[1]2012 International Energy Conservation Code mandate an air leakage rate of less than 3 air changes per hour (at a blower door pressure of 0.2 in. water gauge) for a majority of the houses, that is, climate zones 3 through 8. Houses in the warm southernmost climate zones, climate zones 1 thru 2, are more lenient with an air exchange rate of 5 changes per hour.


Figure 51. Firefighter opening front door (8:00 after ignition)


Figure 52. Firefighter opening back door (10:00 after ignition)

Figure 53. Firefighter opening side window (11:00 after ignition)

7. Field Experiment Results

The results of the ten experiments are detailed in this section. Table 23 details the variables of the experiments. The fuel was varied for Experiment 5, the load was varied for Experiment 6 and each floor system was tested with a maximum and sequenced ventilation scenario. The experiments with the "No/Sequenced" ventilation descriptor experienced collapse prior to ventilation but continued the sequenced ventilation prior to the end of the experiment.

Table 23. Experimental Summary

Experiment	Floor System	Fuel	Load Limiting Criteria		Ventilation
			Stress (Bending Moment)	Deflection (L/360)	
1	Dimensional Lumber	Pallets/boxes	***64*** %	47%	Maximum
2	Dimensional Lumber	Pallets/boxes	***64*** %	47%	Sequenced
3	Engineered I-Joist	Pallets/boxes	45%	***66***%	Maximum
4	Engineered I-Joist	Pallets/boxes	45%	***66***%	No / Sequenced
5	Engineered I-Joist	Pallets only	45%	***66***%	No / Sequenced
6	Engineered I-Joist	Pallets/boxes	49%	***71***%	Maximum

7	Steel C-Joist	Pallets/boxes	42%	***49***%	Maximum
8	Steel C-Joist	Pallets/boxes	42%	***49***%	Sequenced
9	Parallel Chord MPCWT	Pallets/boxes	63%	***67***%	No / Sequenced
10	Parallel Chord MPCWT	Pallets/boxes	63%	***67***%	Maximum

The locations of the labels used in this section are shown in Figure 54. The labels are configured by combining the measurement with the level, location and height as shown in Table 24.

Table 24. Instrument Label Description

Measurement	Level	Location	Height Below Ceiling	Examples
Temperature "TC"	- Basement "B" - First Floor "FF"	- Center "Ce" - Corner "Co" - Base of Stair "BS" - Top of Stair "TS"	0.03 m (1 in) "1" 0.3 m (1 ft) "2" 0.6 m (2 ft) "3" 0.9 m (3 ft) "4" 1.2 m (4 ft) "5" 1.5 m (5 ft) "6" 1.8 m (6 ft) "7" 2.1 m (7 ft) "8"	TCBCe3 TCFFTS7
Velocity "VEL"	- Basement "B" - First Floor "FF"	- Door "D" - Window 1 "W1" - Window 2 "W2" - Window 3 "W3" - Top of Stair "TS"	Top "T" Top/Middle "TM" Middle "M" Bottom Middle "BM" Bottom "B"	VELBDT VELFFTSBM
Deflection "Deflection"	NA	- Front "F" - Center "C" - Rear "R"	NA	Deflection_C

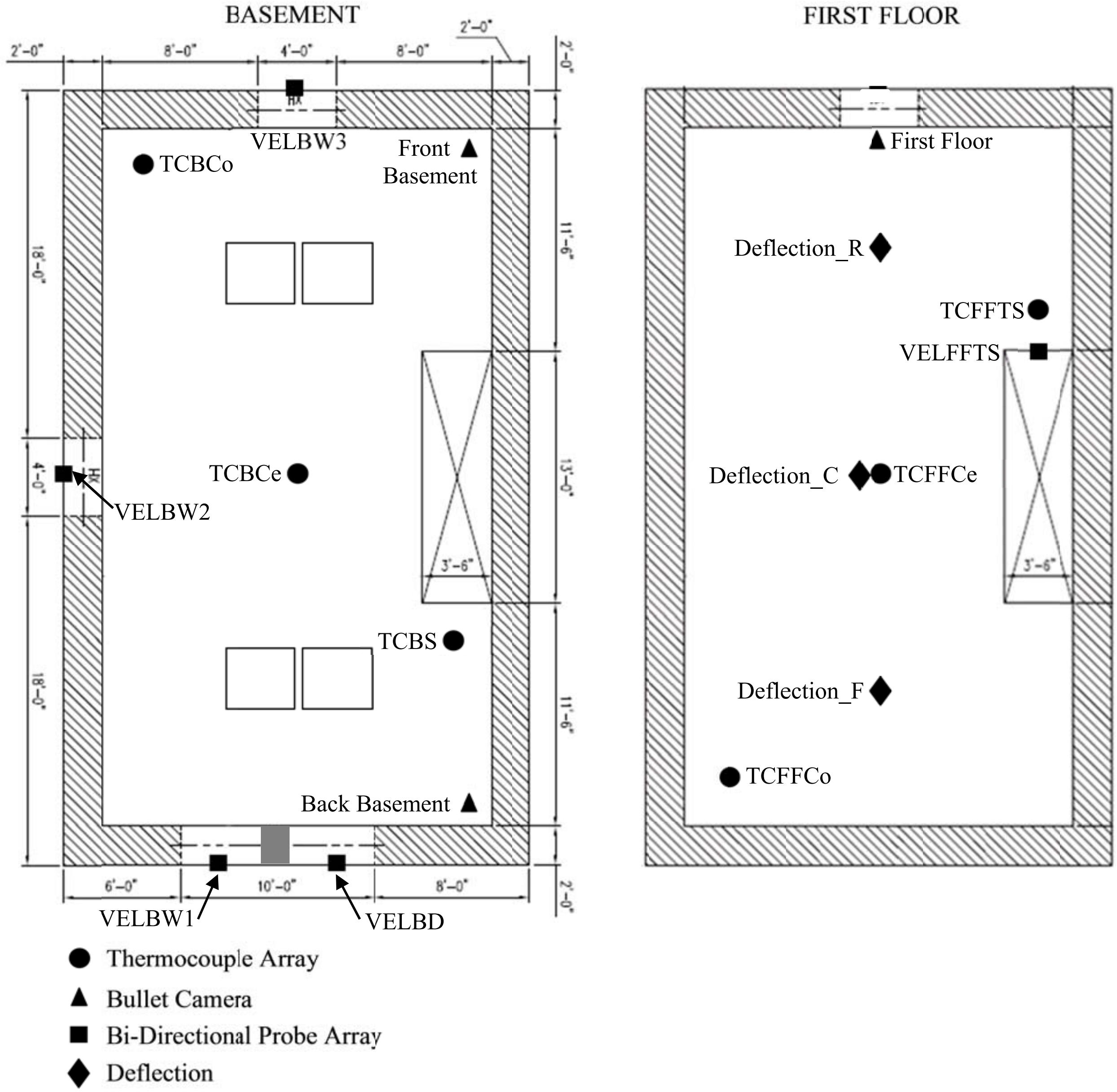

Figure 54. Measurement Locations and Labels

7.1. Experiment 1 – Dimensional Lumber

In this experiment all of the ventilation openings were open prior to ignition and the fire was ignited in the rear fuel package closest to the base of the stairs. The fire spread until the floor system collapsed and then was suppressed. The timeline of events is detailed in Table 25. The results for the experiment are presented in the following sections: observations, temperature, gas velocity, and deflection.

Table 25. Experiment 1 Timeline

Time (s, mm:ss)	Event
0 (0:00)	Ignition
238 (3:58)	Flames attach to the floor system
669 (11:09)	Collapse
675 (11:15)	End of experiment

7.1.1. Observations

The observations are presented as a series of images captured from eight camera locations, six were video cameras and two were thermal imaging cameras. The views were captured at the start of the experiment (0:00, Figure 55), once flames attached to the floor system (3:58, Figure 56), when flames appear at the top of the stairs to the first floor (4:30, Figure 57), and 5 seconds before collapse (11:04, Figure 58).

Figure 55. Experiment 1 video views at 0:00.

Figure 56. Experiment 1 video views at 3:58.

Figure 57. Experiment 1 video views at 4:30.

Figure 58. Experiment 1 video views at 11:04.

7.1.2. Temperature

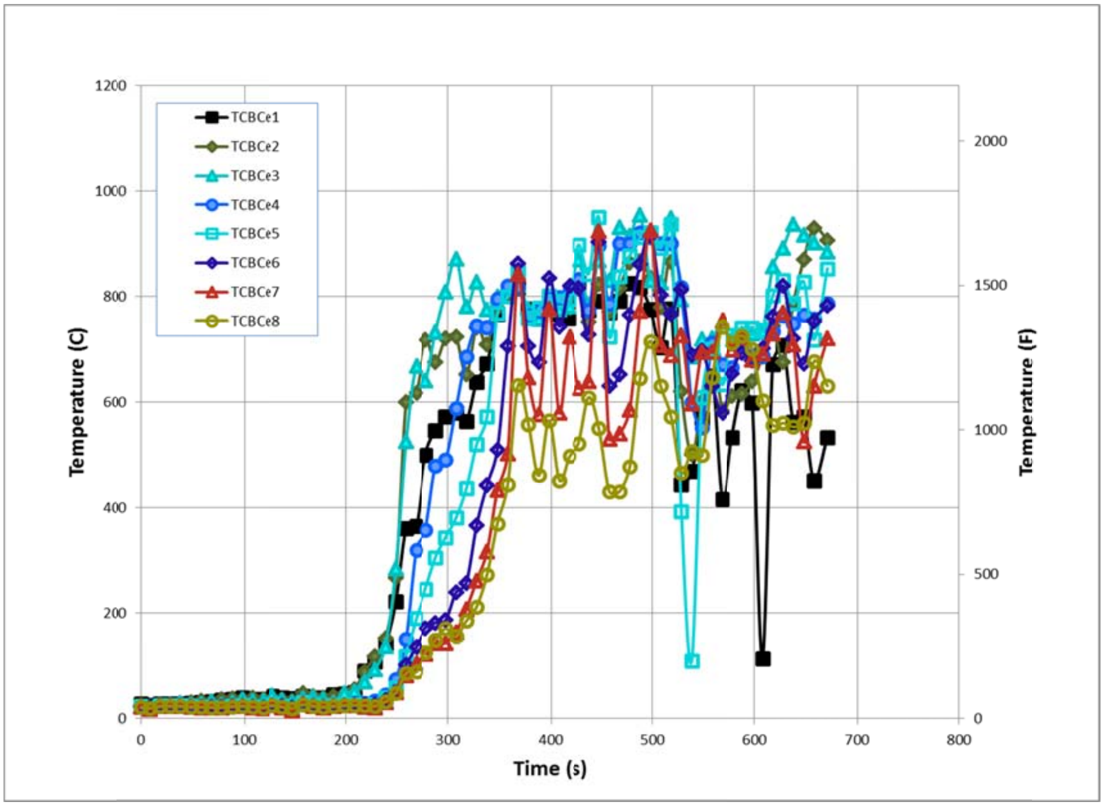

Figure 59. Experiment 1 - Basement Center Temperatures

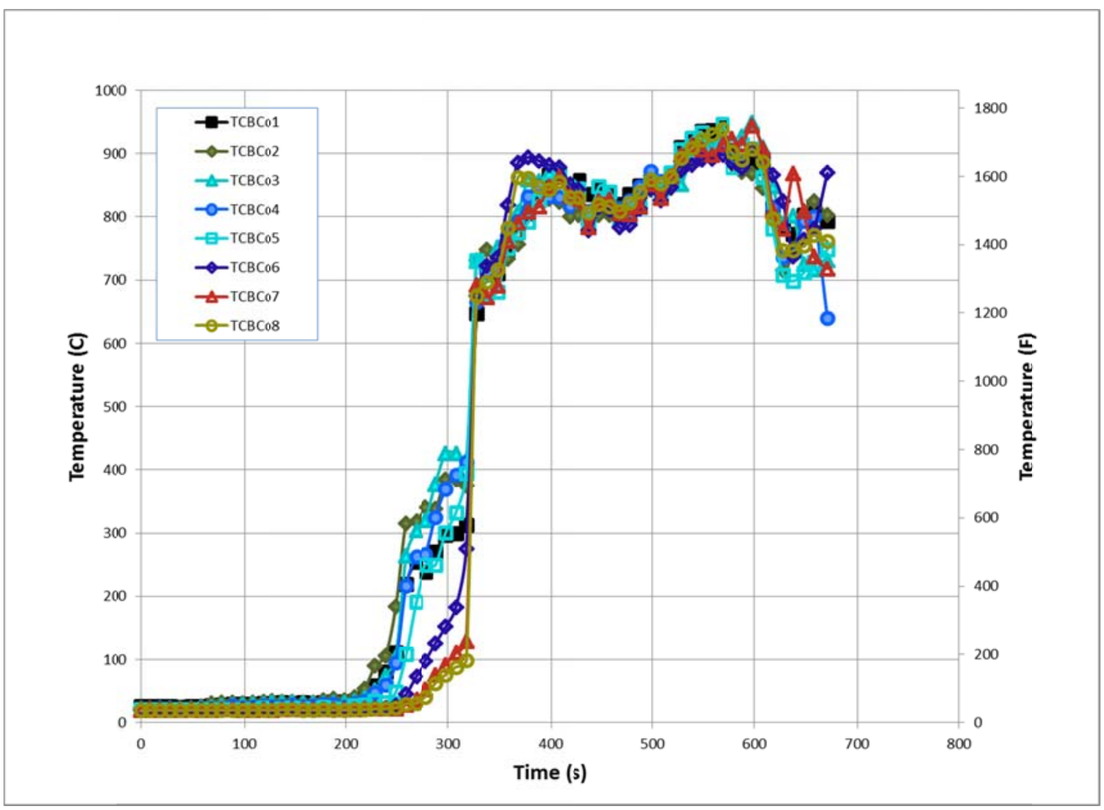

Figure 60. Experiment 1 - Basement Corner Temperatures

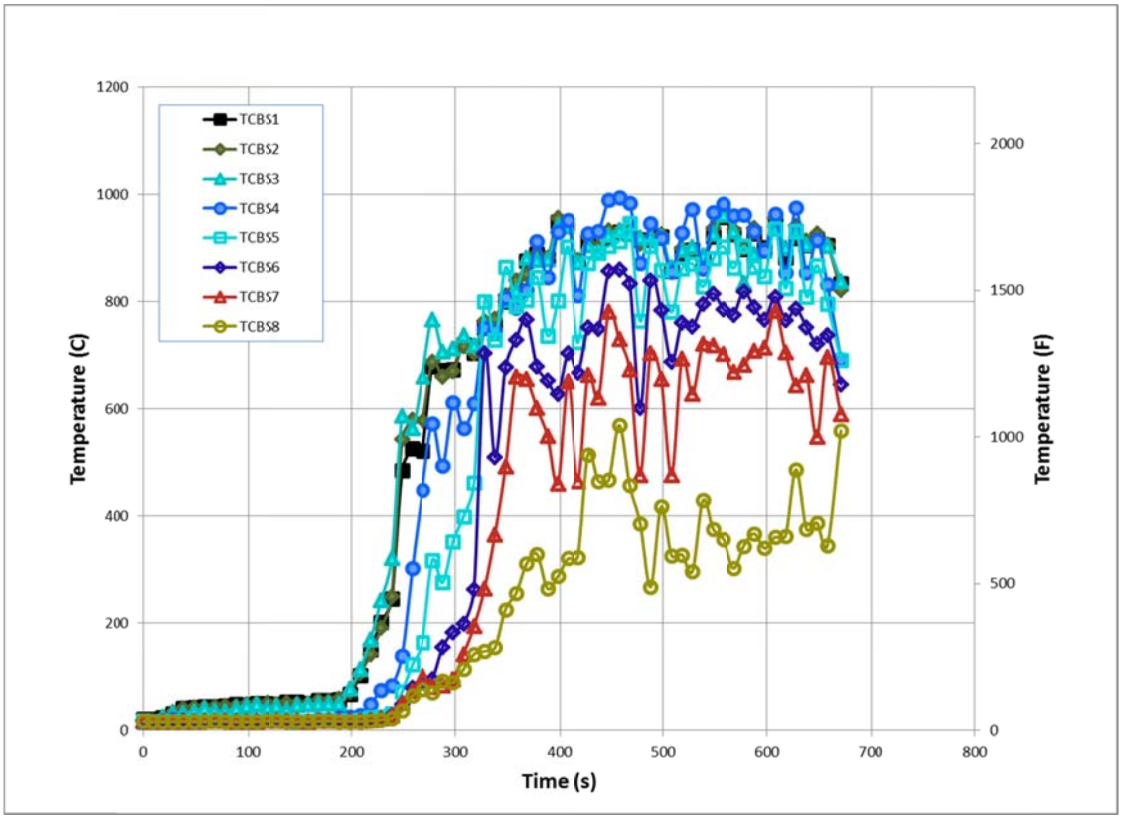

Figure 61. Experiment 1 - Basement Base of Stair Temperatures

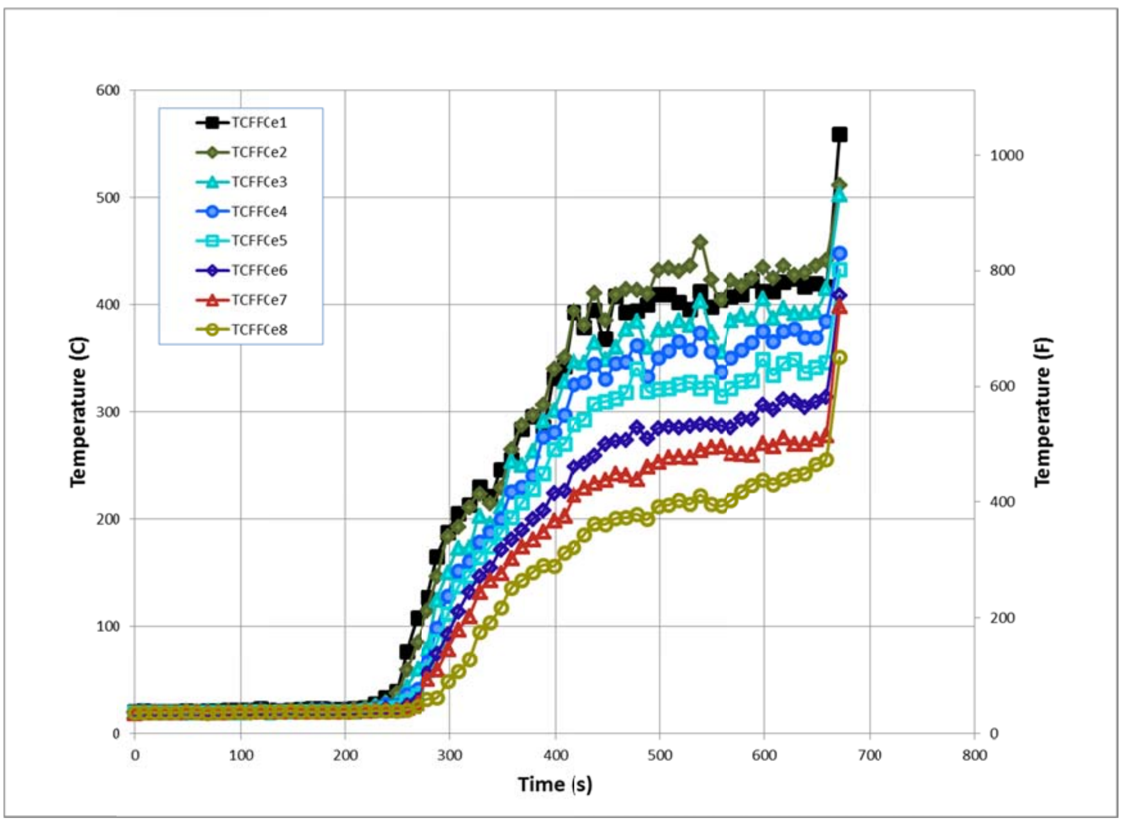

Figure 62. Experiment 1 - First Floor Center Temperatures

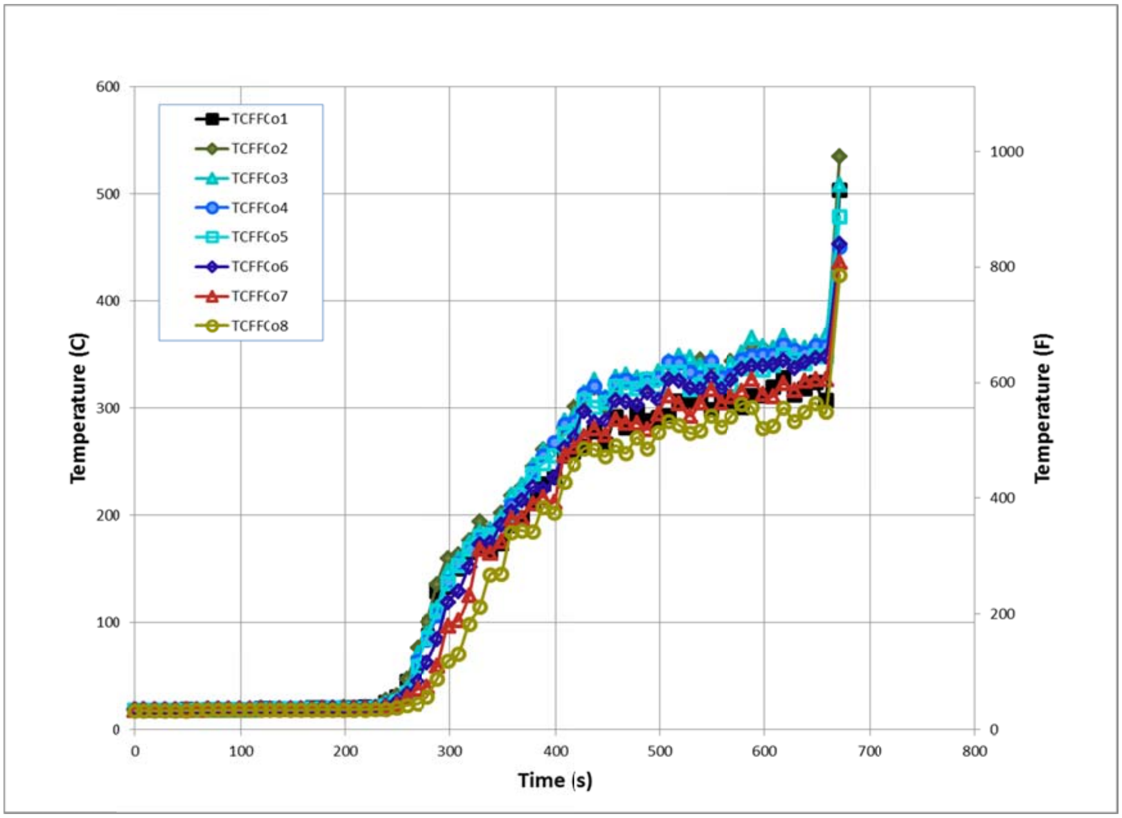

Figure 63. Experiment 1 - First Floor Corner Temperatures

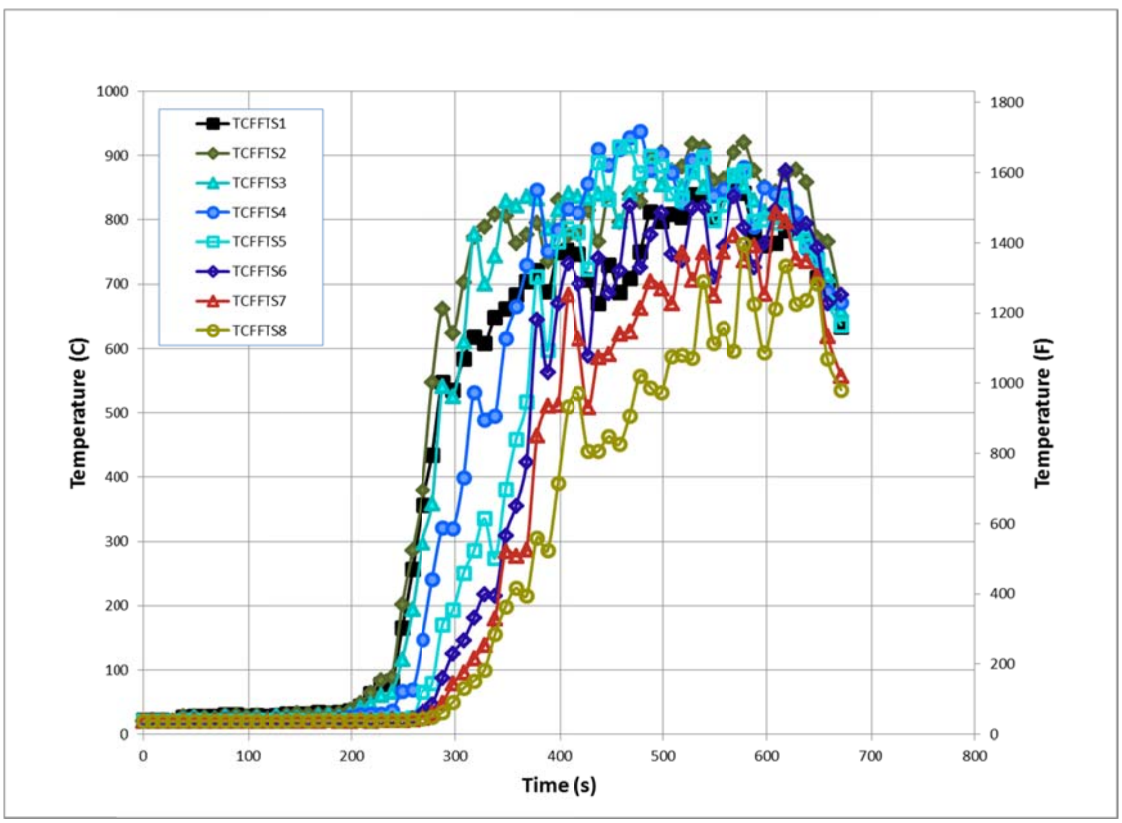

Figure 64. Experiment 1 - First Floor Top of Stair Temperatures

7.1.3. Gas Velocity

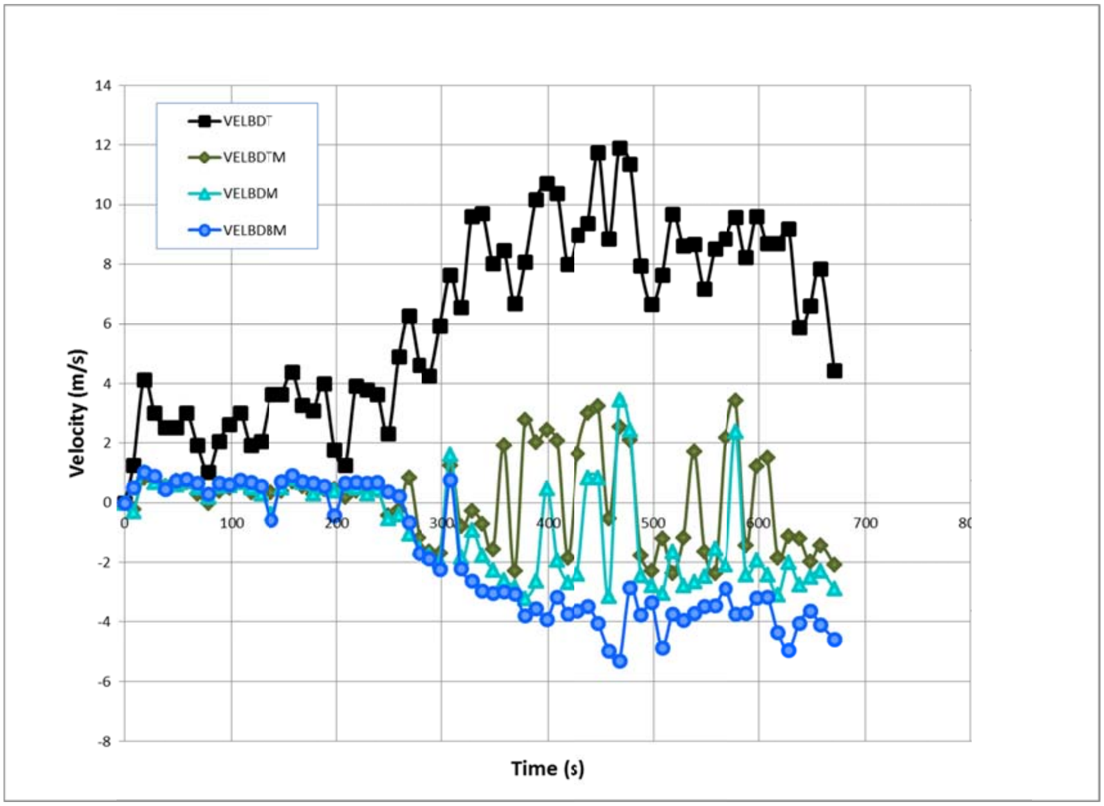

Figure 65. Experiment 1 - Basement Door Velocities

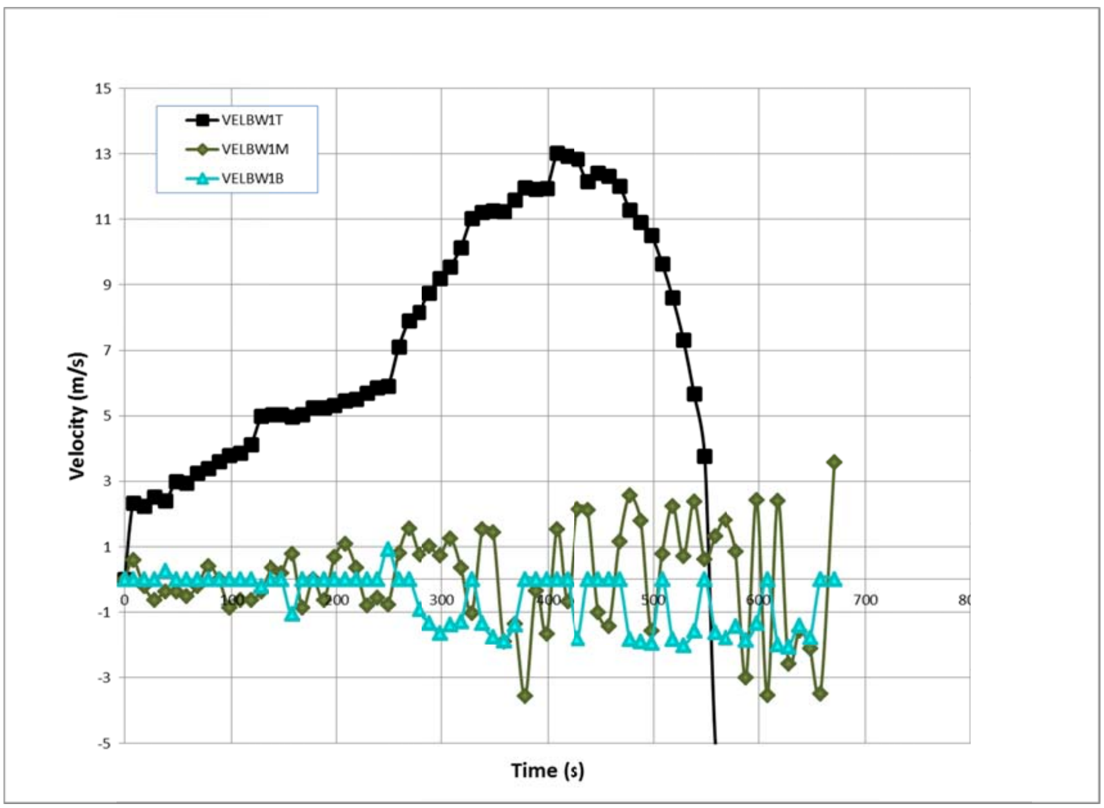

Figure 66. Experiment 1 - Basement Window 1 Velocities

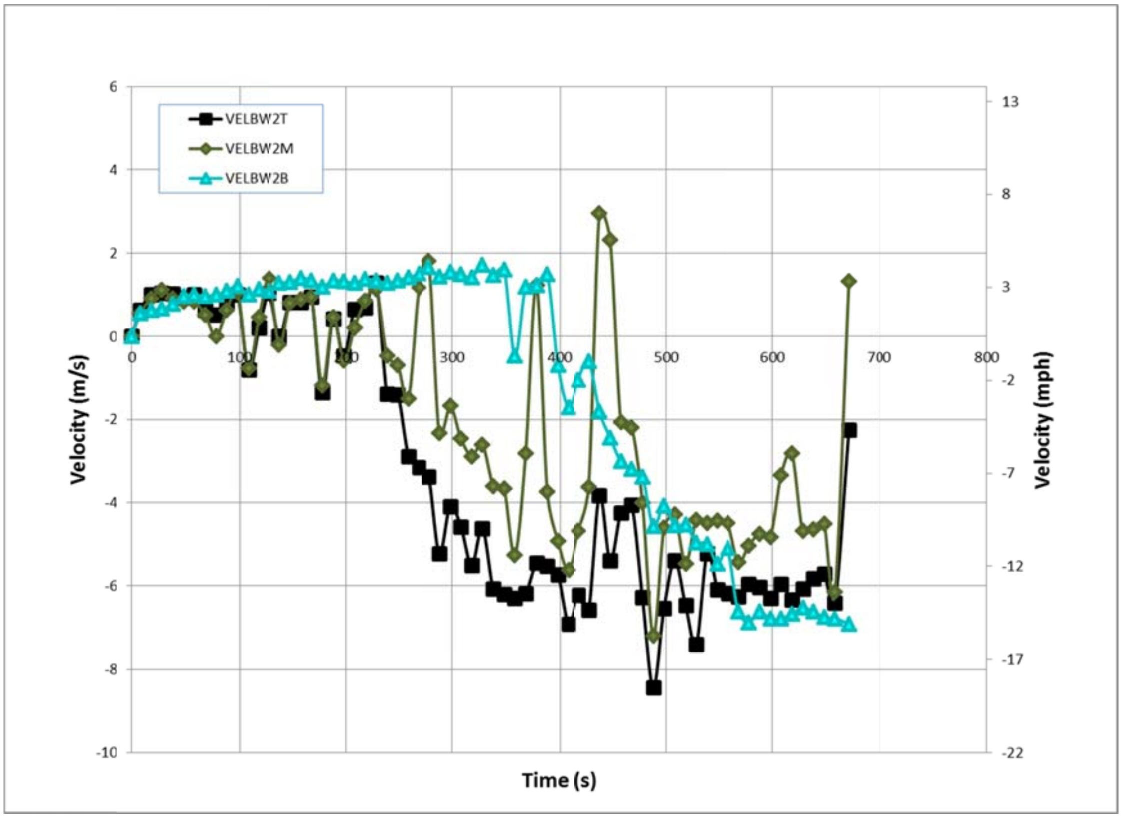

Figure 67. Experiment 1 - Basement Window 2 Velocities

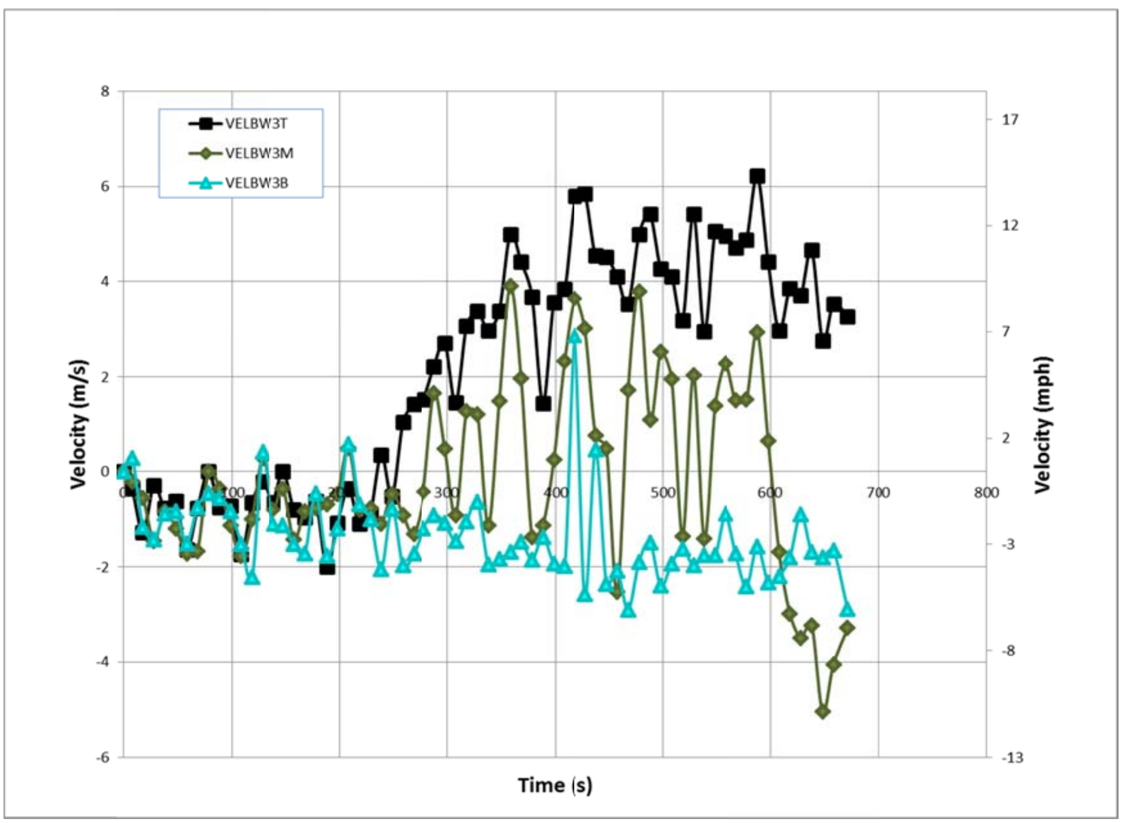

Figure 68. Experiment 1 - Basement Window 3 Velocities

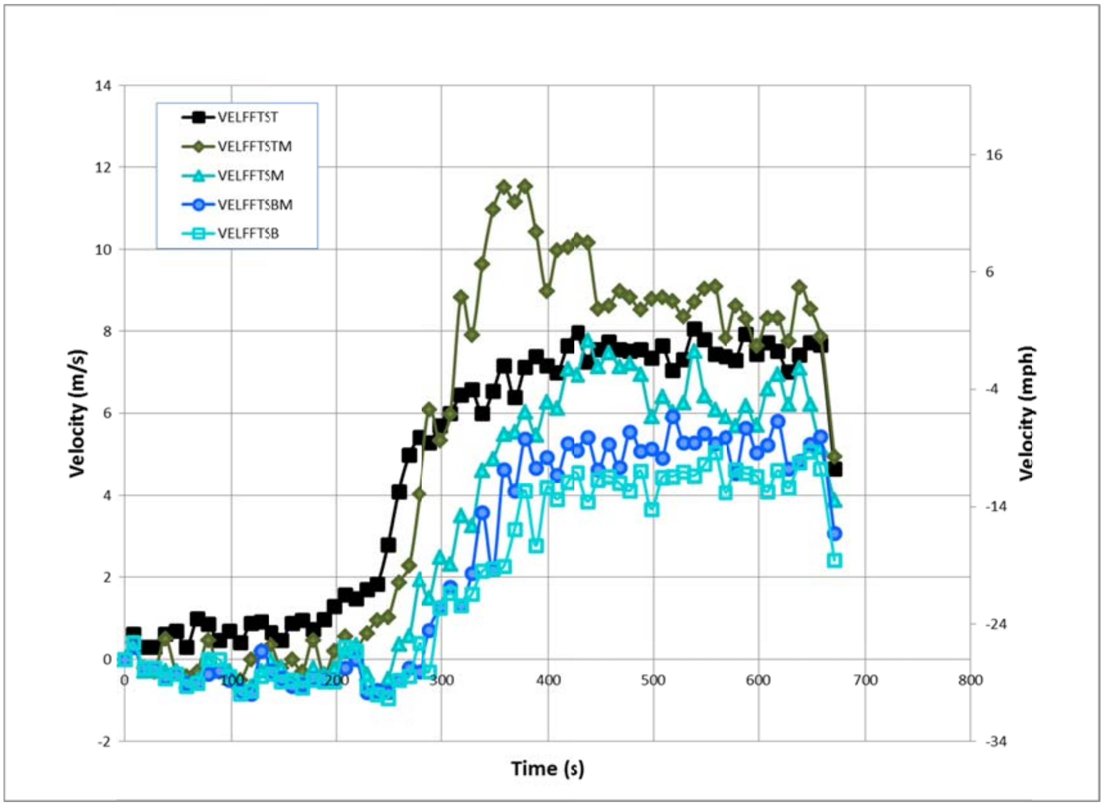

Figure 69. Experiment 1 - First Floor Stair Velocities

7.1.4. Deflection

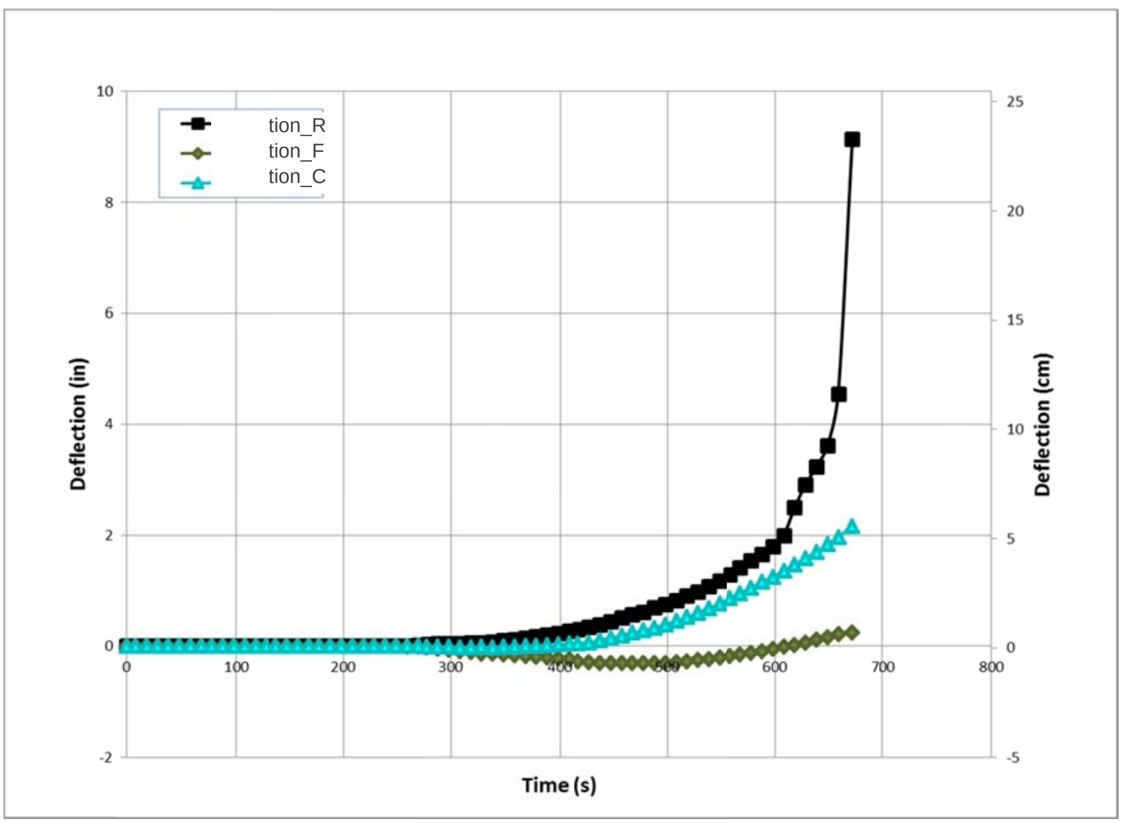

Figure 70. Experiment 1 - Floor System Deflections

7.1.5. Structural Response

The primary structural failure occurred at the rear section of the floor system, local to the initial fire location. A secondary collapse occurred at the center section of the floor system adjacent to the stairway enclosure moments later (Figure 71). The failure mode for the traditional dimensional lumber joists was due to charring of the three fire-exposed sides of the joist which produced a reduction of the joist cross-sectional area. This area reduction of the wood induced joist ruptures (Figure 72, Figure 73 and Figure 74). Failure of the rear section at the joist header condition was also noted due to joist rotation and fastener mechanical separation (Figure 75). The floor system began to progressively deflect from approximately 300 seconds until the end of the test. Experiment 1 induced a collapse of approximately 50 % of the total floor structure (Figure 76). The collapse time for the Experiment 1 was 11:09 after ignition. The collapse time respective of the structural element fire involvement for Experiment 1 was 7:11.

Figure 71 Collapse of ruptured joist at center span adjacent to span.

Figure 72 Partial rupture of joists at center span.

Figure 73 Partial rupture of joists at center span.

Figure 74 Cross section of ruptured joist from rear section of floor system.

Figure 75 Connection mechanical separation at rear section of floor system header support condition.

Figure 76 Exterior view of percentage of collapsed area.

7.2. Experiment 2 – Dimensional Lumber

In this experiment all of the ventilation openings were closed prior to ignition and the fire was ignited in the rear fuel package closest to the base of the stairs. The ventilation openings were opened sequentially to simulate fire department operations. The fire spread until the floor system collapsed and then was suppressed. The timeline of events is detailed in Table 26. The results for the experiment are presented in the following sections: observations, temperature, gas velocity, and deflection.

Table 26. Experiment 2 Timeline

Time (s, mm:ss)	Event
0 (0:00)	Ignition
120 (2:00)	Flames attach to the floor system
480 (8:00)	First floor door opened
600 (10:00)	Back basement door opened
630 (10:30)	Back basement window opened
660 (11:00)	Side basement window opened
720 (11:30)	Front basement window opened
765 (12:45)	Collapse
770 (12:50)	End of experiment

7.2.1. Observations

The observations are presented as a series of images captured from eight camera locations, seven were video cameras and one was a thermal imaging camera. The views were captured at the start of the experiment (0:00, Figure 77), once flames attached to the floor system (2:00, Figure 78), when there was zero visibility on the first floor (2:56, Figure 79), 5 seconds after the basement door and first window are opened (10:35, Figure 80) and 5 seconds before collapse (12:40, Figure 81).

Figure 77. Experiment 2 video views at 0:00.

Figure 78. Experiment 2 video views at 2:00.

Figure 79. Experiment 2 video views at 2:56.

Figure 80. Experiment 2 video views at 10:35.

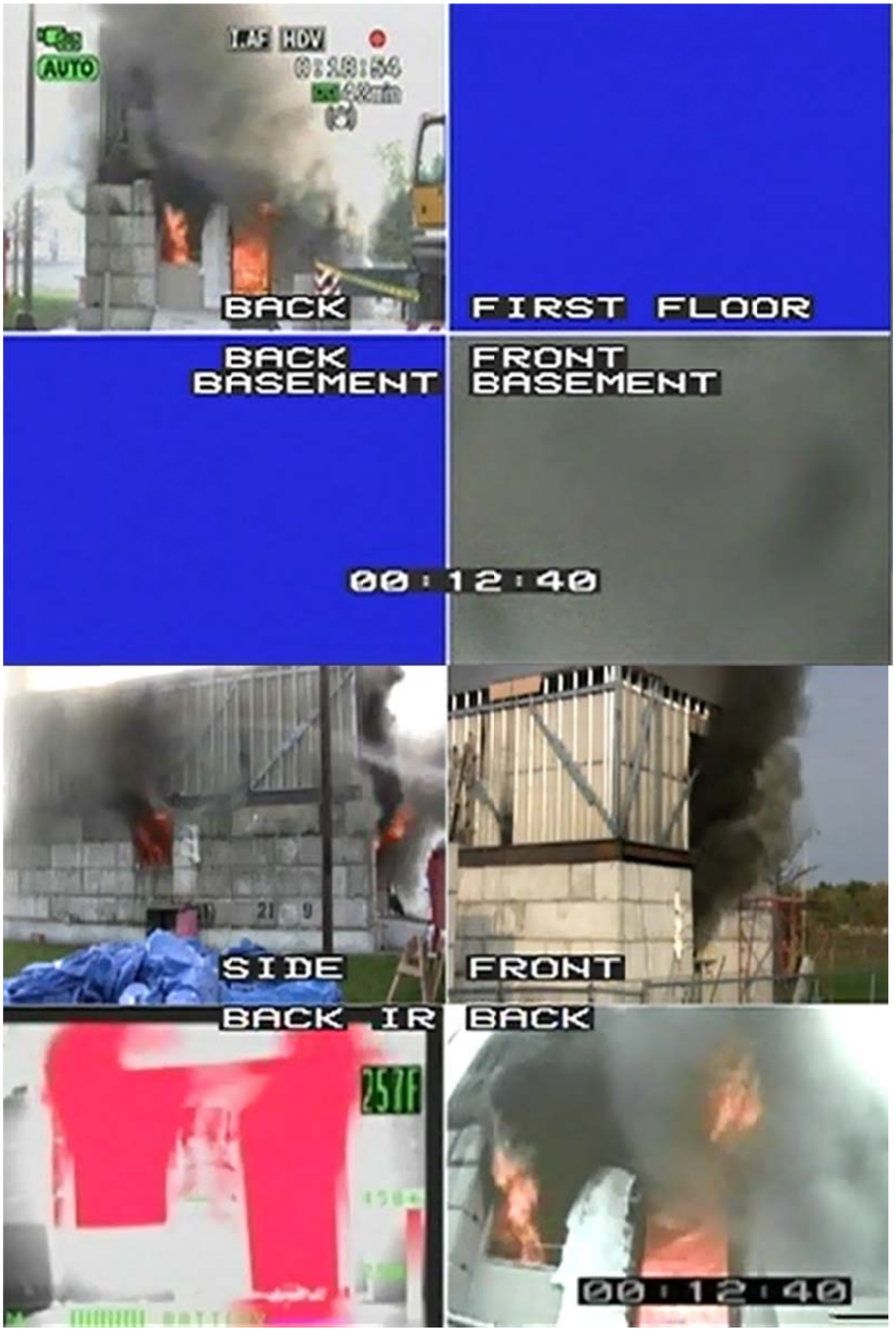

Figure 81. Experiment 2 video views at 12:40.

7.2.2. Temperature

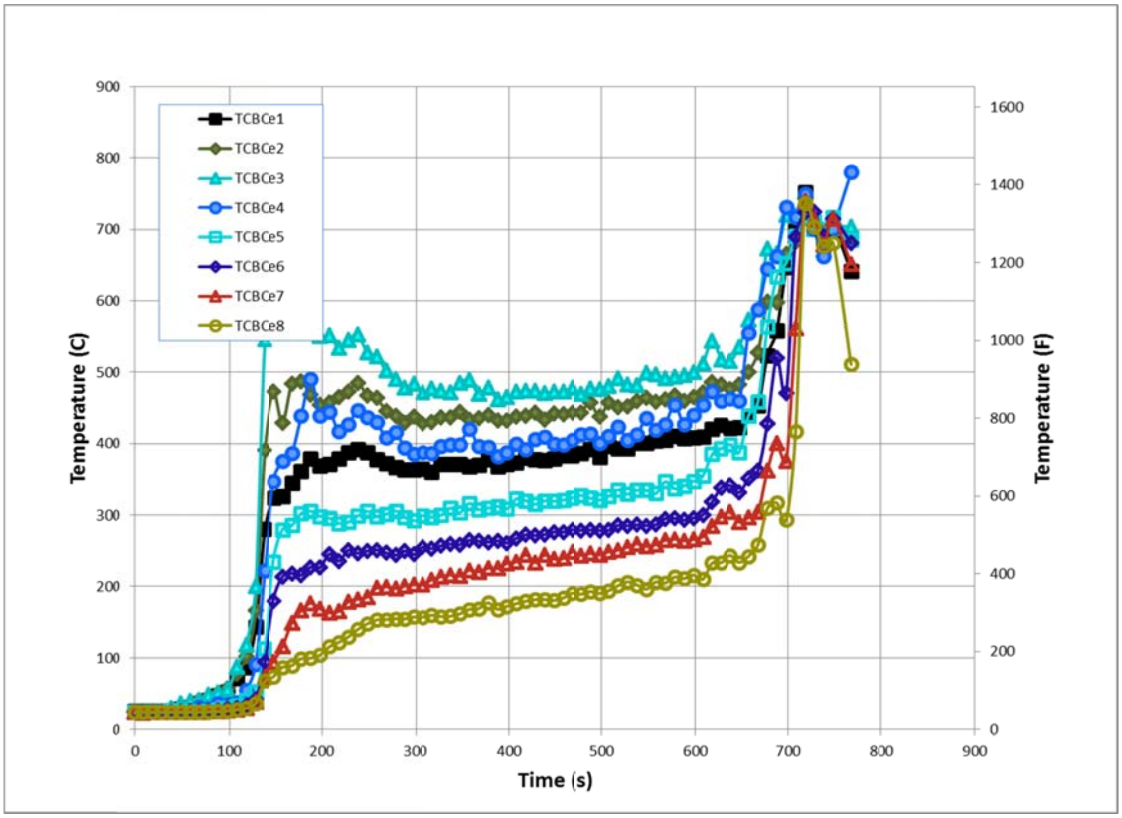

Figure 82. Experiment 2 - Basement Center Temperatures

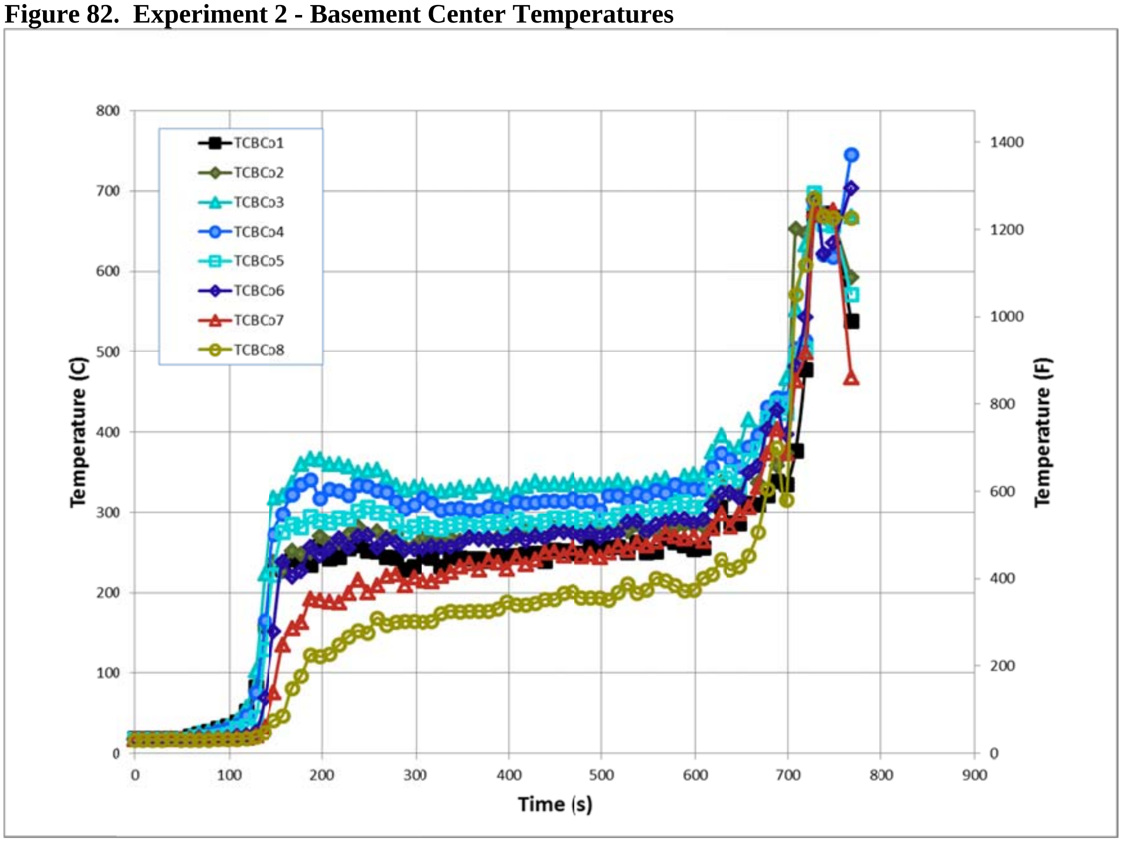

Figure 83. Experiment 2 - Basement Corner Temperatures

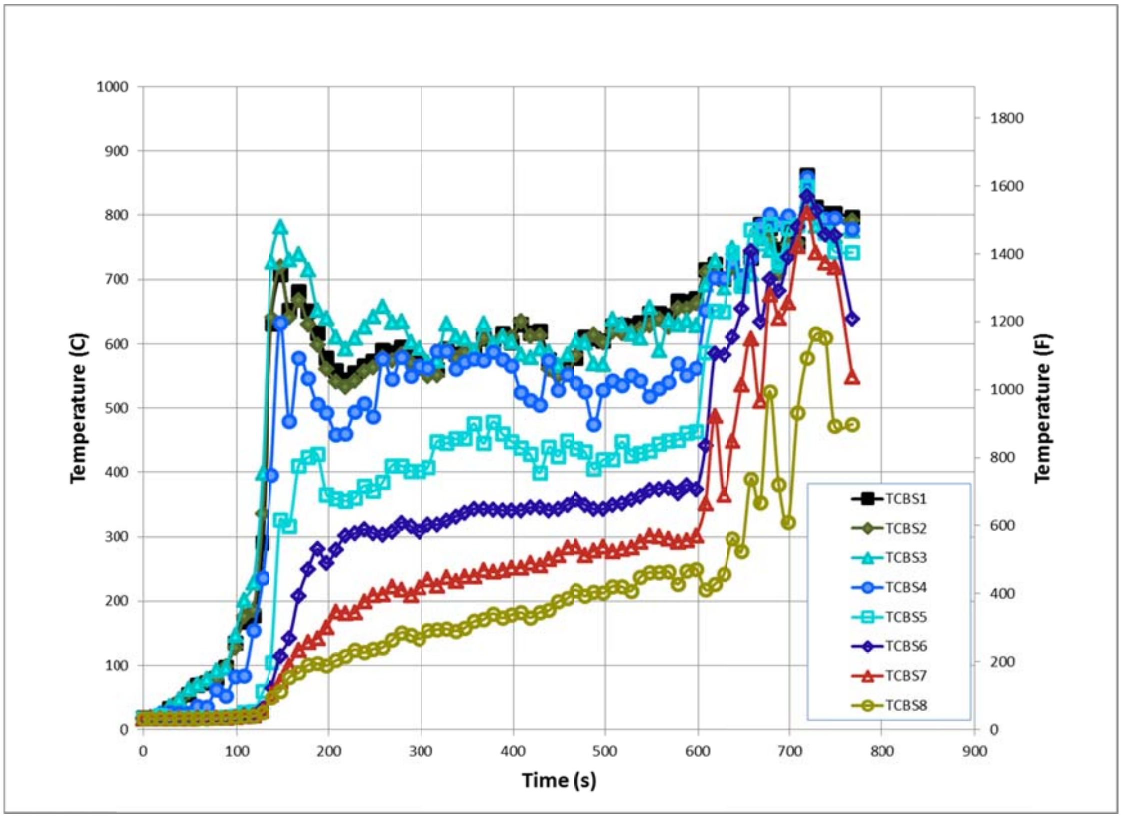

Figure 84. Experiment 2 - Basement Base of Stair Temperatures

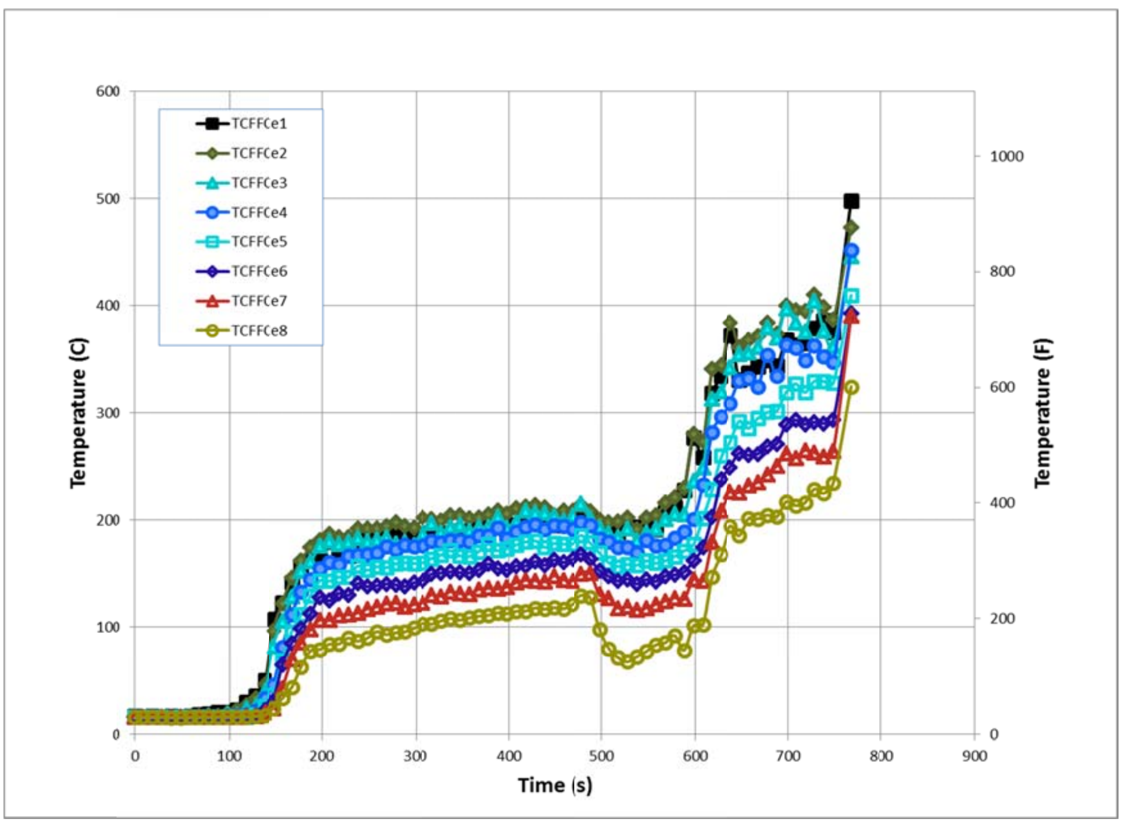

Figure 85. Experiment 2 – First Floor Center Temperatures

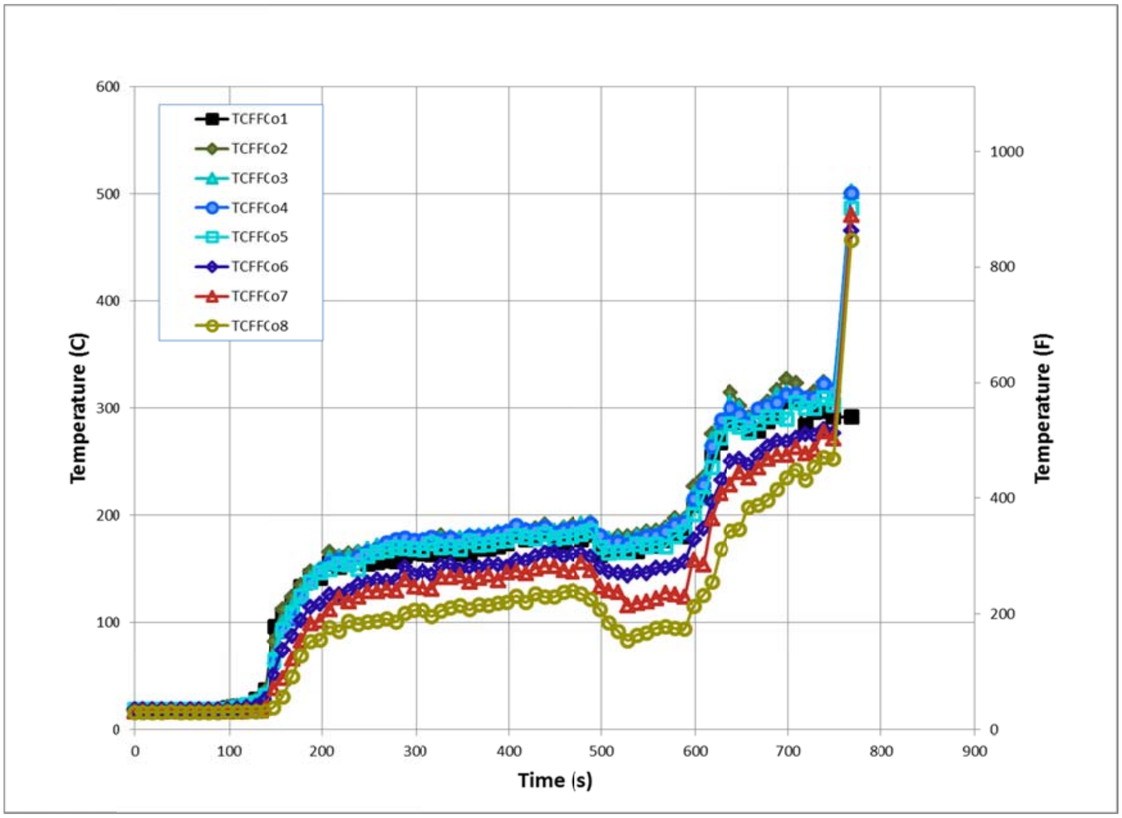

Figure 86. Experiment 2 – First Floor Corner Temperatures

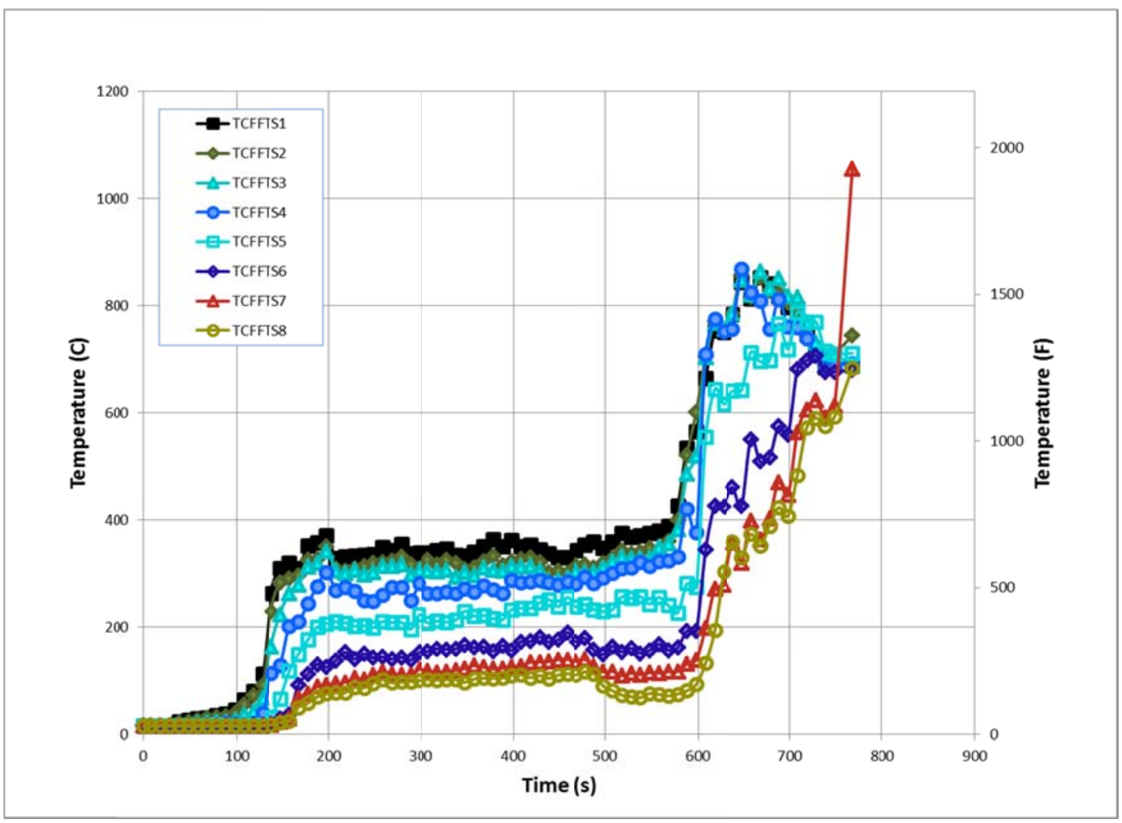

Figure 87. Experiment 2 – First Floor Top of Stair Temperatures

7.2.3. Gas Velocity

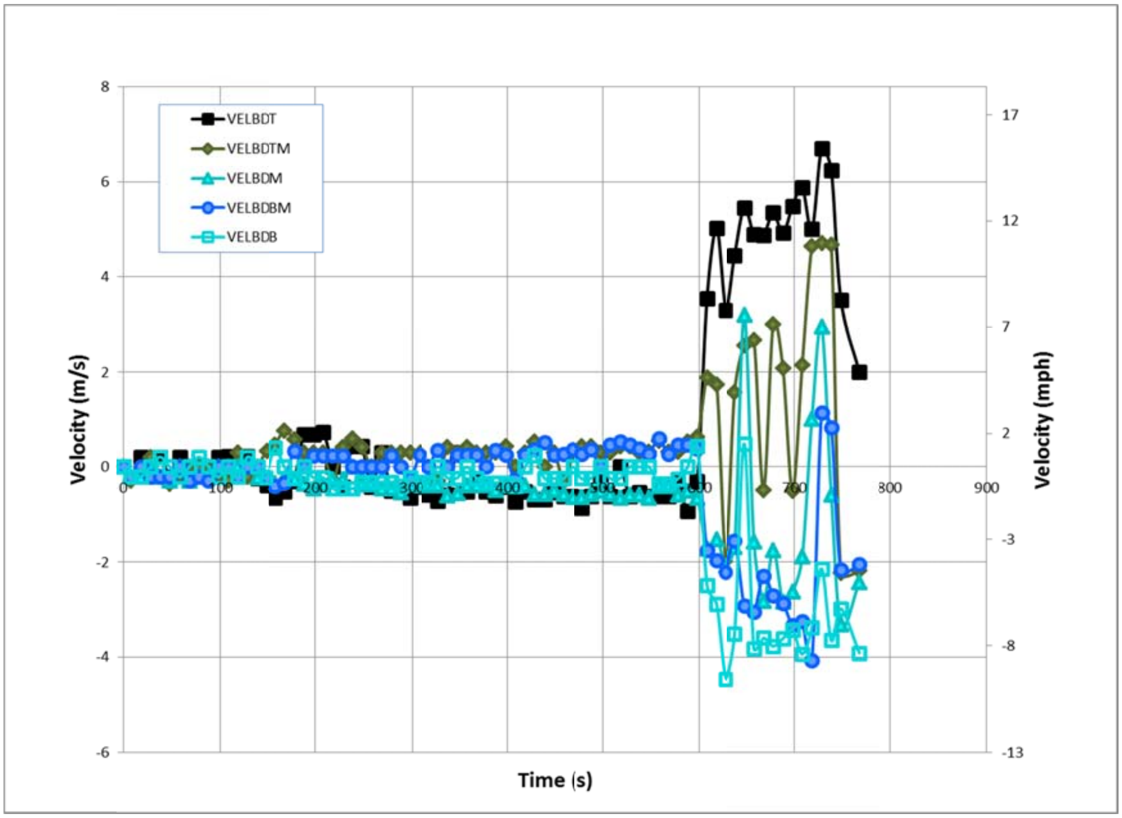

Figure 88. Experiment 2 - Basement Door Velocities

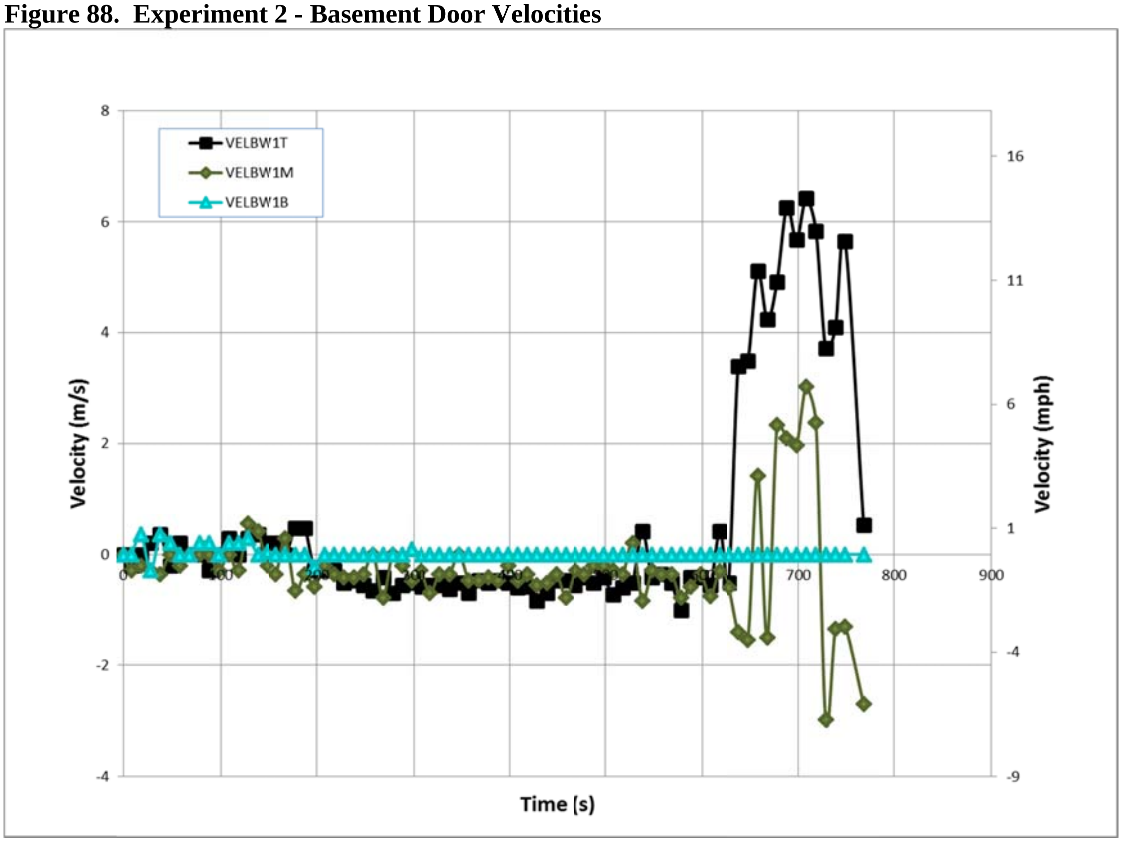

Figure 89. Experiment 2 - Basement Window 1 Velocities

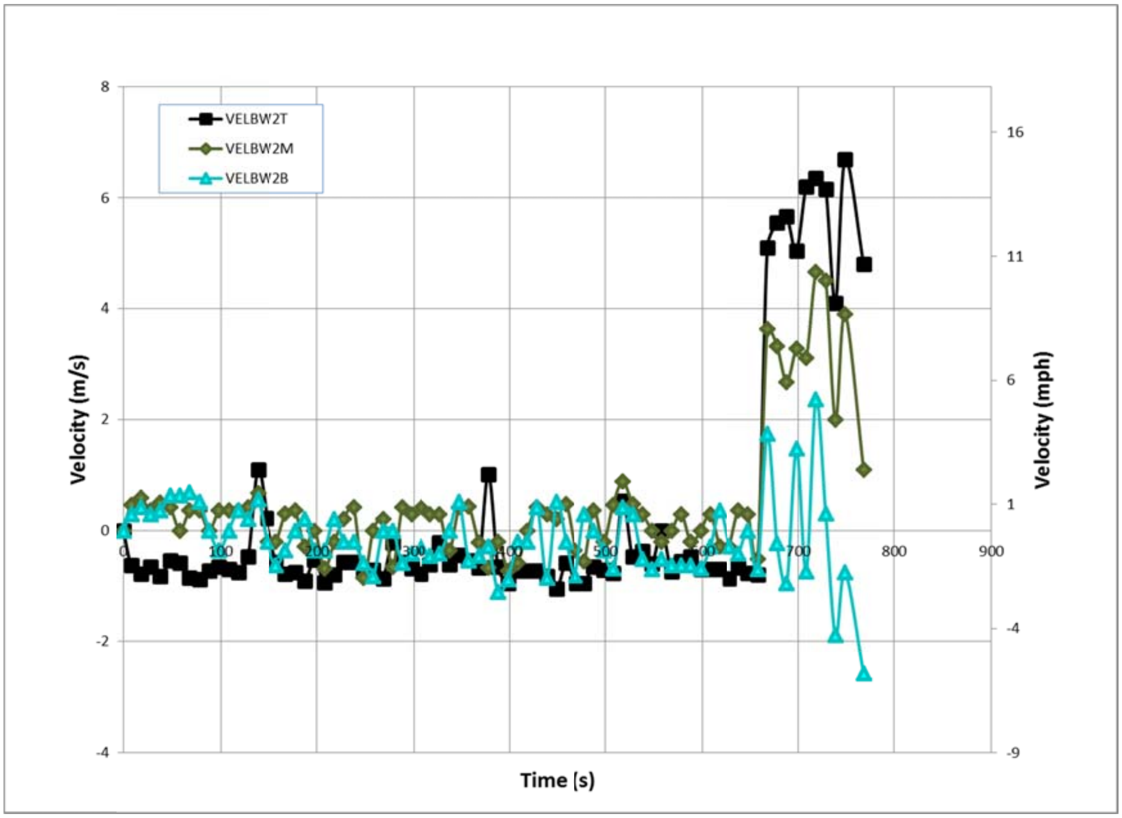

Figure 90. Experiment 2 - Basement Window 2 Velocities

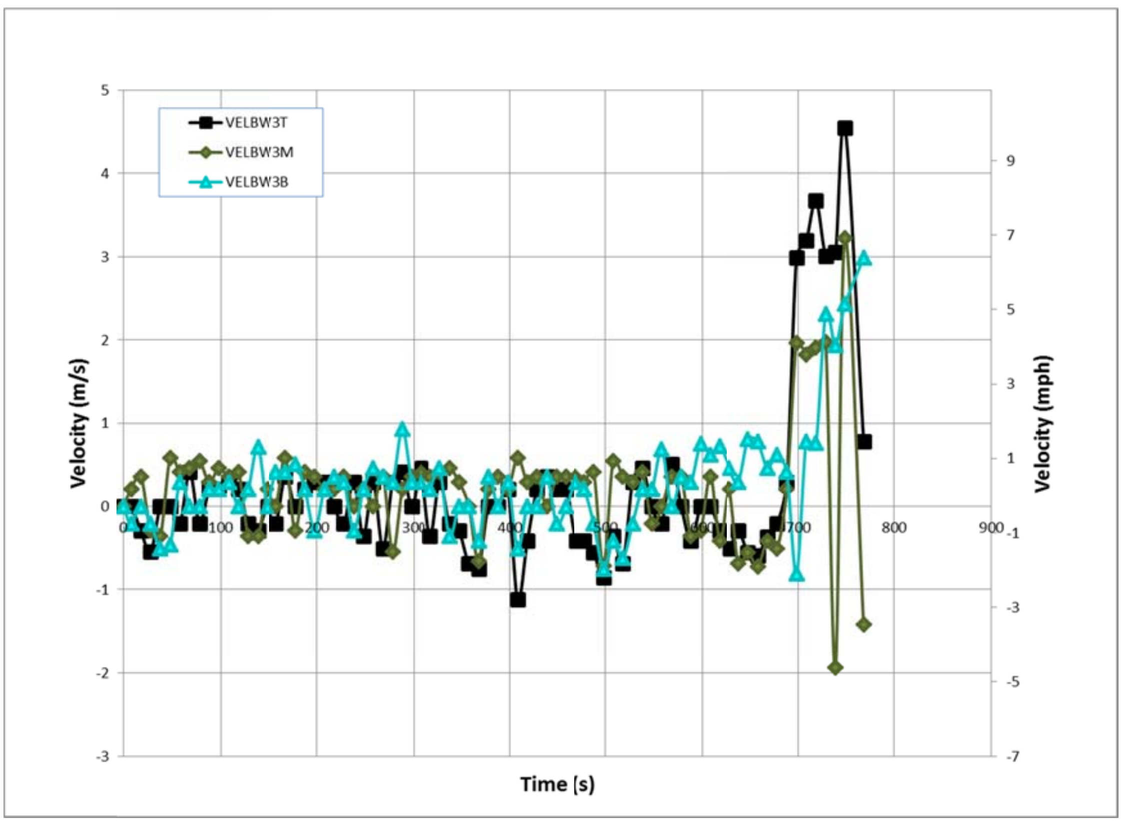

Figure 91. Experiment 2 - Basement Window 3 Velocities

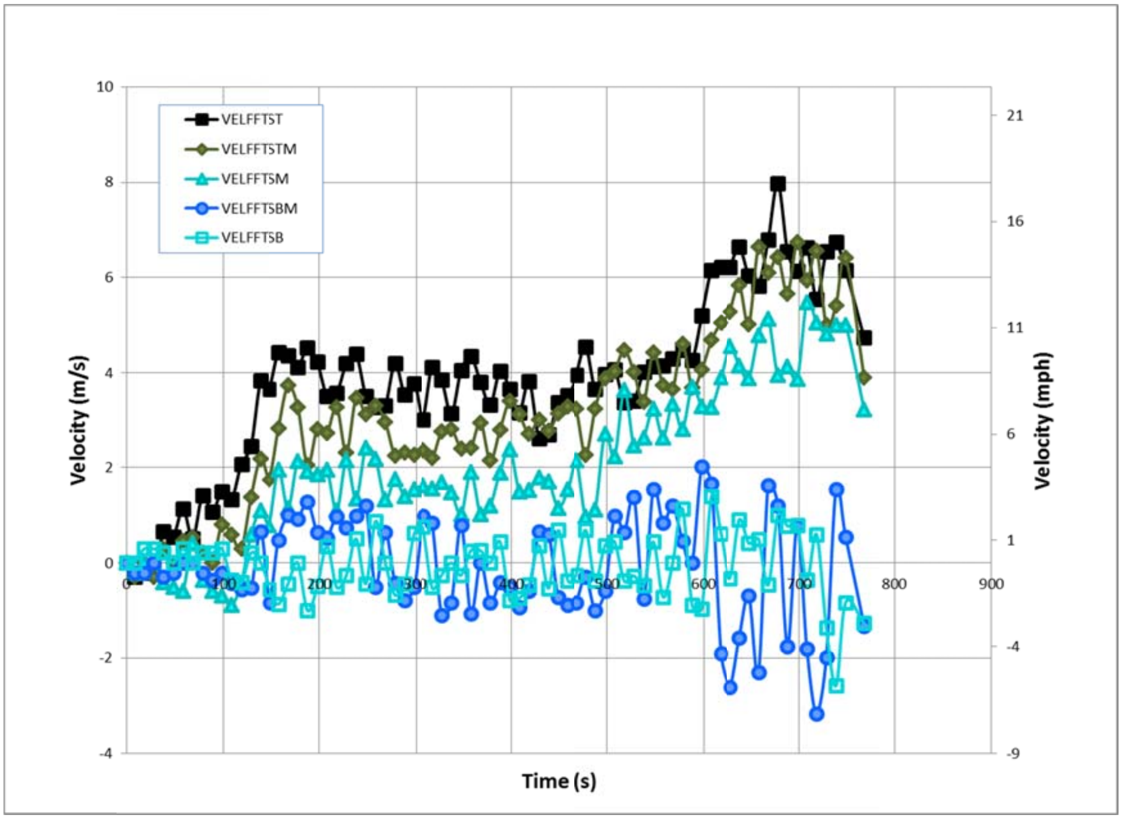

Figure 92. Experiment 2 - First Floor Stair Velocities

7.2.4. Deflection

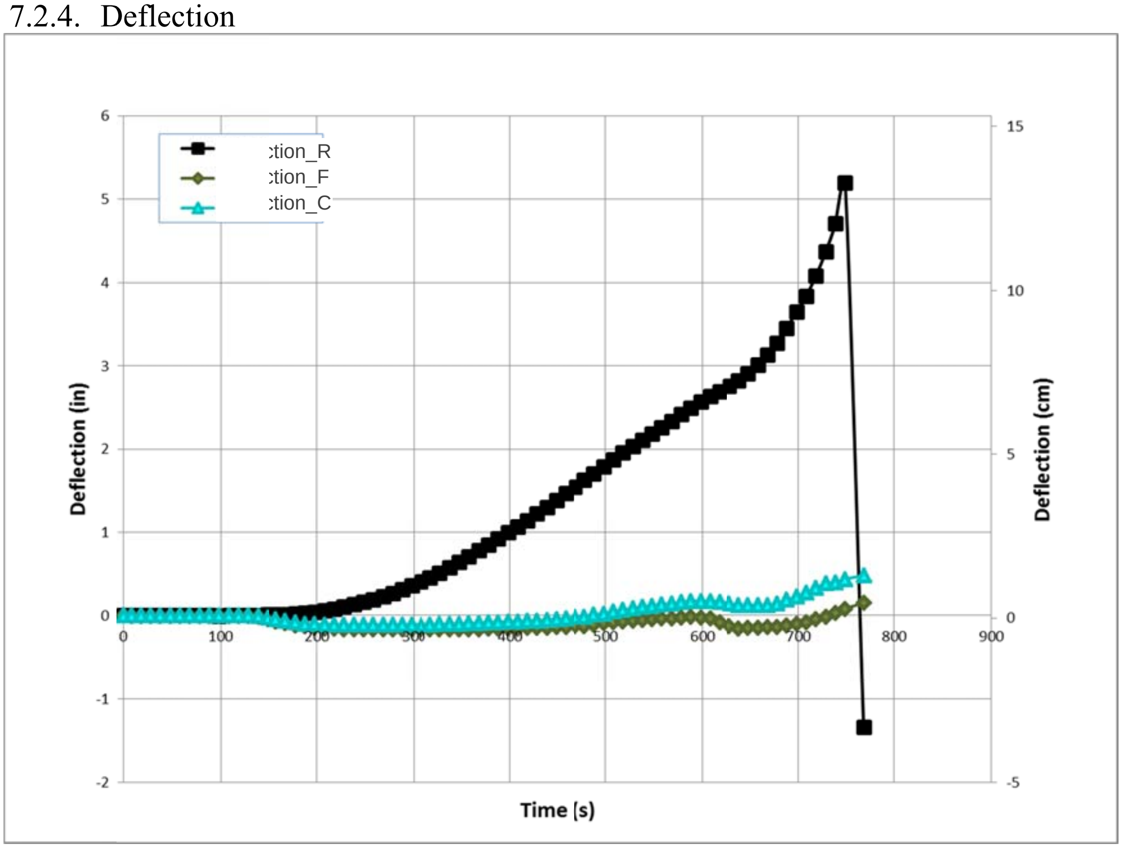

Figure 93. Experiment 2 - Floor System Deflections

7.2.5. Structural Response

The primary structural failure occurred at the rear section of the floor system, local to the initial fire location. A secondary collapse occurred at the center section of the floor system adjacent to the stairway enclosure moments later (Figure 94 and Figure 95). The failure mode for the traditional dimensional lumber joists was due to charring of the three fire-exposed sides of the joist which produced a reduction of the joist cross-sectional area. This area reduction of the wood induced joist ruptures (Figure 96 and Figure 97). Failure of the rear section at the joist header condition was also noted due to joist rotation and fastener mechanical separation (Figure 98). The floor system began to progressively deflect from approximately 150 seconds until the end of the test. Experiment 2 induced a collapse of approximately 50 % of the total floor structure (Figure 99). The collapse time for Experiment 2 was 12:45 after ignition. The collapse time respective of the structural element fire involvement for Experiment 2 was 10:45.

Figure 94 Collapse of ruptured joist at center section of floor system.

Figure 95 Collapse of ruptured joist at center section of floor system.

Figure 96 Cross section of ruptured joist from rear section joist.

Figure 97 Cross section of ruptured joist from rear section joist adjacent to the stairway.

Figure 98 Connections mechanical separation at rear span header support condition.

Figure 99 Exterior view of percentage of collapsed area.

7.3. Experiment 3 – Engineered I Joist

In this experiment all of the ventilation openings were open prior to ignition and the fire was ignited in the rear fuel package closest to the base of the stairs. The fire spread until the floor system collapsed and then was suppressed. The timeline of events is detailed in Table 27. The results for the experiment are presented in the following sections: observations, temperature, gas velocity, and deflection.

Table 27. Experiment 3 Timeline

Time (s, mm:ss)	Event
0 (0:00)	Ignition
195 (3:15)	Flames attach to the floor system
360 (6:00)	Collapse
375 (6:15)	End of experiment

7.3.1. Observations

The observations are presented as a series of images captured from eight camera locations, seven were video cameras and one was a thermal imaging camera. The views were captured at the start of the experiment (0:00, Figure 100), once flames attached to the floor system (3:15, Figure 101), when flames are seen exiting the doorway to the first floor (3:28, Figure 102), and 5 seconds before collapse (5:55, Figure 103).

Figure 100. Experiment 3 video views at 0:00.

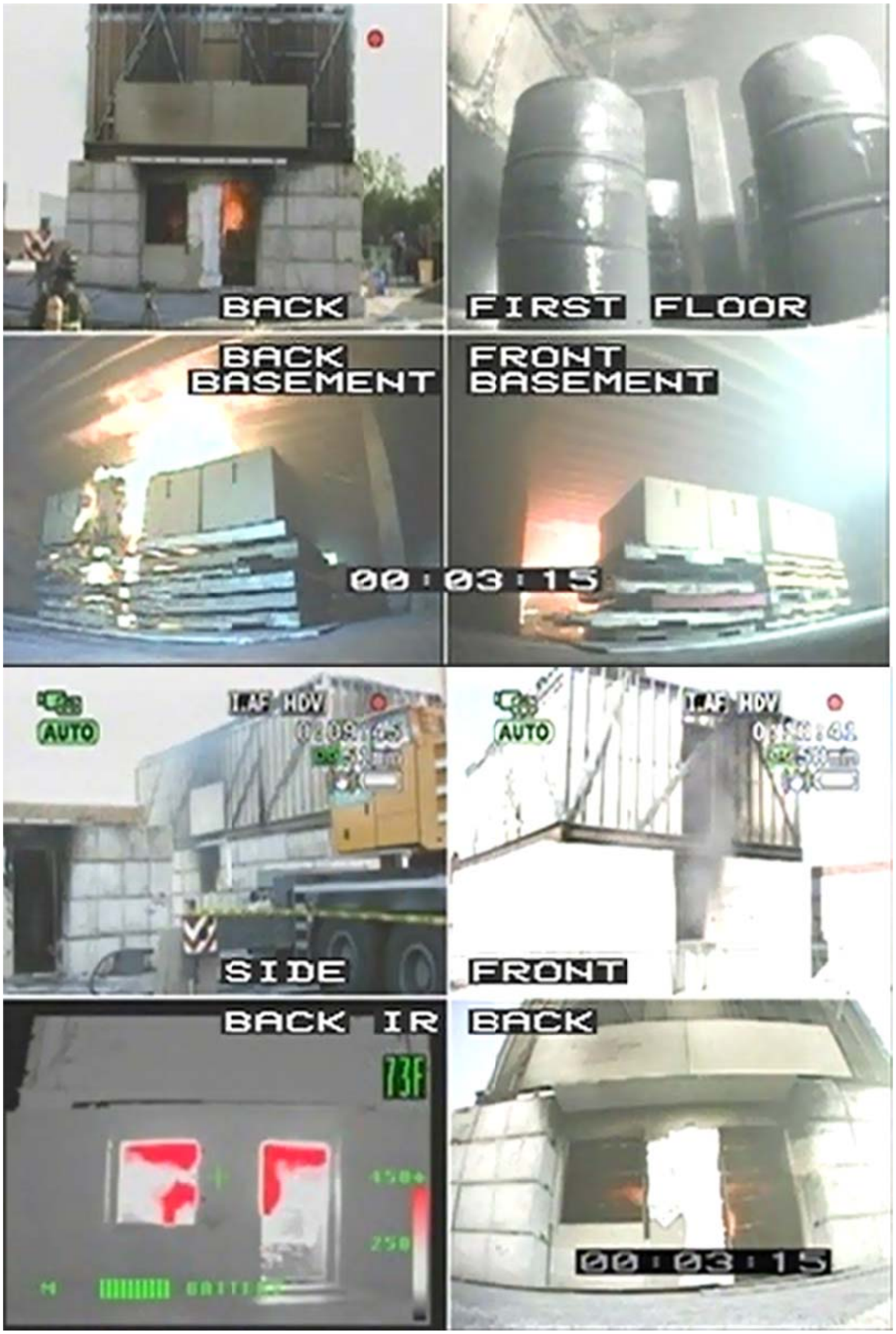

Figure 101. Experiment 3 video views at 3:15.

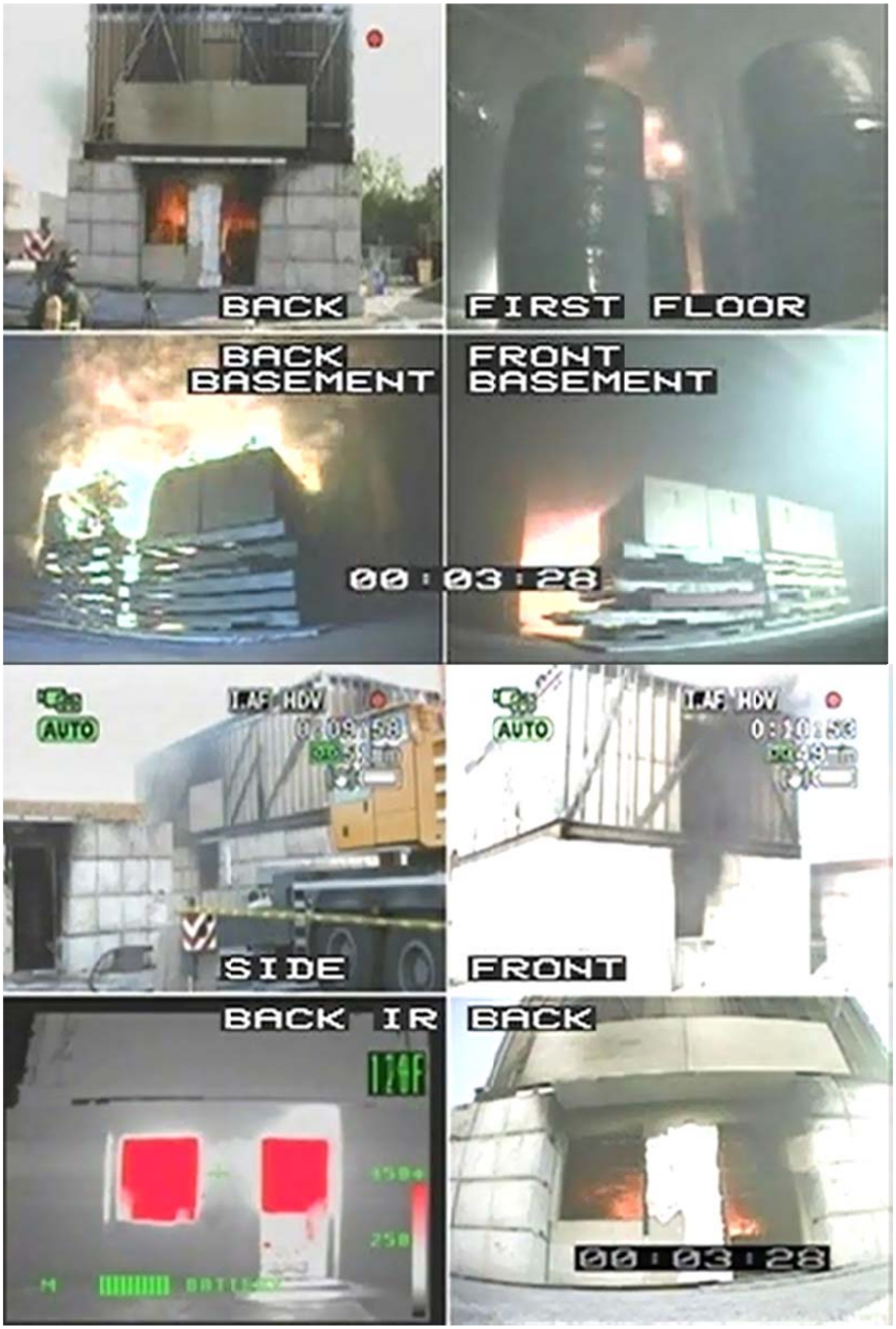

Figure 102. Experiment 3 video views at 3:28.

Figure 103. Experiment 3 video views at 5:55.

7.3.2. Temperature

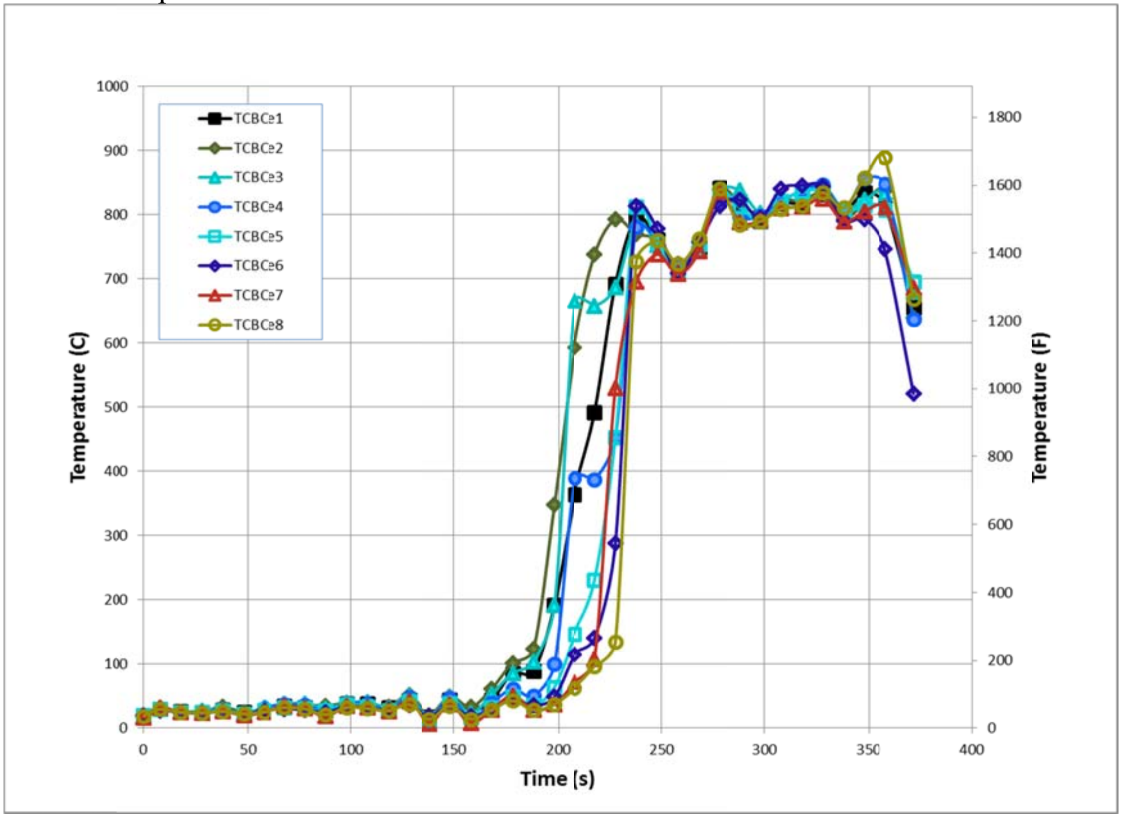

Figure 104. Experiment 3 - Basement Center Temperatures

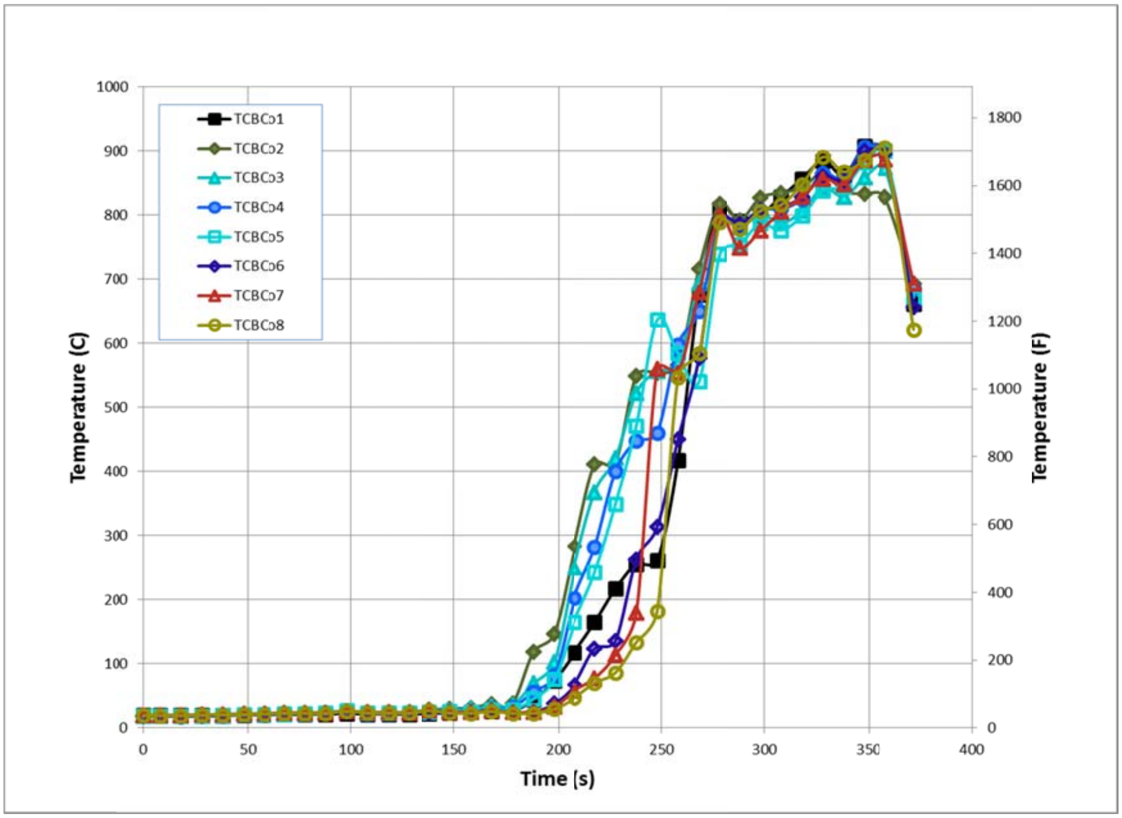

Figure 105. Experiment 3 - Basement Corner Temperatures

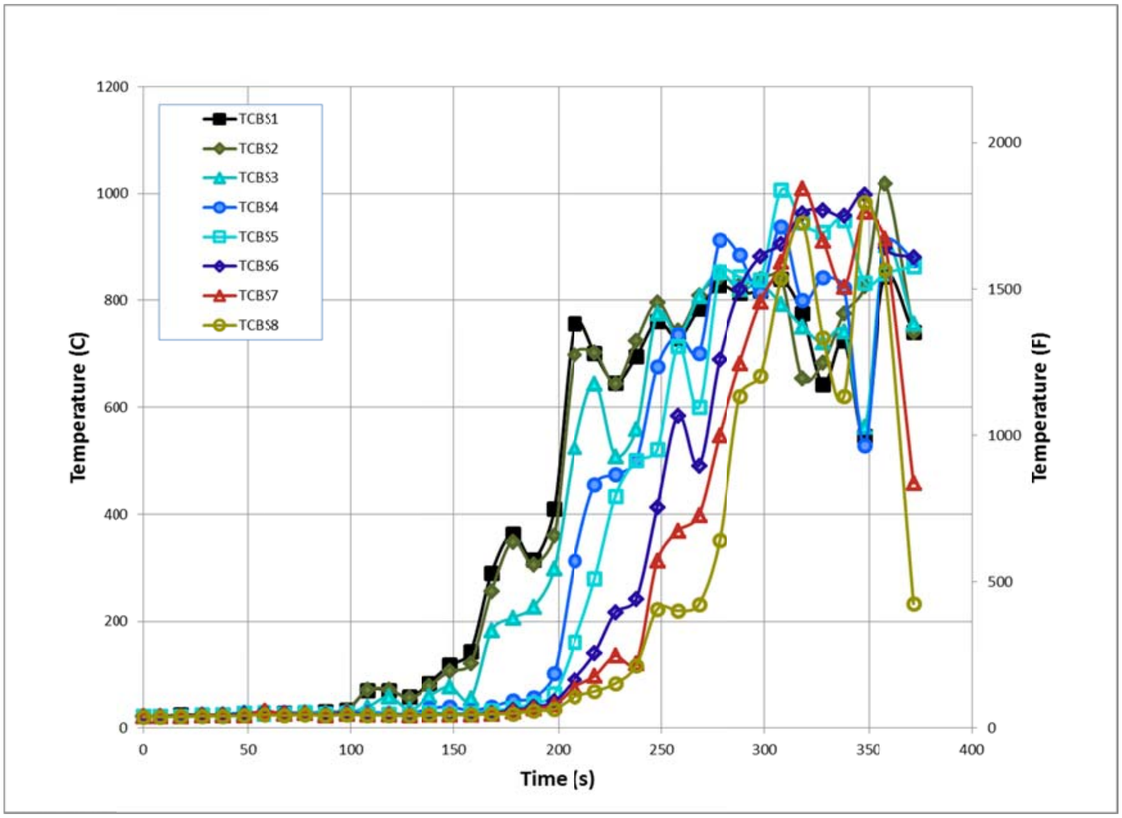

Figure 106. Experiment 3 - Basement Base of Stair Temperatures

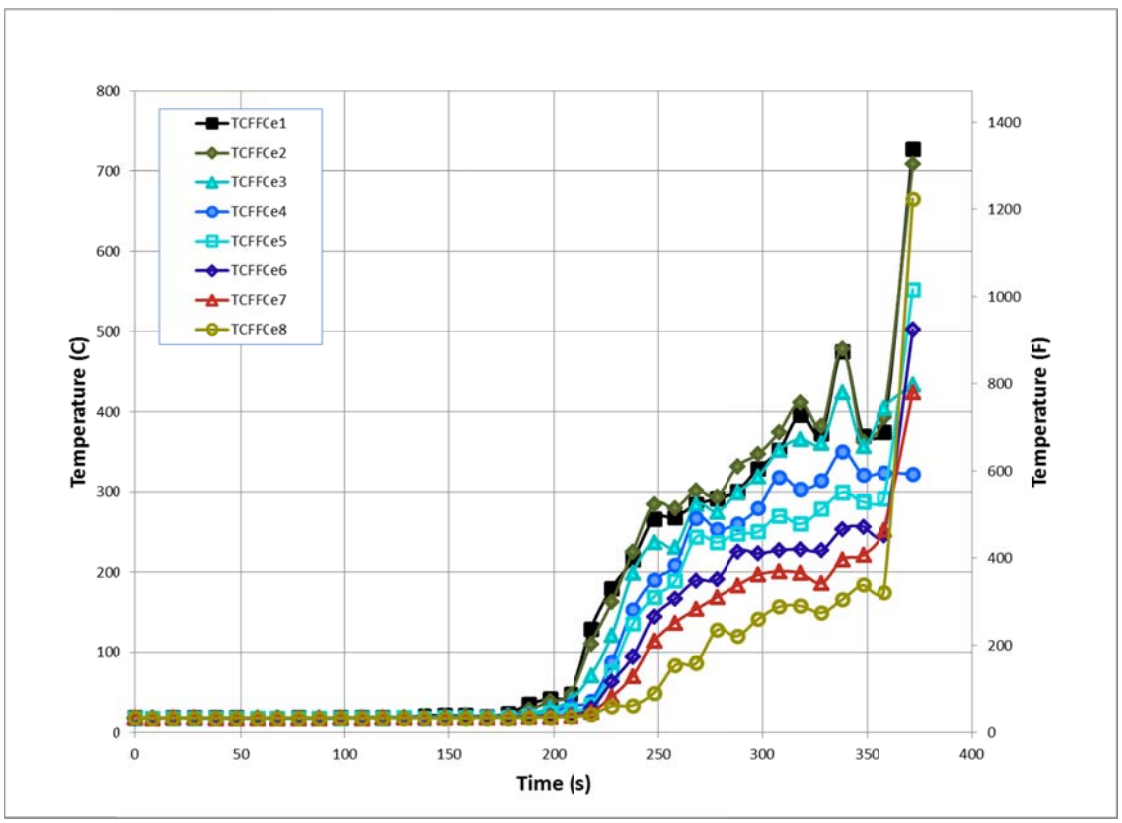

Figure 107. Experiment 3 - First Floor Center Temperatures

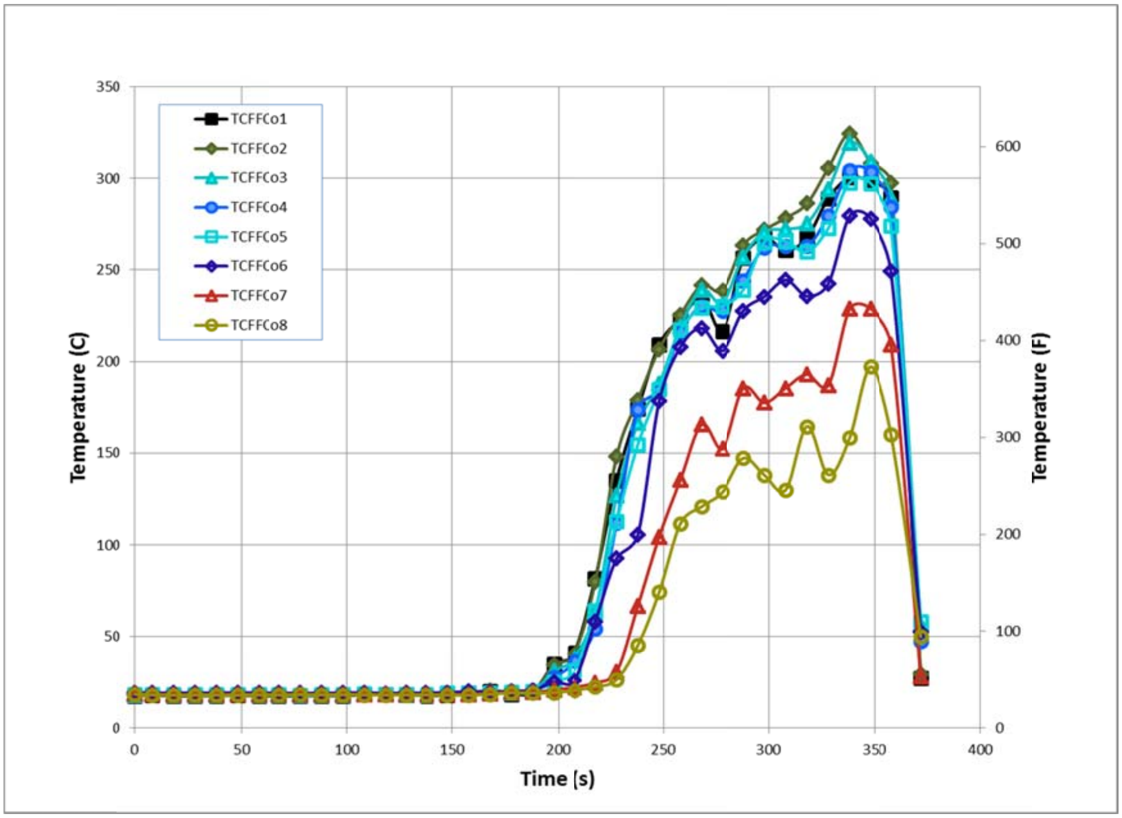

Figure 108. Experiment 3 - First Floor Corner Temperatures

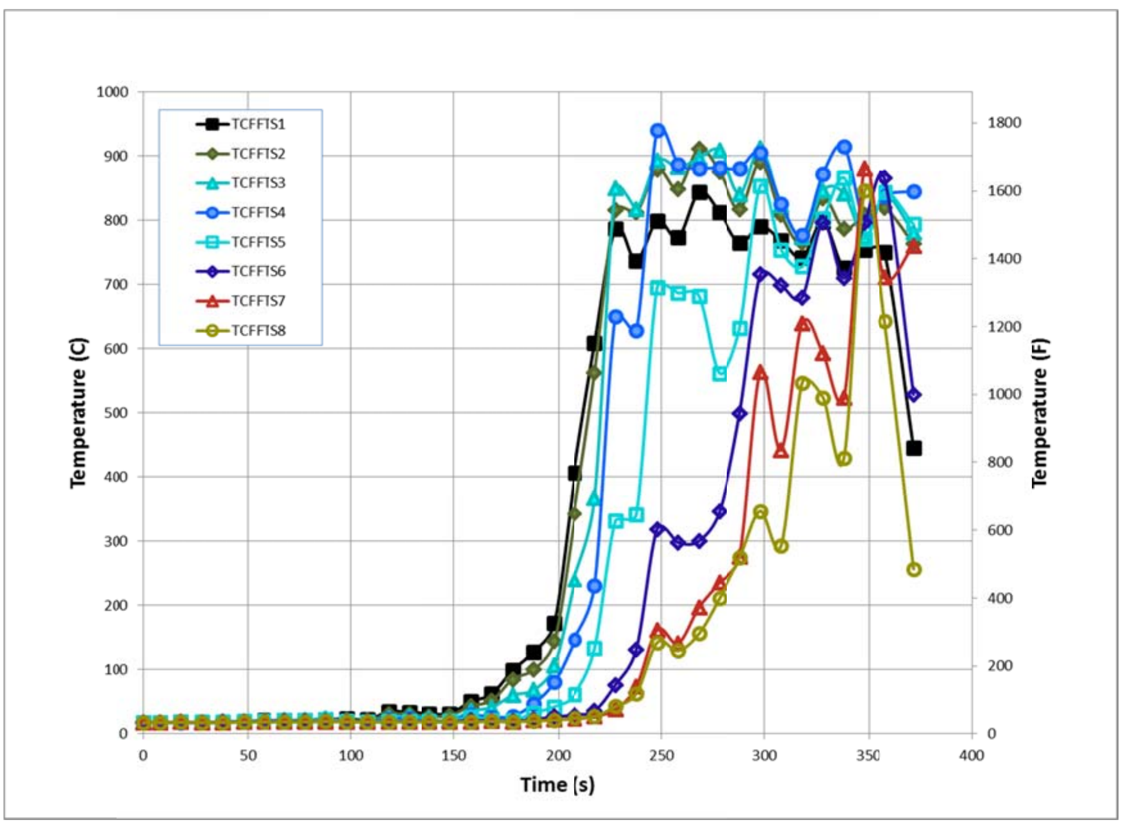

Figure 109. Experiment 3 - First Floor Top of Stair Temperatures

7.3.3. Gas Velocity

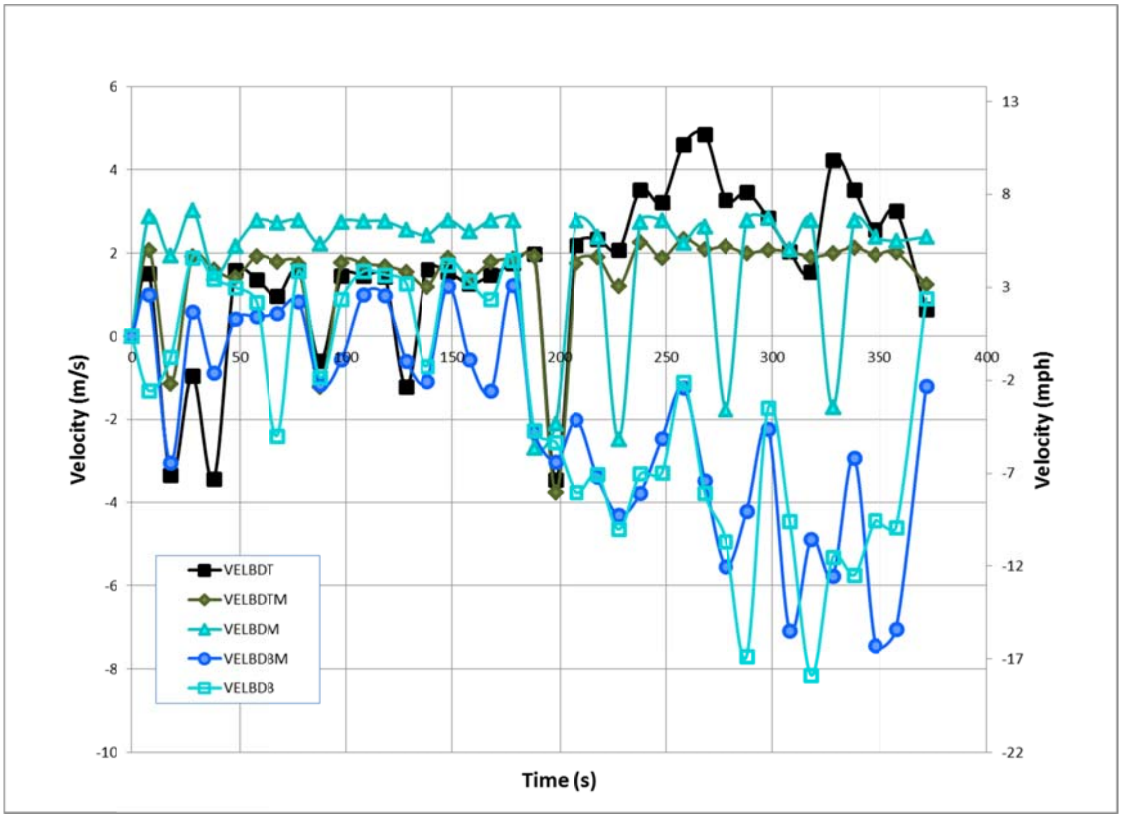

Figure 110. Experiment 3 - Basement Door Velocities

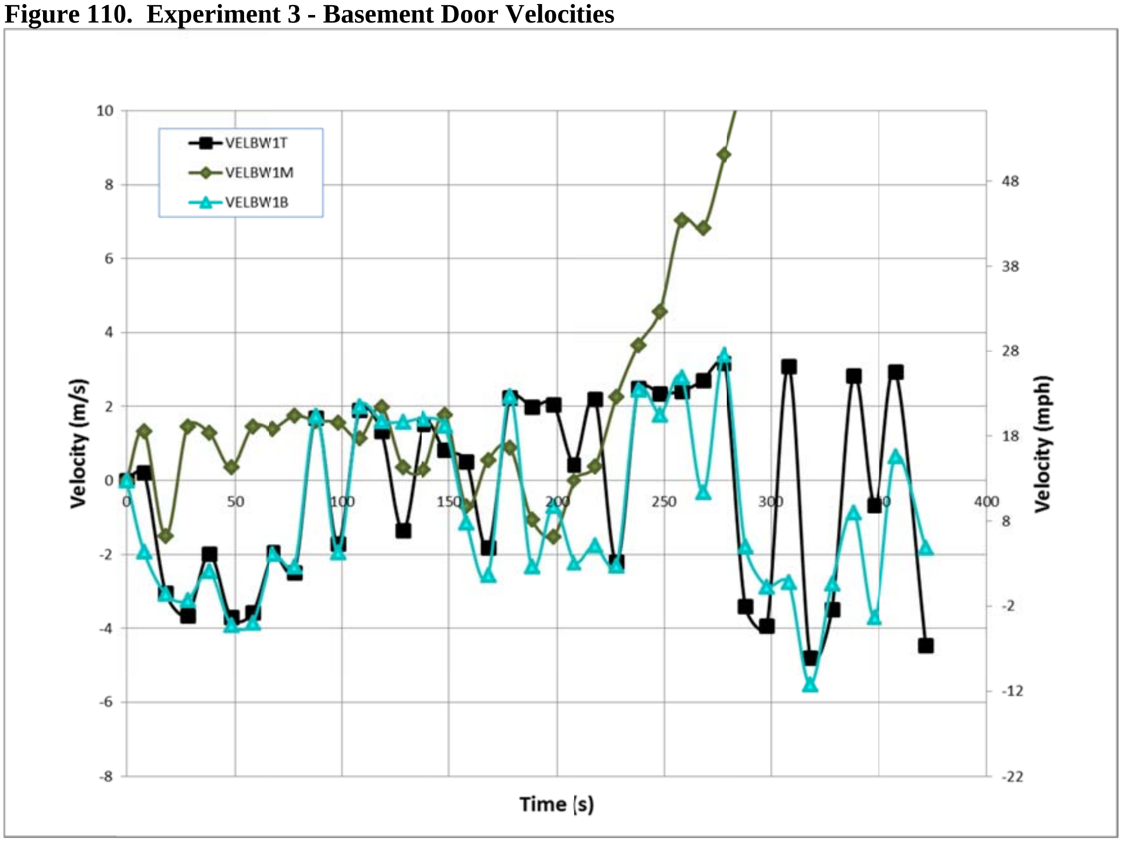

Figure 111. Experiment 3 - Basement Window 1 Velocities

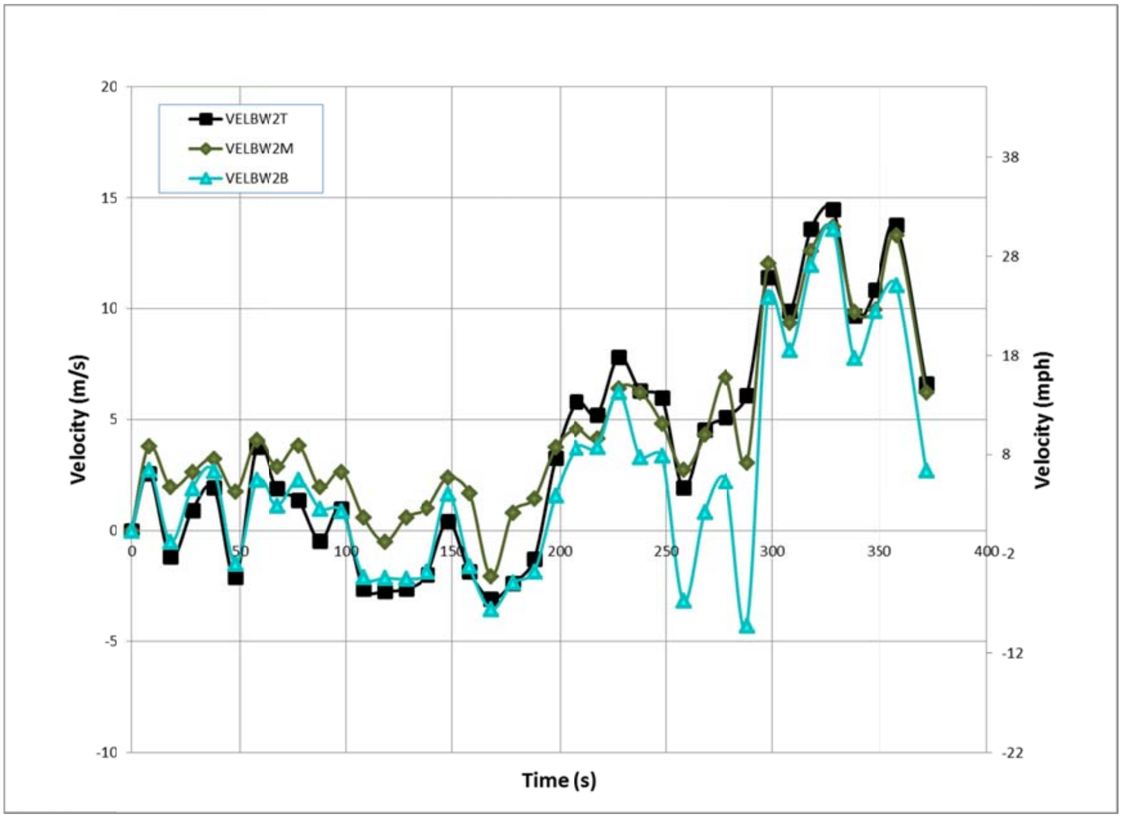

Figure 112. Experiment 3 - Basement Window 2 Velocities

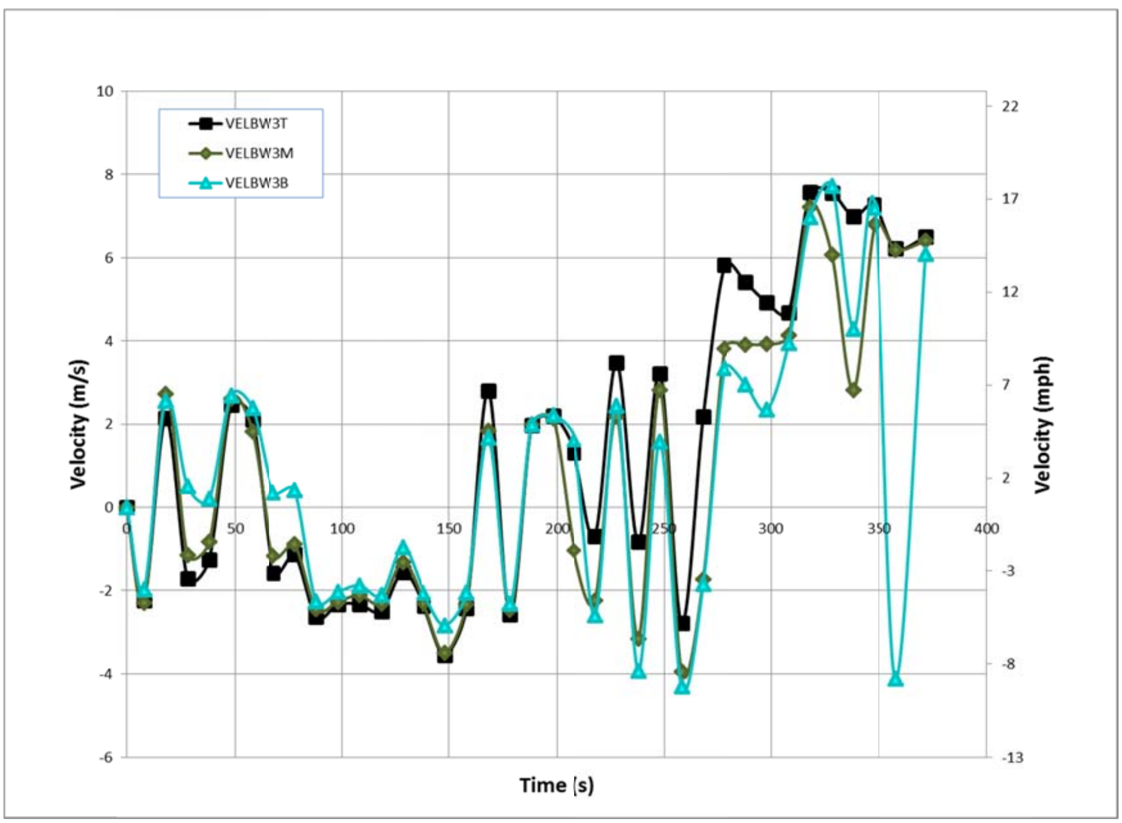

Figure 113. Experiment 3 - Basement Window 3 Velocities

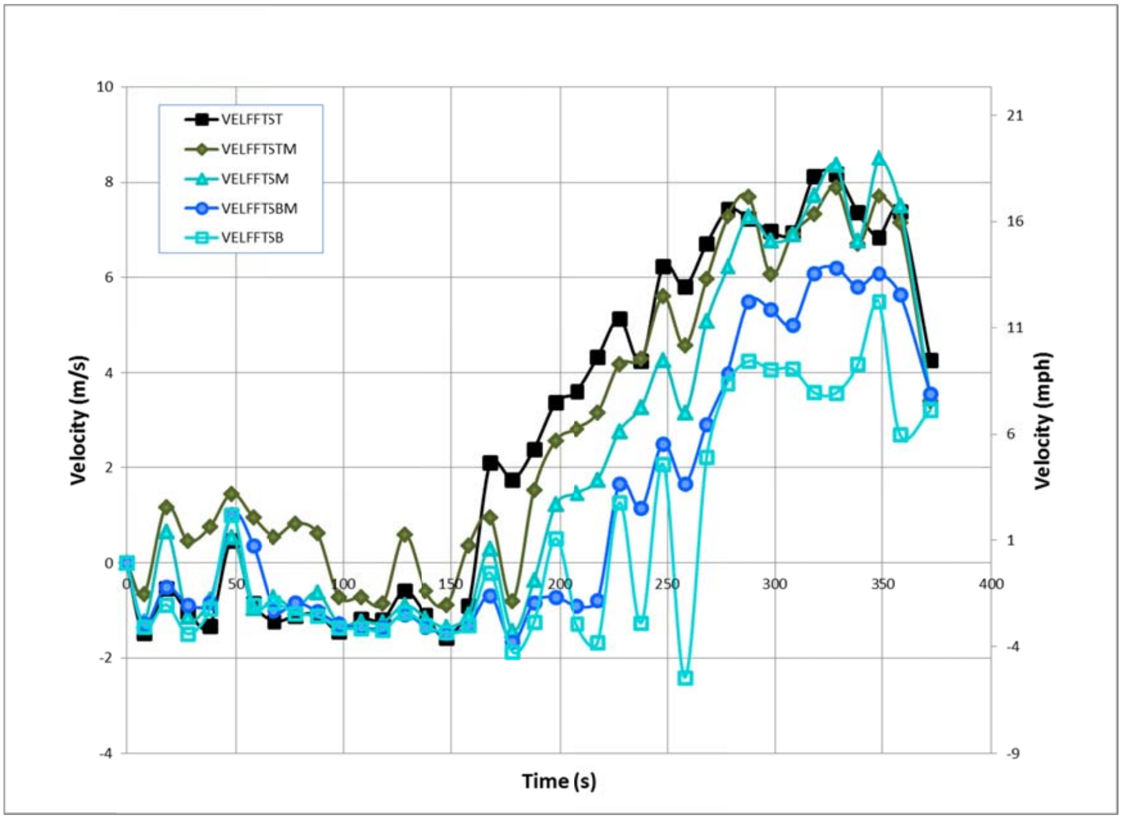

Figure 114. Experiment 3 - First Floor Stair Velocities

7.3.4. Deflection

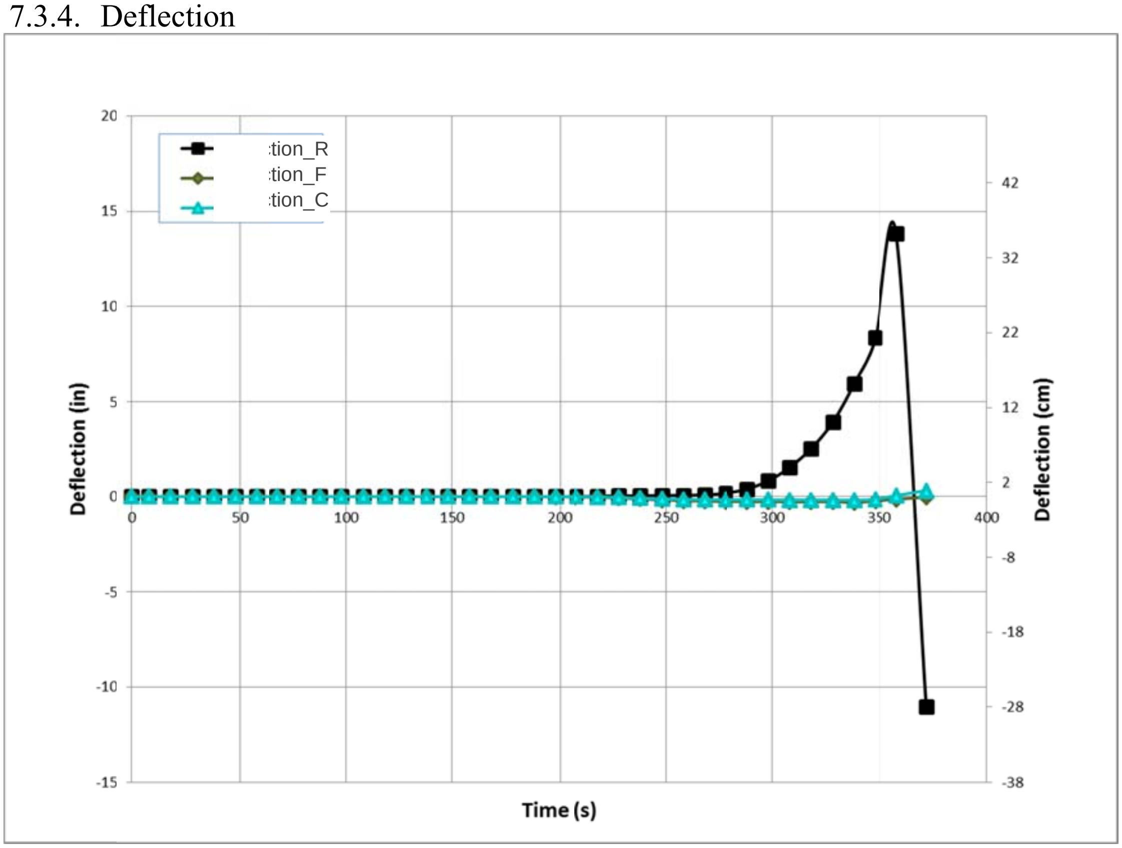

Figure 115. Experiment 3 - Floor System Deflections

7.3.5. Structural Response

The primary structural failure occurred at the rear section of the floor system, local to the initial fire location. A secondary collapse of the center and front sections occurred moments later (Figure 116). The failure mode for the engineered I-joists was due to burn-out of the web members (Figure 119). The web burn-out induced separation of the top and bottom chord members, in some cases causing complete rupture of the chord members (Figure 117). Engineered I-Joists most remote from the initial fire location collapsed due to a stability failures. Mechanical separations local to initial burn thru areas and stress concentrations were also noted in the front section joists (Figure 119 and Figure 120). The floor system began to progressively deflect from approximately 250 seconds until the end of the test. Experiment 3 induced a collapse of approximately 100% of the total floor structure (Figure 118). The collapse time for the Experiment 3 was 6:00 after ignition. The collapse time respective of the structural element fire involvement for Experiment 3 was 2:45.

Figure 116 Web burn-out induced separation of the top and bottom chord members inducing collapse at rear span.

Figure 117 The web burn-out induced causing complete rupture of the chord members at center span.

Figure 118 Interior view of collapse area from rear span.

Figure 119 Interior view of collapsed joist at front span.

Figure 120 Engineered I-joist web burn-out and sheathing failure at front section of floor system joist bearing.

7.4. Experiment 4 – Engineered I Joist

In this experiment all of the ventilation openings were closed prior to ignition and the fire was ignited in the rear fuel package closest to the base of the stairs. The floor collapsed prior to a ventilation opening being made however; the ventilation openings were still opened sequentially to simulate fire department operations. The experiment was terminated at the onset of suppression. The timeline of events is detailed in Table 28. The results for the experiment are presented in the following sections: observations, temperature, gas velocity, and deflection.

Table 28. Experiment 4 Timeline

Time (s, mm:ss)	Event
0 (0:00)	Ignition
163 (2:43)	Flames attach to the floor system
409 (6:49)	Collapse
480 (8:00)	First floor door opened
603 (10:03)	Back basement door opened
638 (10:38)	Back basement window opened
660 (11:00)	Side basement window opened
690 (11:30)	Front basement window opened
940 (15:40)	End of experiment

7.4.1. Observations

The observations are presented as a series of images captured from eight camera locations, seven were video cameras and one was a thermal imaging camera. The views were captured at the start of the experiment (0:00, Figure 121), once flames attached to the floor system (2:43, Figure 122), when visibility was lost on the first floor (3:29, Figure 123), 5 seconds before collapse (6:44, Figure 124), and 15 seconds after the basement door and first window were opened (10:45, Figure 125).

Figure 121. Experiment 4 video views at 0:00.

Figure 122. Experiment 4 video views at 2:43.

Figure 123. Experiment 4 video views at 3:29.

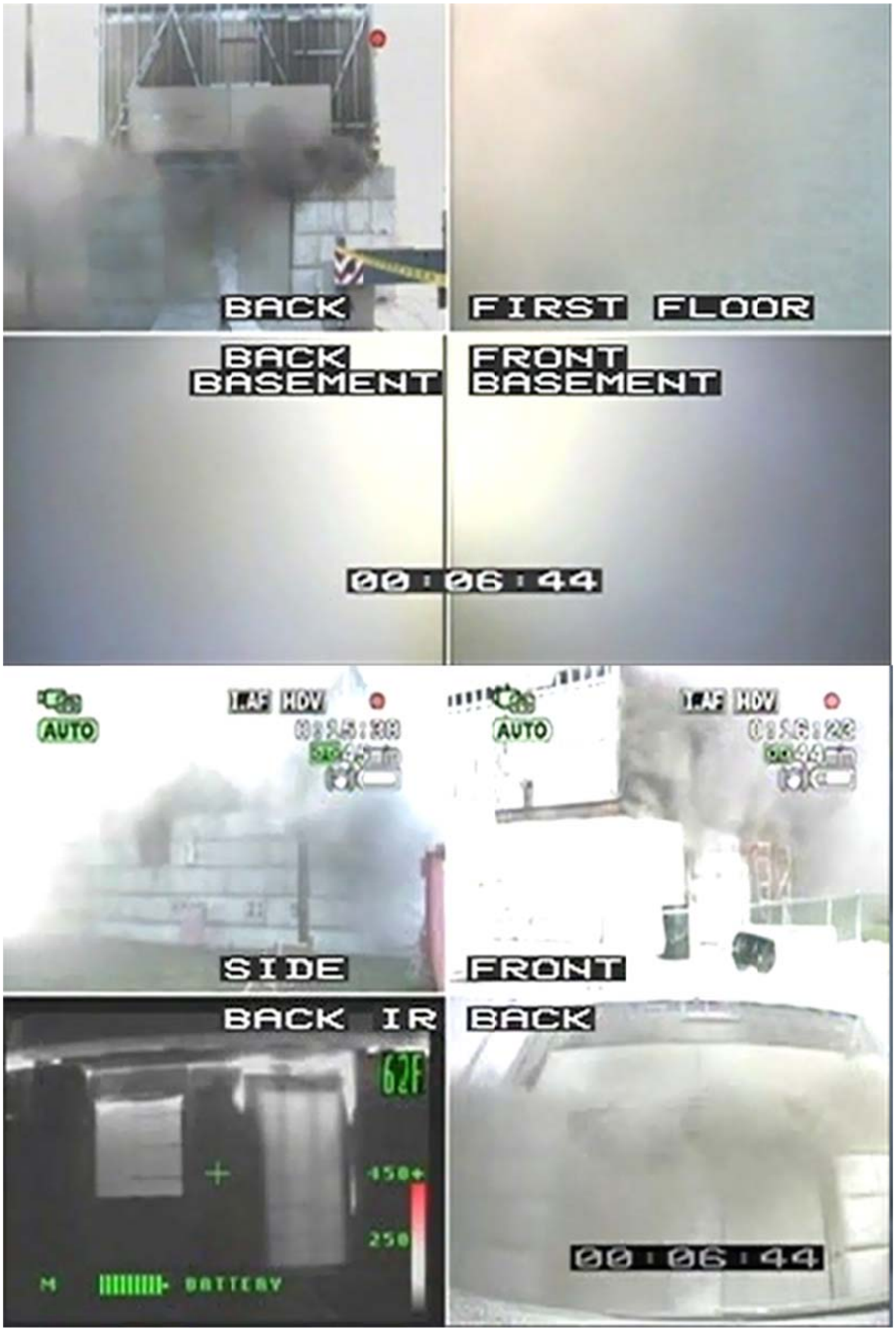

Figure 124. Experiment 4 video views at 6:44.

Figure 125. Experiment 4 video views at 10:45.

7.4.2. Temperature

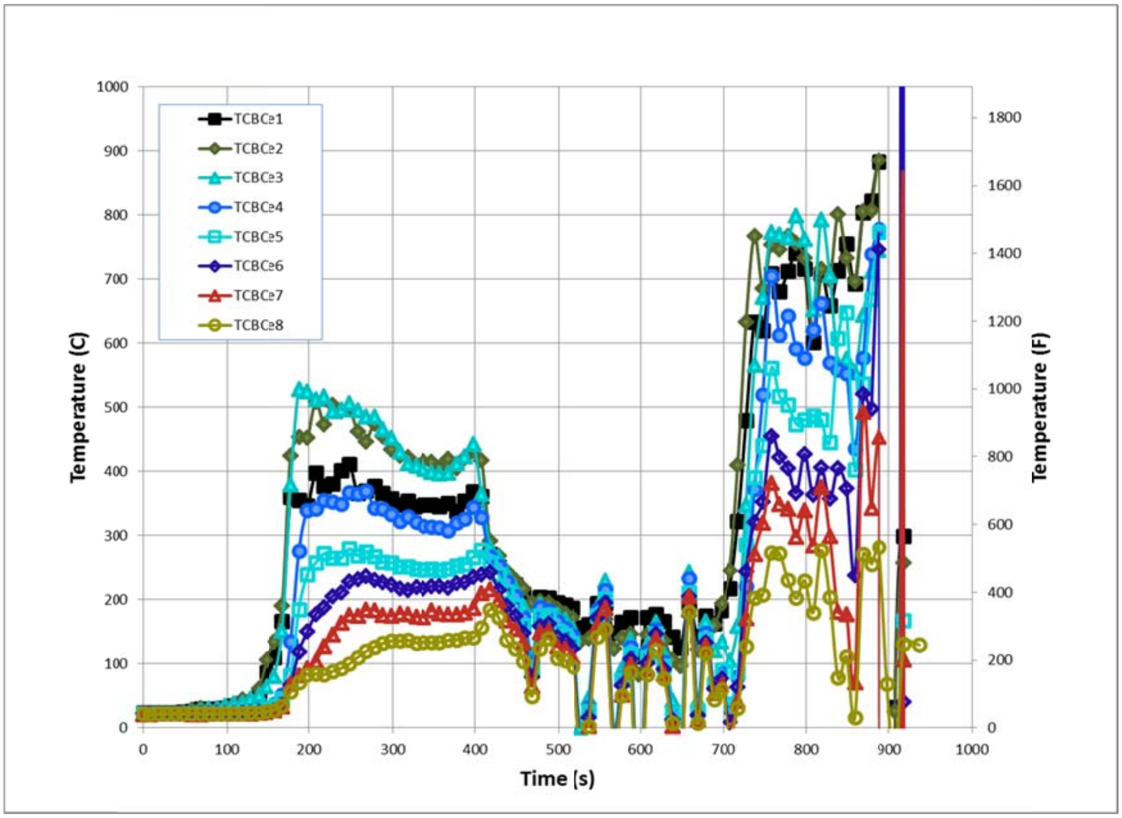

Figure 126. Experiment 4 - Basement Center Temperatures

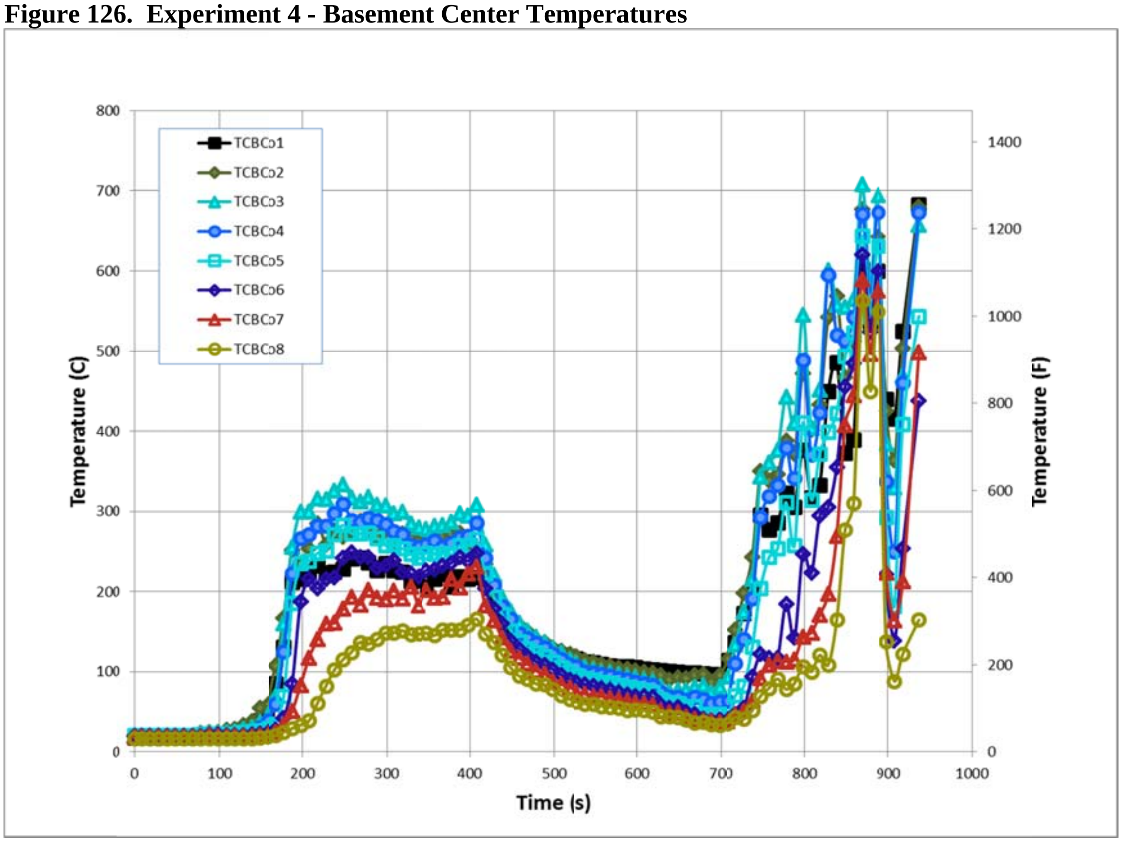

Figure 127. Experiment 4 - Basement Corner Temperatures

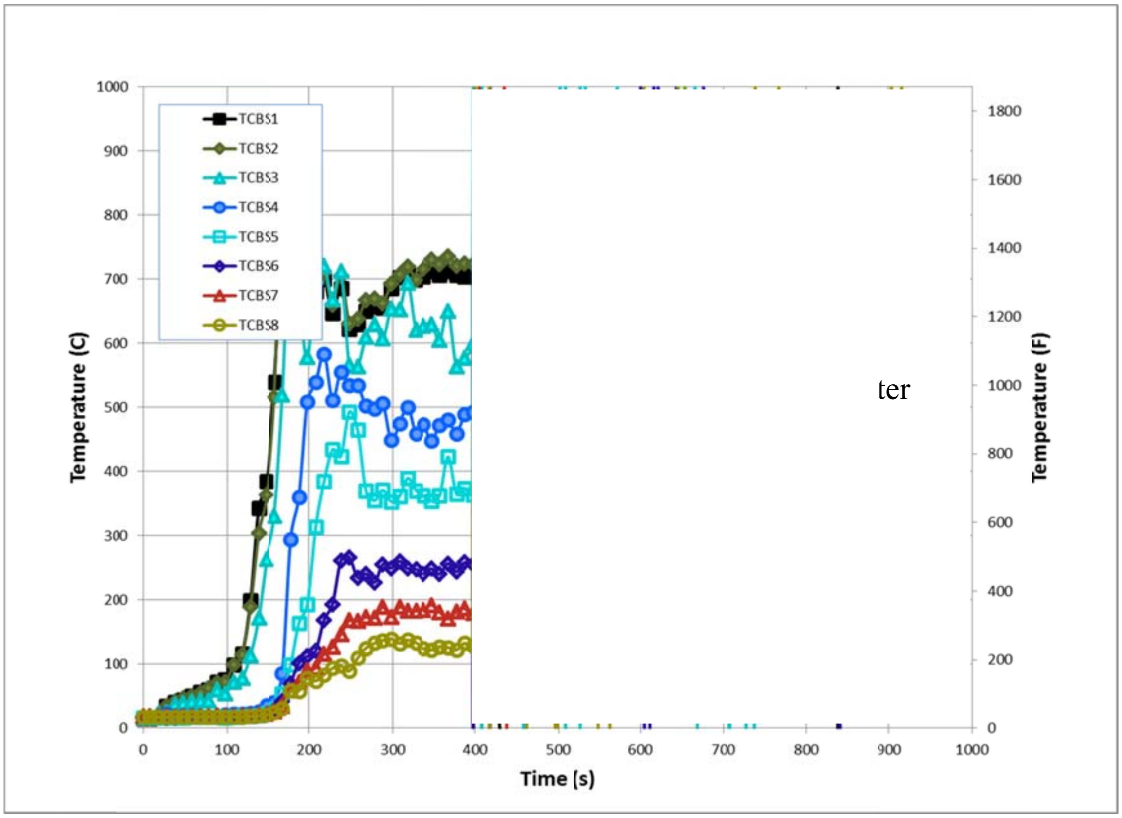

Figure 128. Experiment 4 - Basement Base of Stair Temperatures

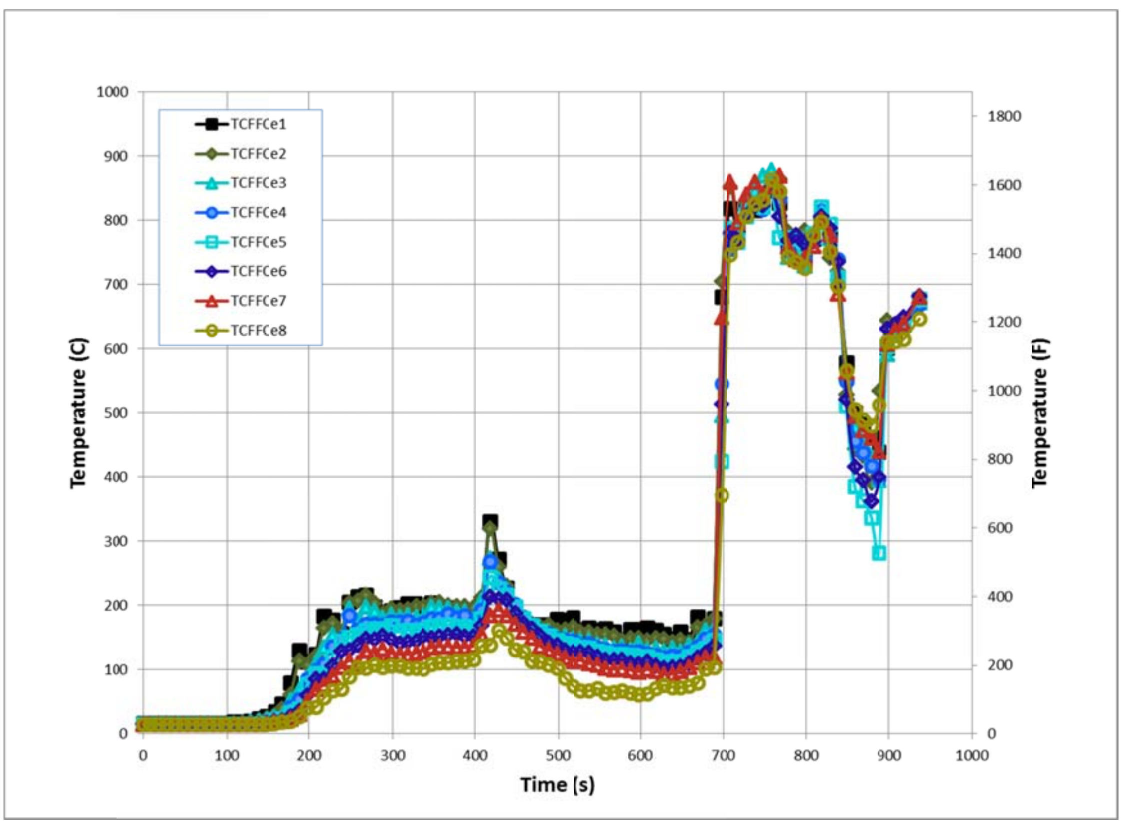

Figure 129. Experiment 4 - First Floor Center Temperatures

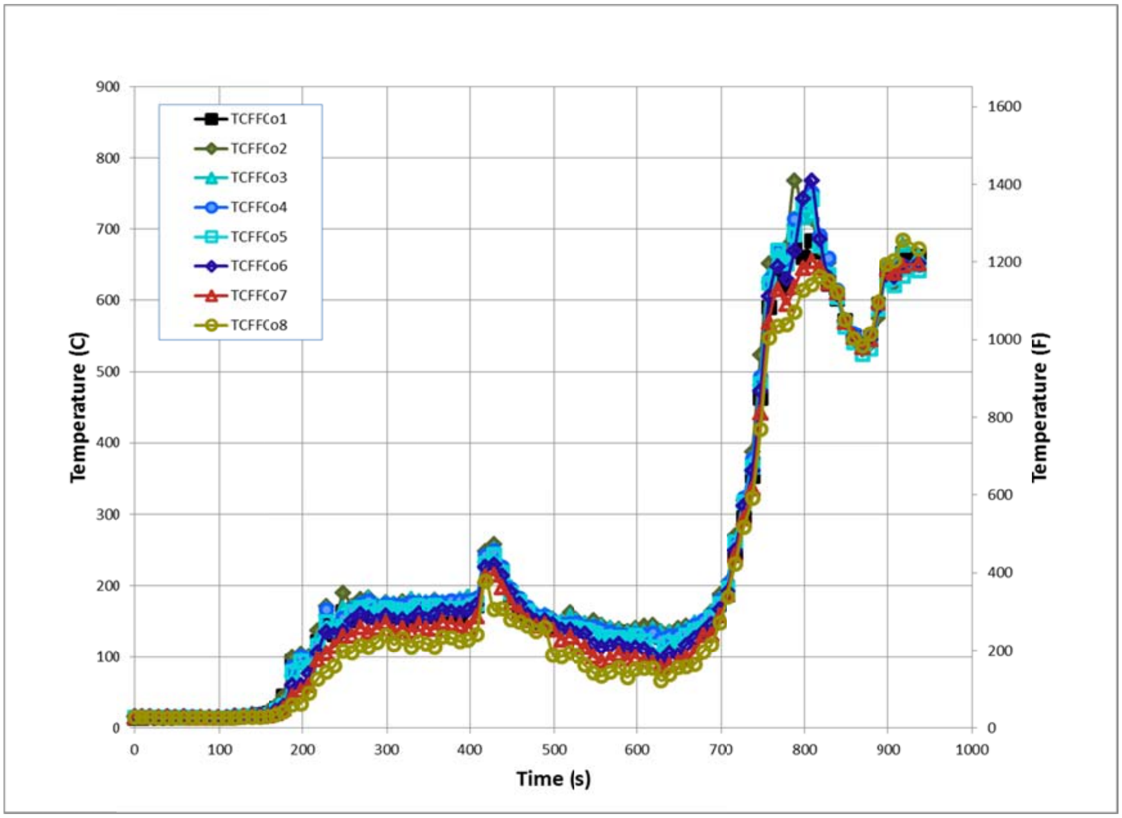

Figure 130. Experiment 4 - First Floor Corner Temperatures

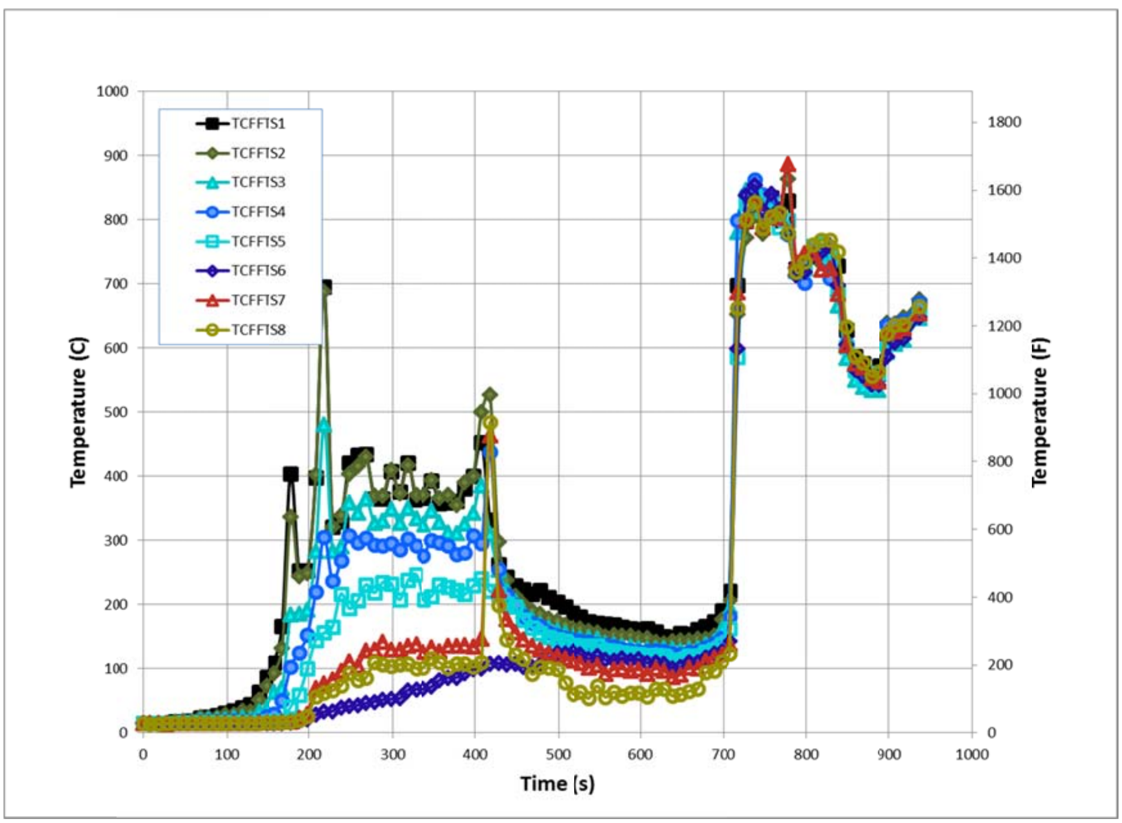

Figure 131. Experiment 4 - First Floor Top of Stair Temperatures

7.4.3. Gas Velocity

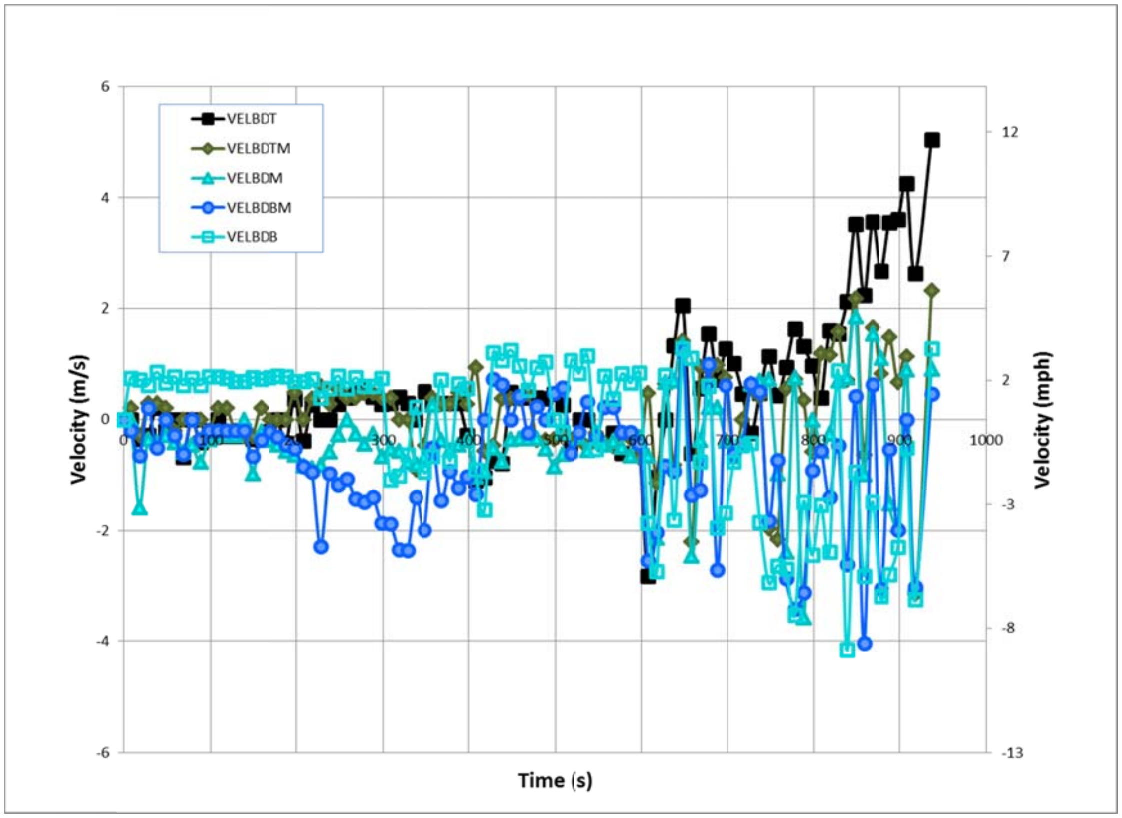

Figure 132. Experiment 4 - Basement Door Velocities

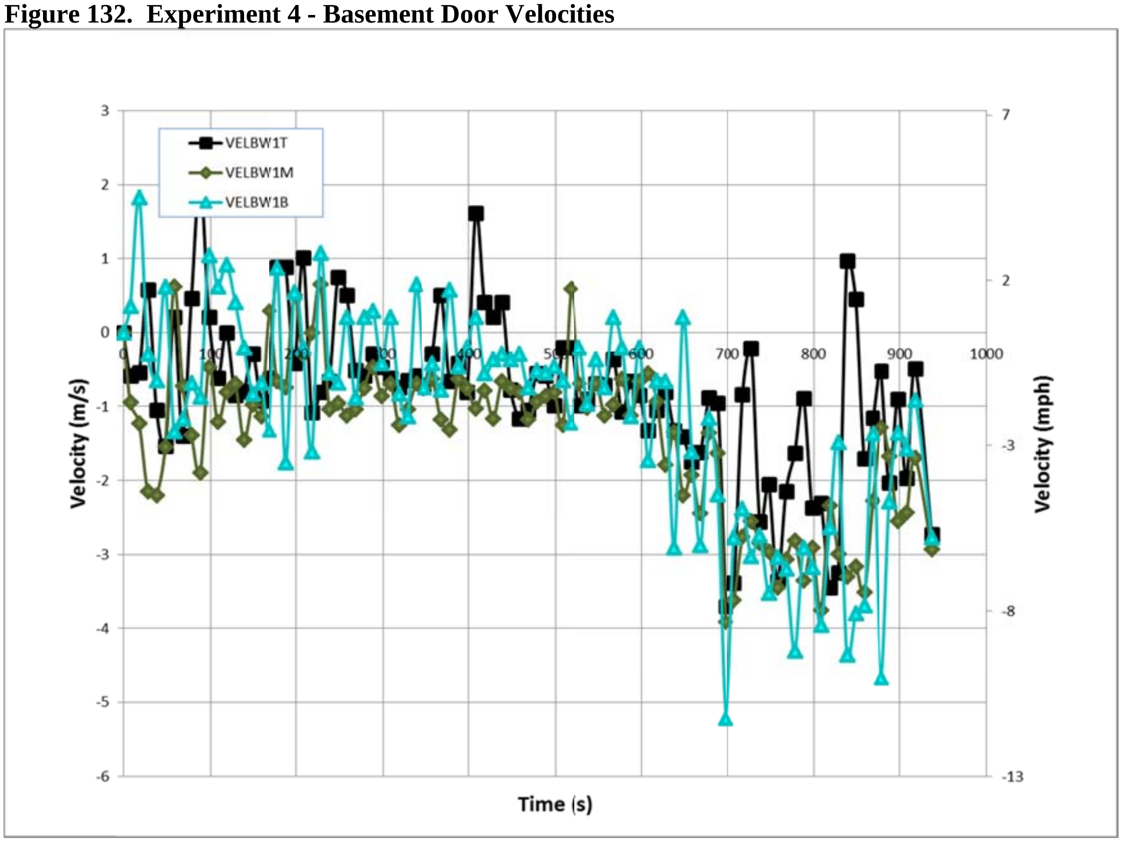

Figure 133. Experiment 4 - Basement Window 1 Velocities

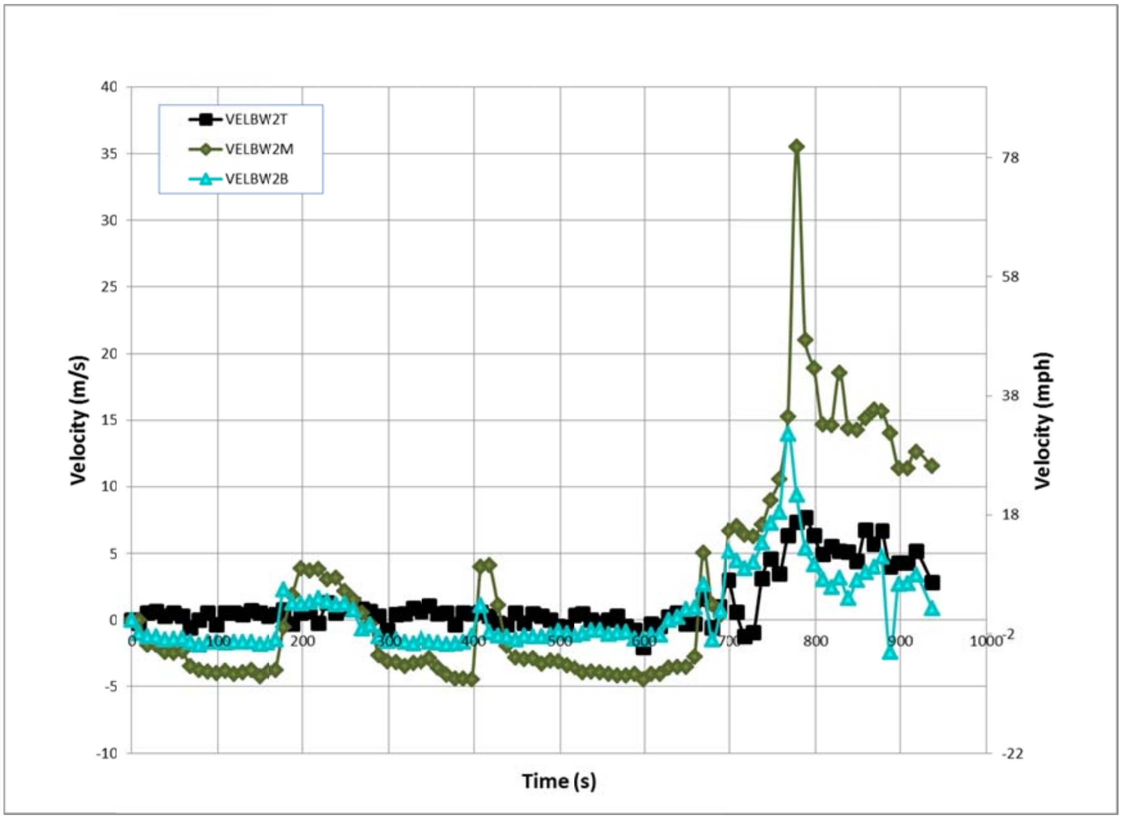

Figure 134. Experiment 4 - Basement Window 2 Velocities

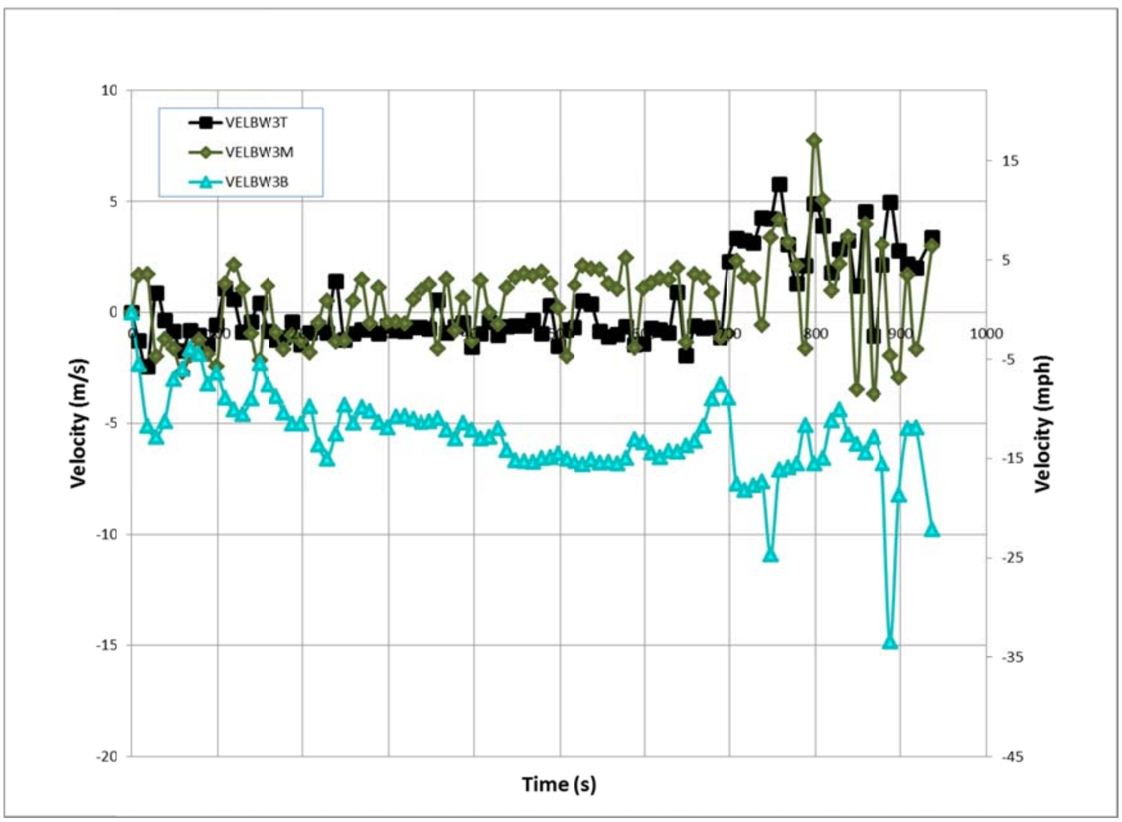

Figure 135. Experiment 4 - Basement Window 3 Velocities

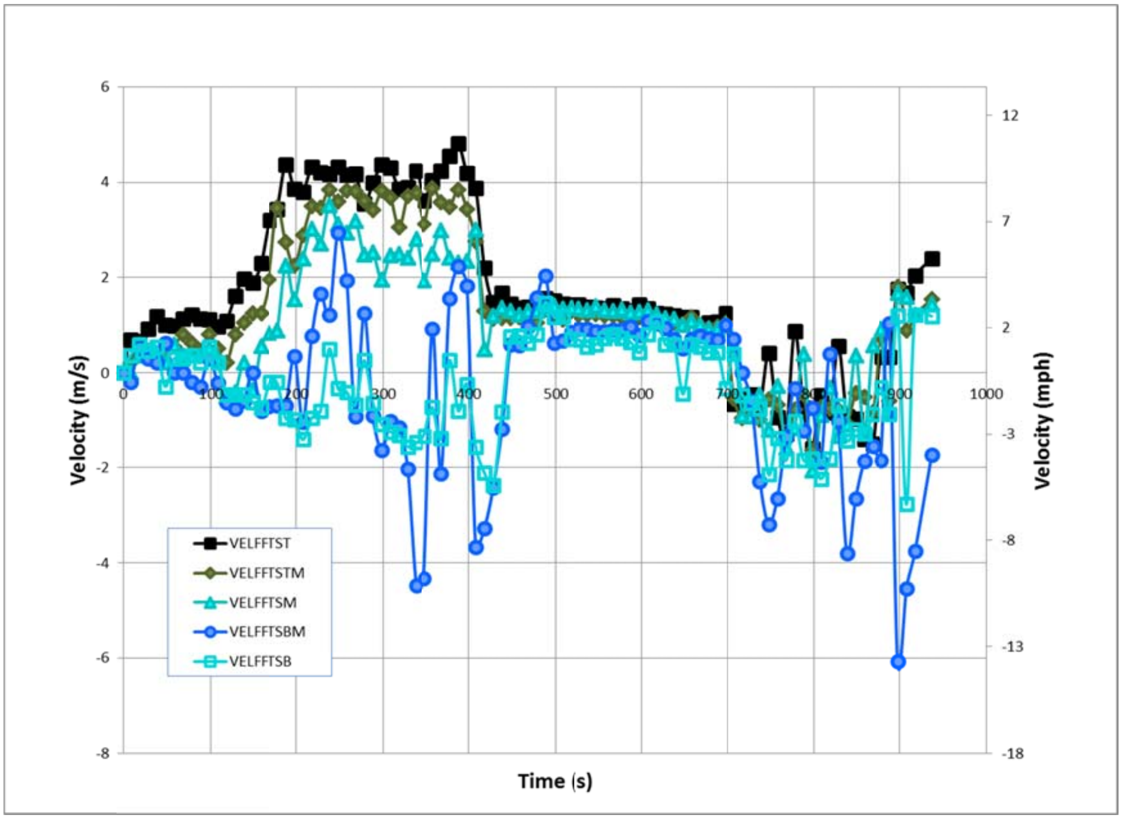

Figure 136. Experiment 4 - First Floor Stair Velocities

7.4.4. Deflection

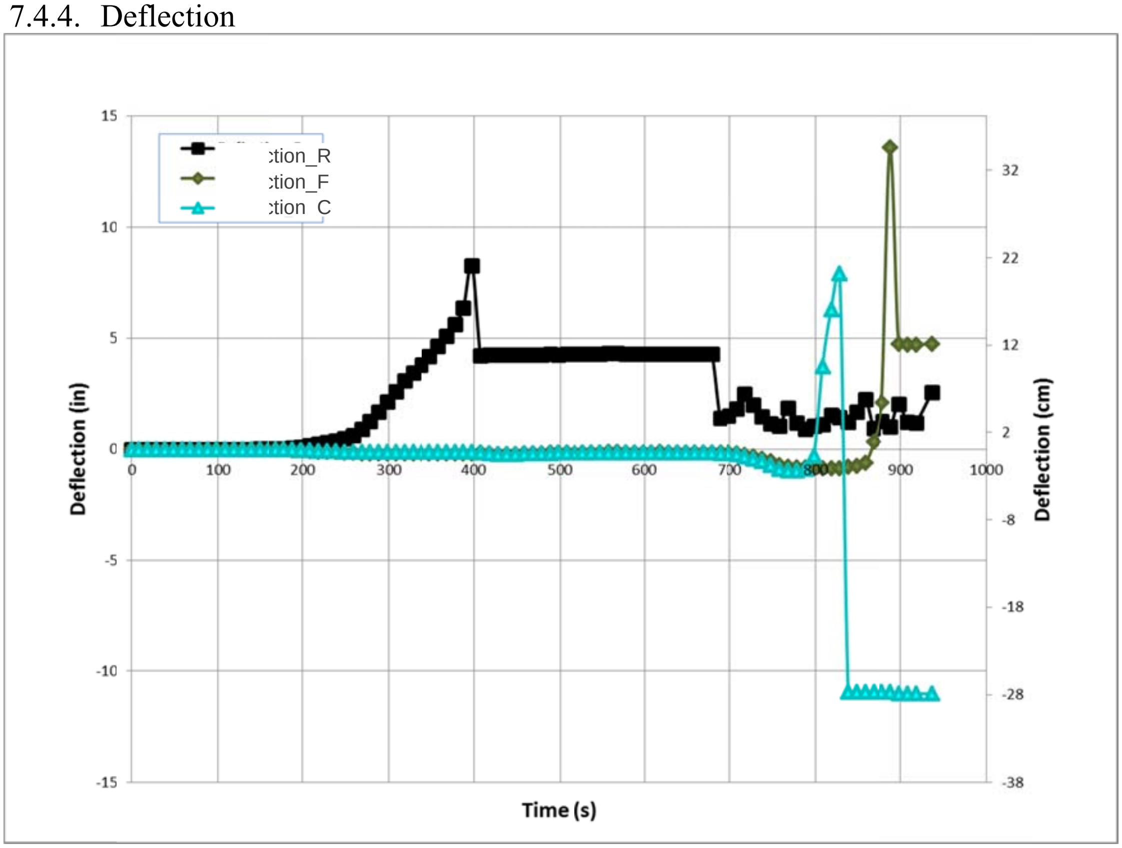

Figure 137. Experiment 4 - Floor System Deflections

7.4.5. Structural Response

The primary structural failure occurred at the rear section of the floor system, local to the initial fire location. The initial failure mode for the engineered I-joists was due to burn-out of the web members. Confirmation of the failure mechanism for experiment 4 was not possible as the fire event was allowed to continue to burn beyond the documented collapse time. Engineered I-Joists most remote from the initial fire location collapsed due to a stability failures. Various states of damage were noted in remaining sections of engineered I-joists (Figure 138 - Figure 141). The floor system began to progressively deflect from approximately 250 seconds until the end of the test. Experiment 4 ultimately induced a collapse of approximately 100% of the total floor structure. The collapse time for the Experiment 4 was 6:49 after ignition. The collapse time respective of the structural element fire involvement for Experiment 4 was 4:06.

Figure 138 Stability failure of joists, web rupture with separation of sheathing due to fastener mechanical separation.

Figure 139 Engineered I-Joist web rupture.

Figure 140 Localized areas of web burn out.

Figure 141 Minimal damage of joist bearing area at front span of floor structure.

7.5. Experiment 5 – Engineered I Joist

In this experiment all of the ventilation openings were closed prior to ignition and the fire was ignited in the rear fuel package closest to the base of the stairs. The fuel package for this experiment was modified by removing the boxes of expanded polystyrene trays. The floor collapsed during the sequential ventilation, after the opening of the first floor door. The experiment was terminated just after collapse, at the onset of suppression. The timeline of events is detailed in Table 29. The results for the experiment are presented in the following sections: observations, temperature, gas velocity, and deflection.

Table 29. Experiment 5 Timeline

Time (s, mm:ss)	Event
0 (0:00)	Ignition
225 (3:45)	Flames attach to the floor system
480 (8:00)	First floor door opened
507 (8:27)	Collapse
525 (8:45)	End of experiment

7.5.1. Observations

The observations are presented as a series of images captured from eight camera locations, seven were video cameras and one was a thermal imaging camera. The views were captured at the start of the experiment (0:00, Figure 142), once flames attached to the floor system (3:45, Figure 143), when flames are seen exiting the doorway to the first floor (4:20, Figure 144), and 5 seconds before collapse (8:22, Figure 145).

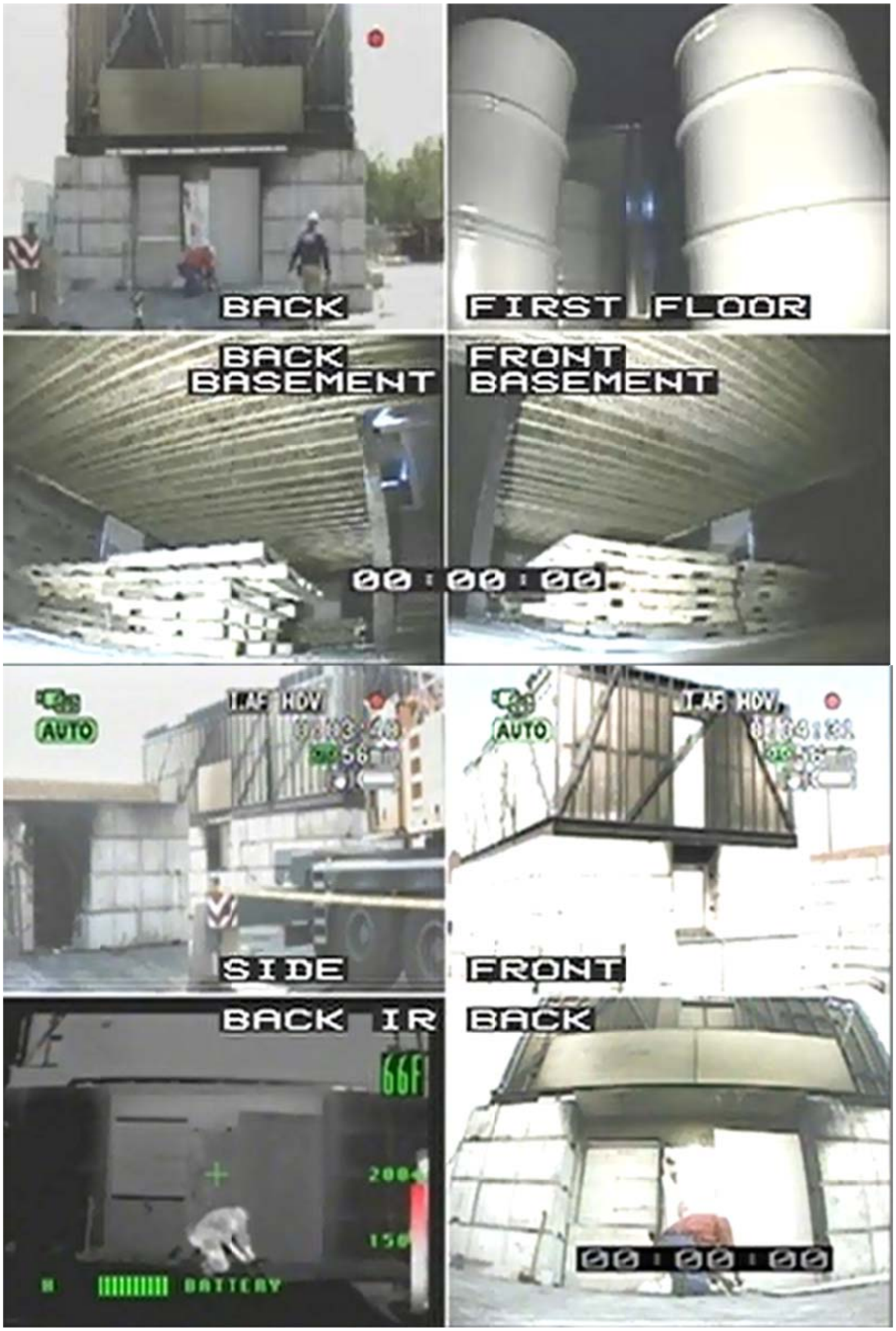

Figure 142. Experiment 5 video views at 0:00.

Figure 143. Experiment 5 video views at 3:45.

Figure 144. Experiment 5 video views at 4:20.

Figure 145. Experiment 5 video views at 8:22.

7.5.2. Temperature

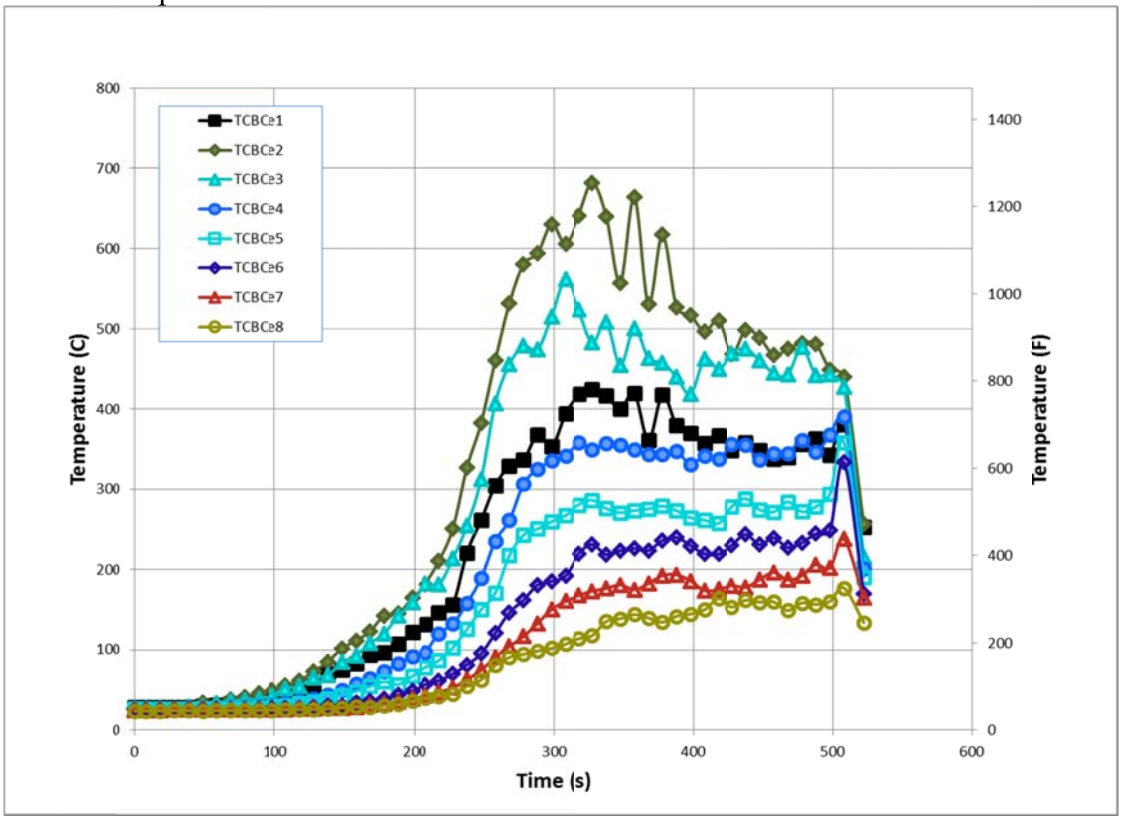

Figure 146. Experiment 5 - Basement Center Temperatures

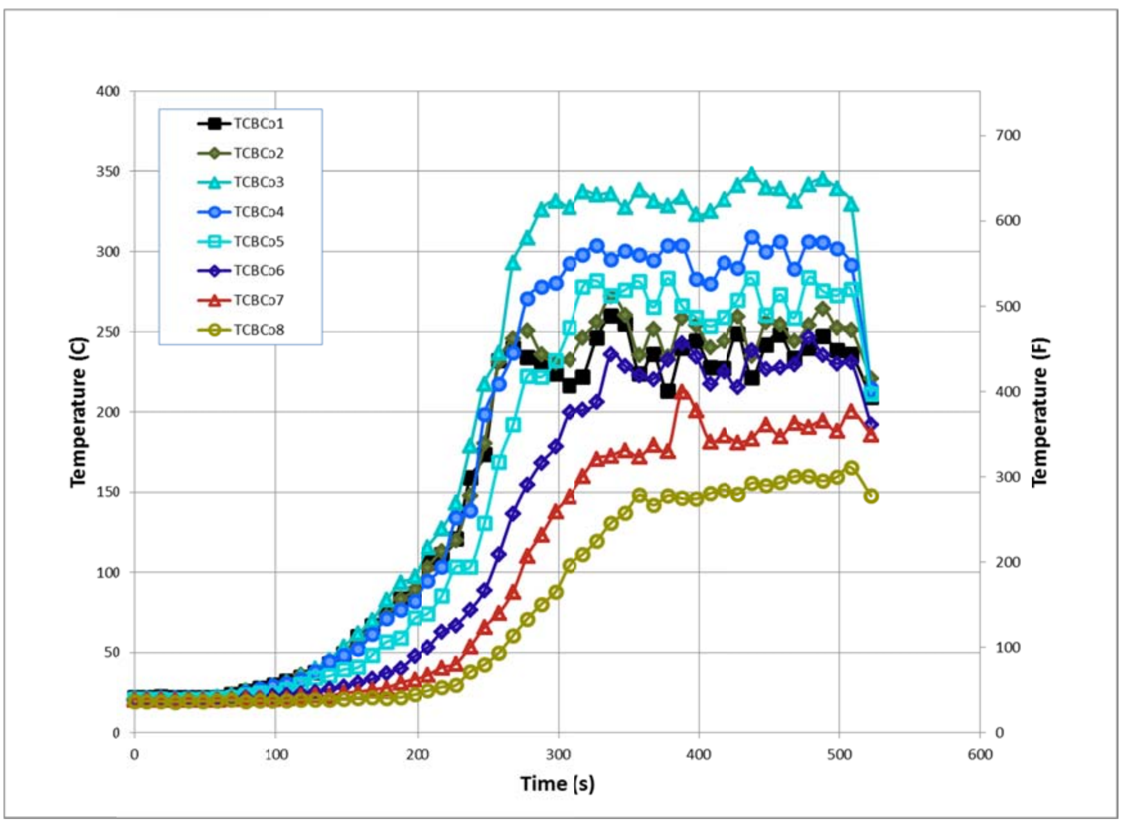

Figure 147. Experiment 5 - Basement Corner Temperatures

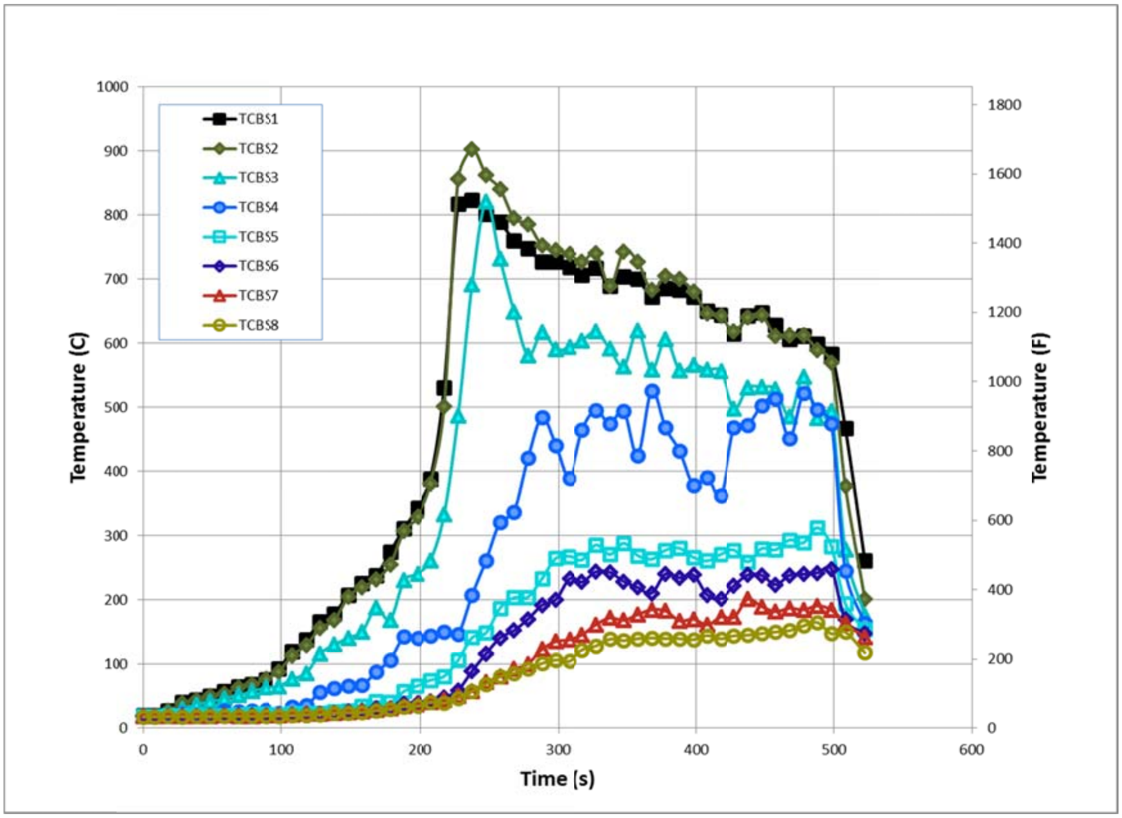

Figure 148. Experiment 5 - Basement Base of Stair Temperatures

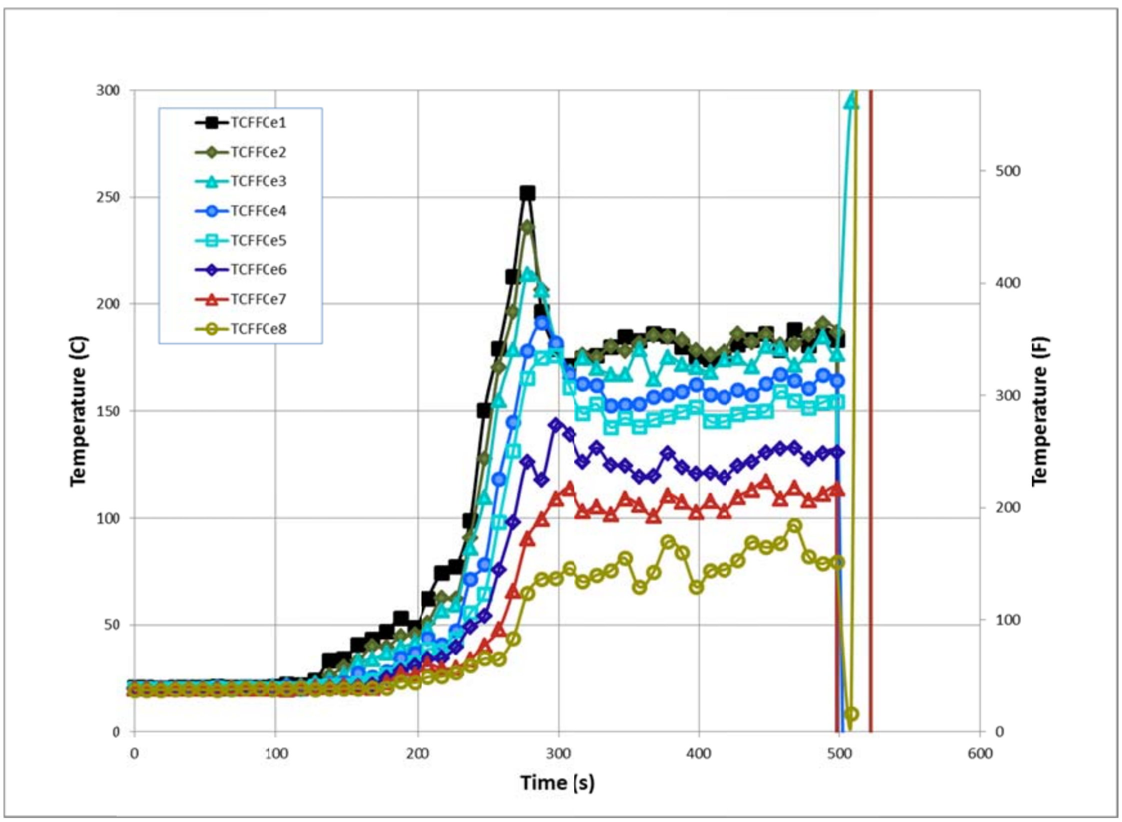

Figure 149. Experiment 5 - First Floor Center Temperatures

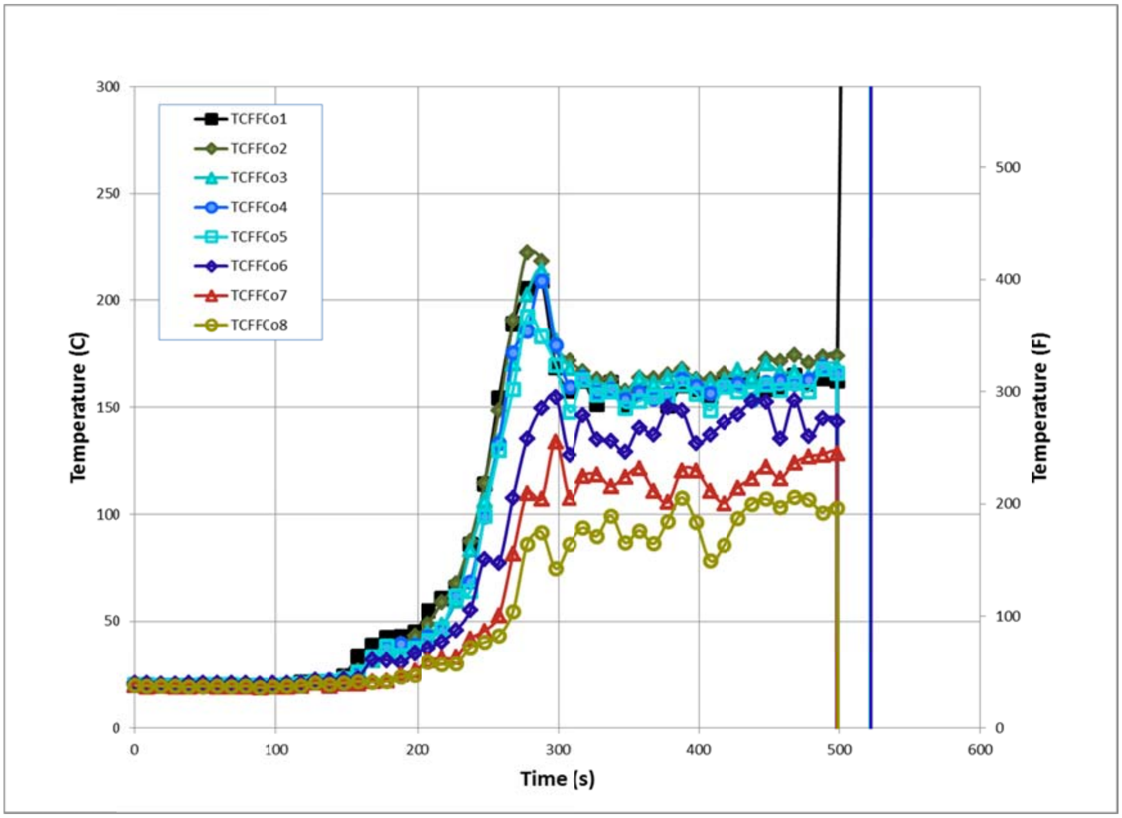

Figure 150. Experiment 5 - First Floor Corner Temperatures

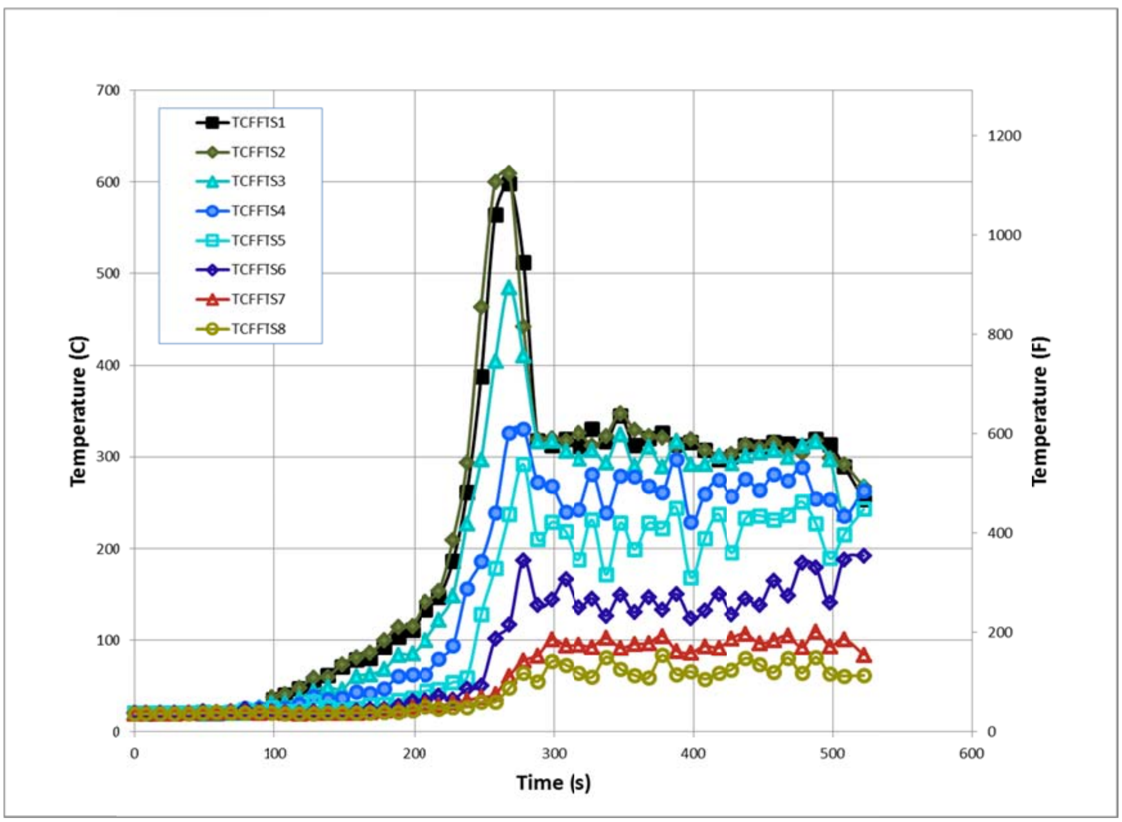

Figure 151. Experiment 5 - First Floor Top of Stair Temperatures

7.5.3. Gas Velocity

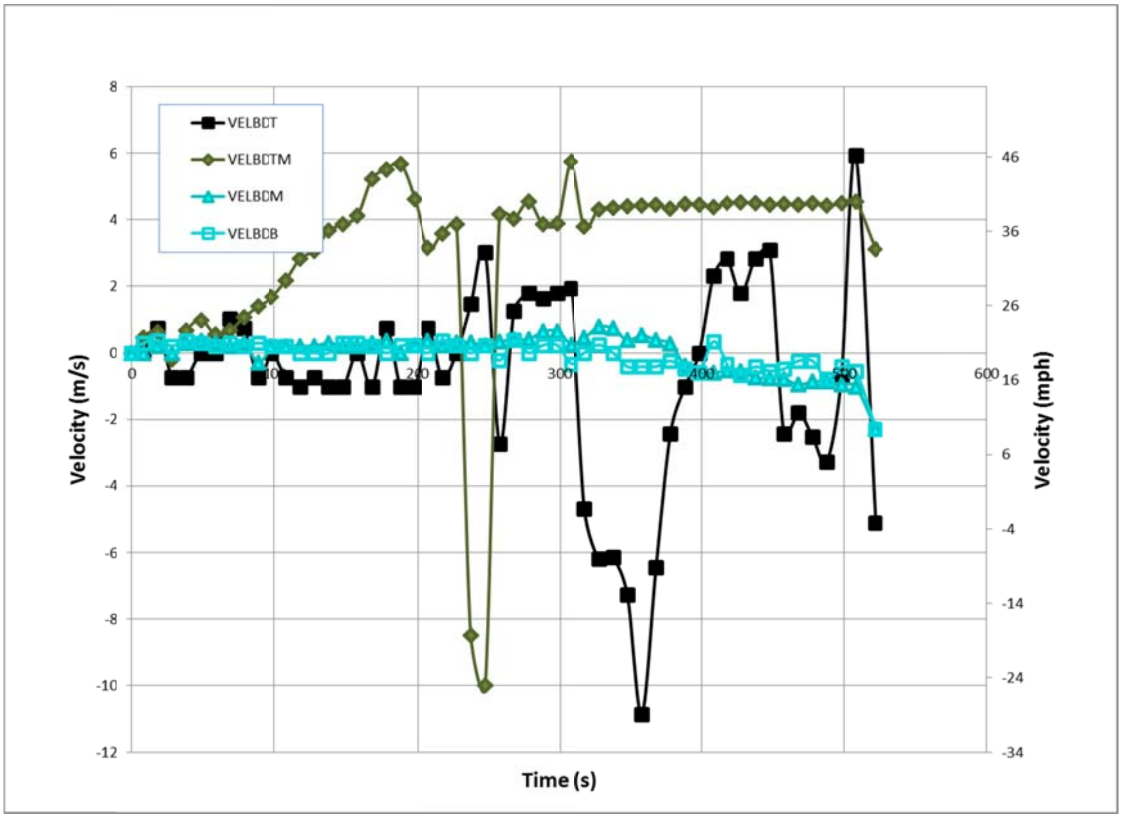

Figure 152. Experiment 5 - Basement Door Velocities

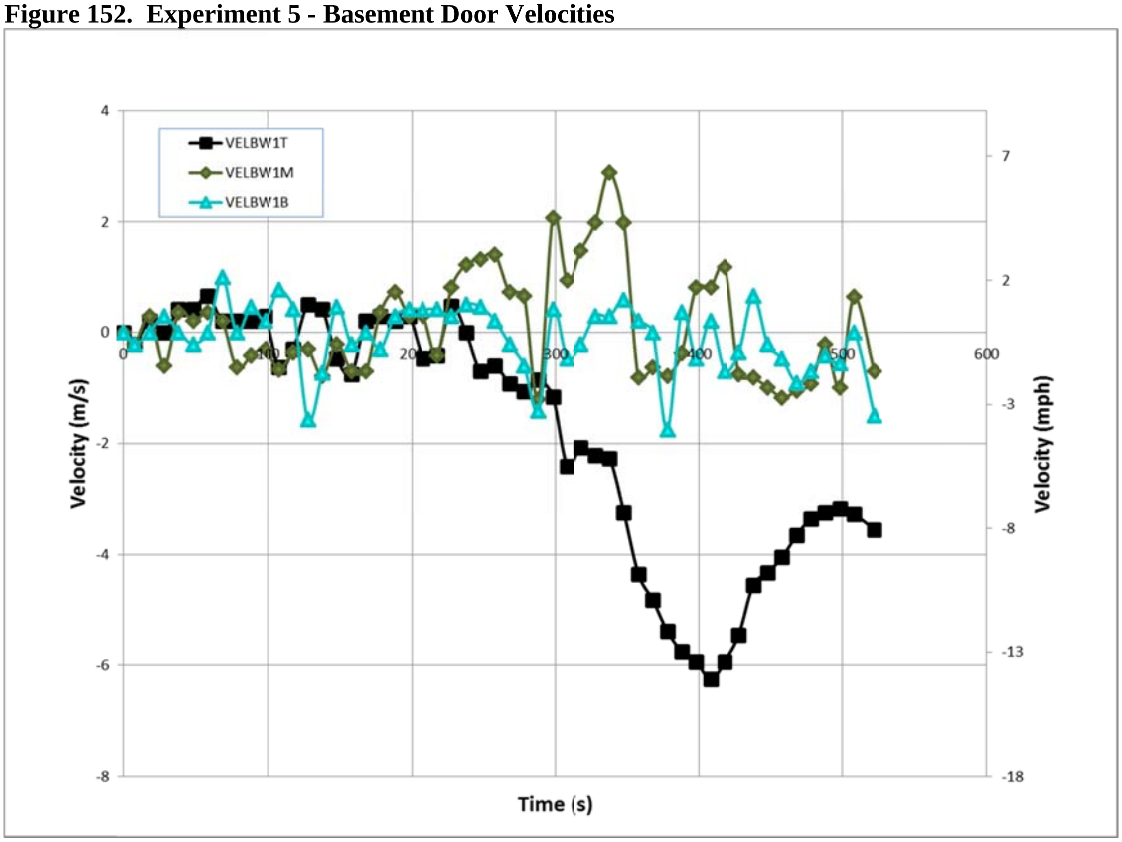

Figure 153. Experiment 5 - Basement Window 1 Velocities

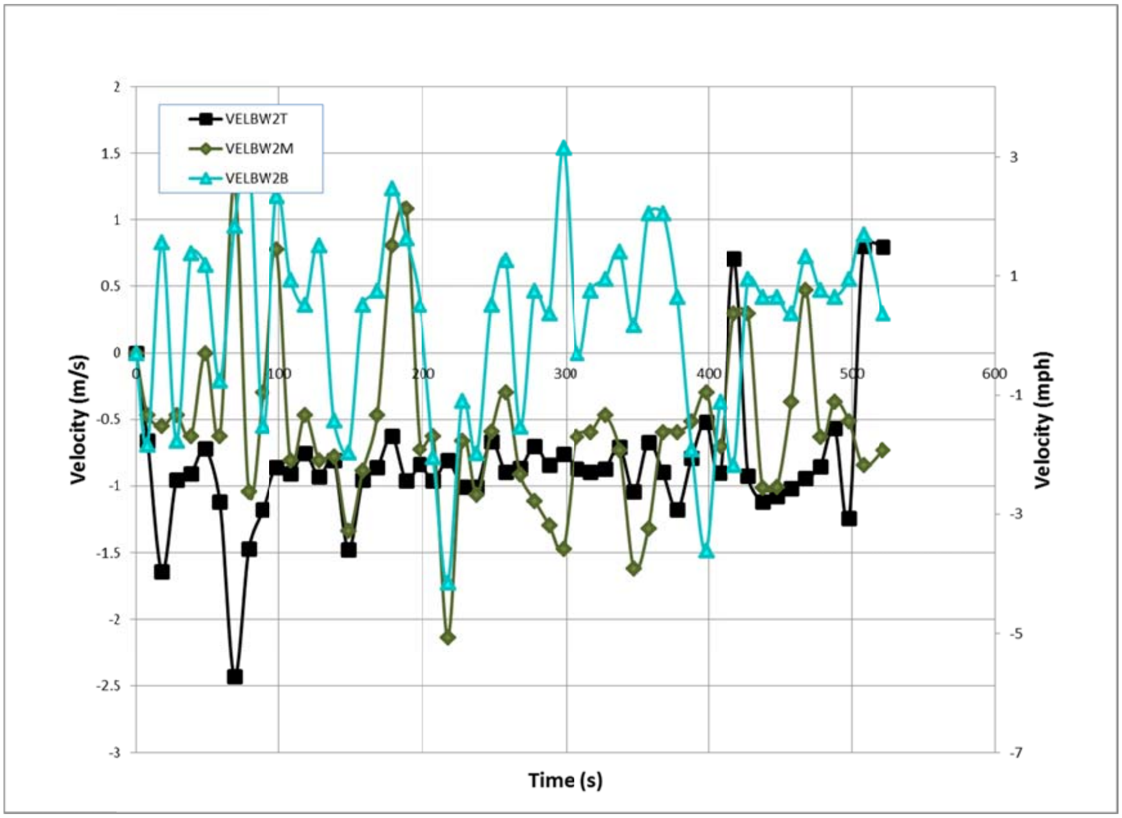

Figure 154. Experiment 5 - Basement Window 2 Velocities

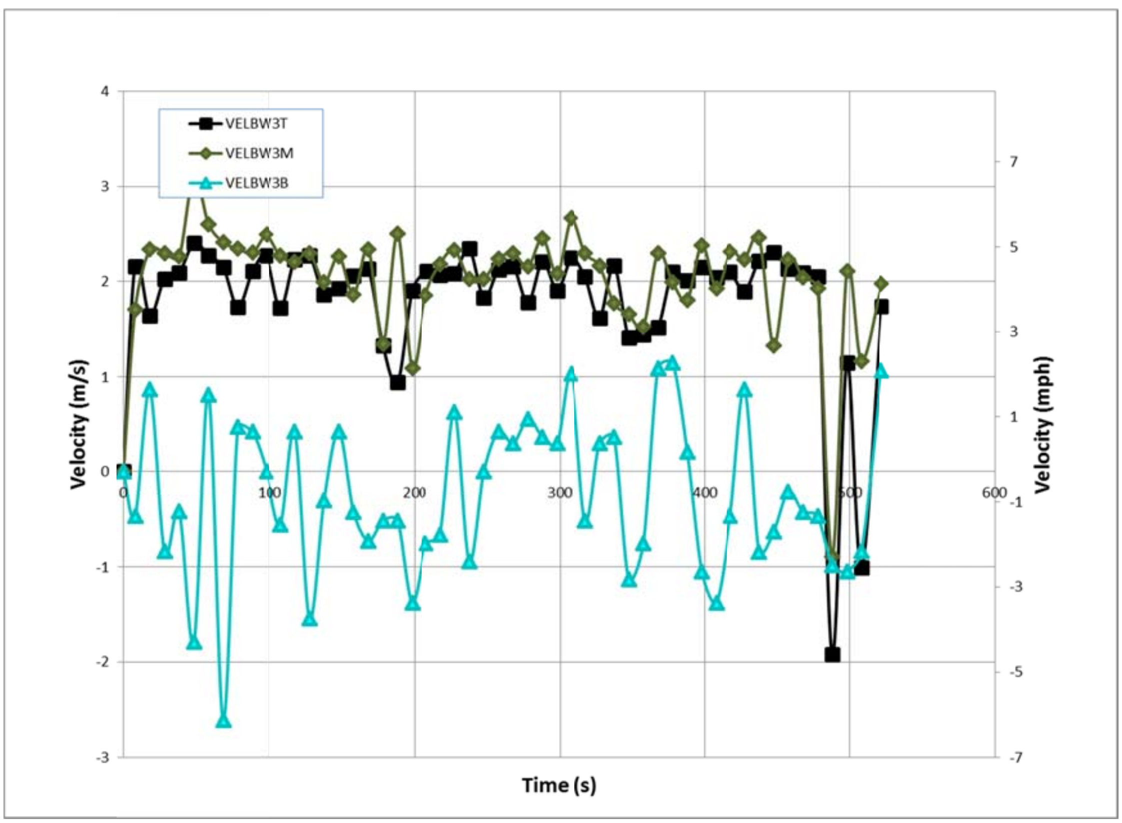

Figure 155. Experiment 5 - Basement Window 3 Velocities

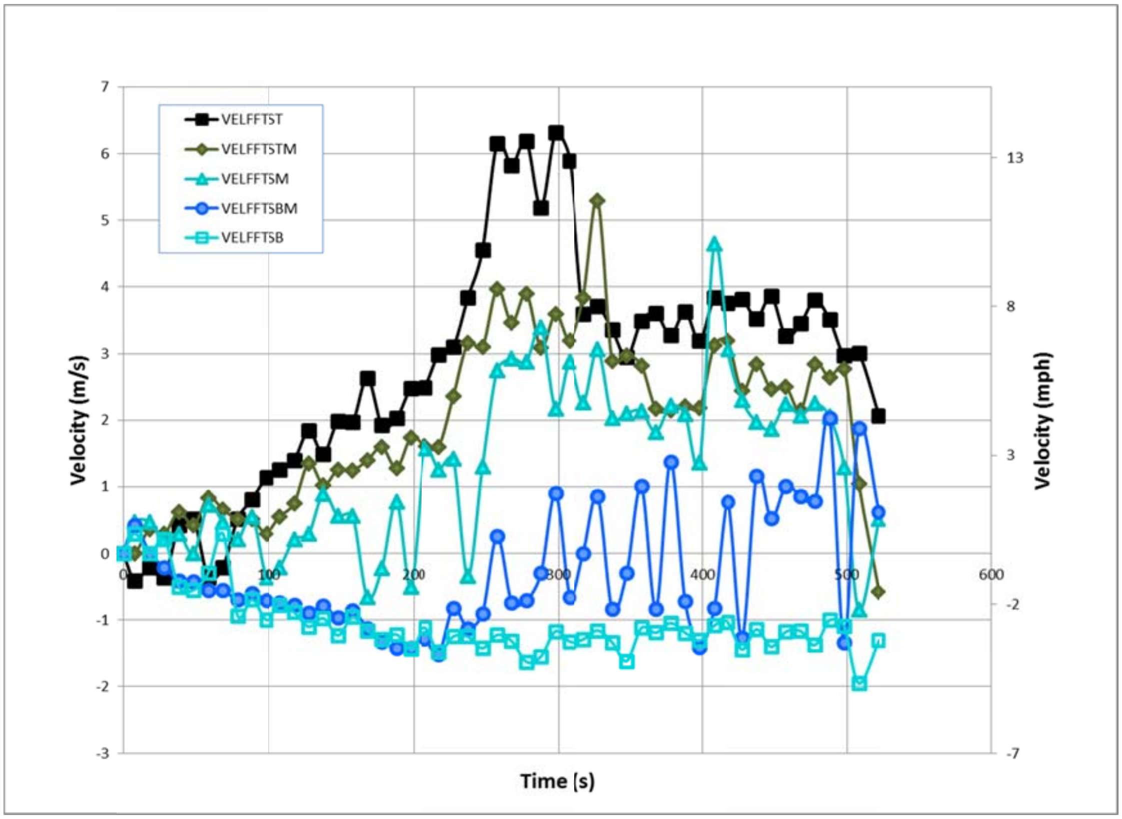

Figure 156. Experiment 5 - First Floor Stair Velocities

7.5.4. Deflection

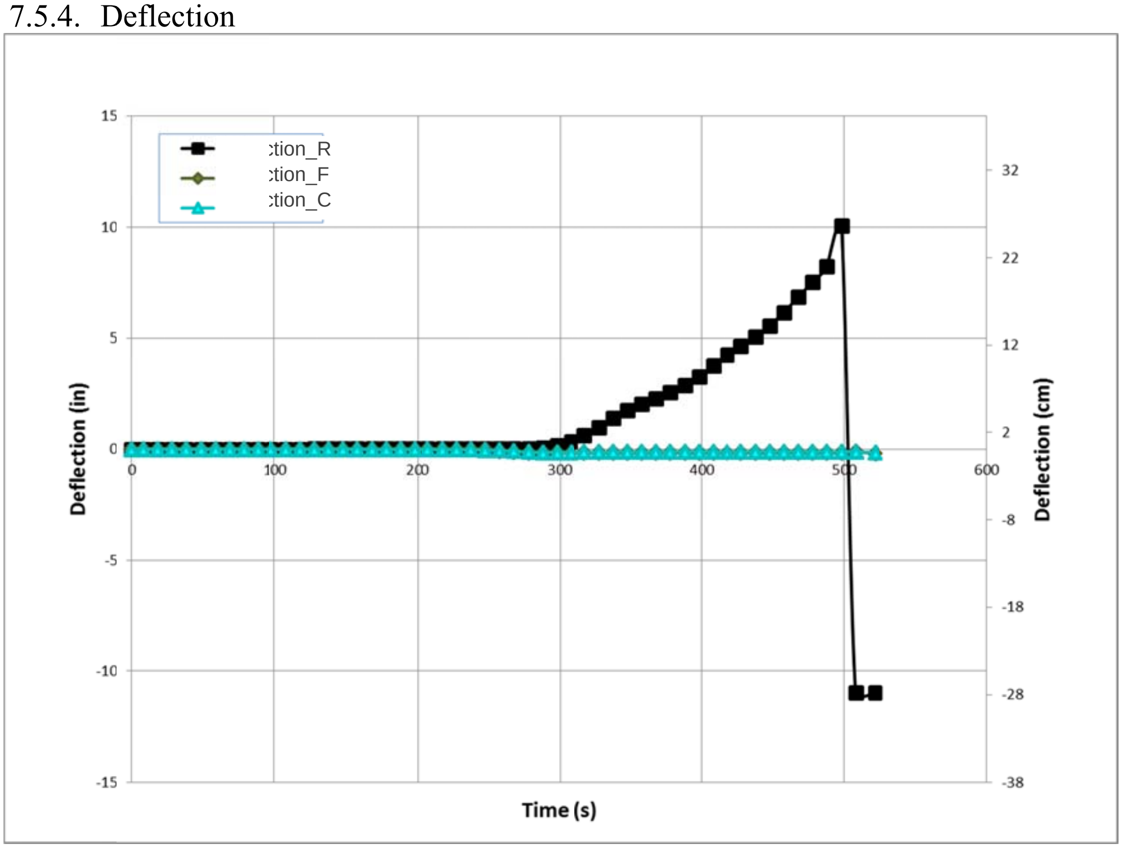

Figure 157. Experiment 5 - Floor System Deflections

7.5.5. Structural Response

The primary structural failure occurred at the rear section of the floor system, local to the initial fire location. The failure mode for the engineered I-joists was due to burn-out of the web members (Figure 158 and Figure 159). The web burn-out induced separation of the top and bottom chord members, in some cases causing separation of the subfloor due to fastener mechanical separation (Figure 160). Rupture of the chord members was also noted throughout the collapsed area (Figure 161 and Figure 162). Internal hinges developed at web member butt joint locations for some framing members (Figure 163). The floor system began to progressively deflect from approximately 300 seconds until the end of the test. Experiment 5 induced a collapse of approximately 33 % of the total floor structure (Figure 164). The collapse time for the Experiment 5 was 8:27 after ignition. The collapse time respective of the structural element fire involvement for Experiment 5 was 4:42.

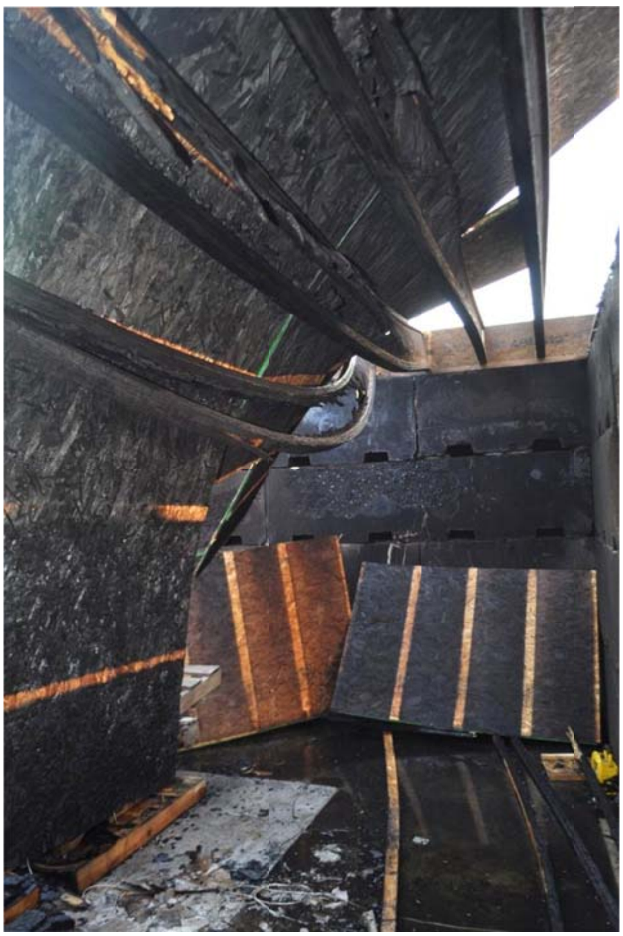
Figure 158 Web burn-out of engineered I-joists at rear section of floor area.


Figure 159 Web burn-out of engineered I-joists at rear section of floor area.


Figure 160 Separation of subfloor due to fastener mechanical separation.

Figure 161 Engineered I-joist at center section of floor area adjacent to rear floor section collapse.

Figure 162 Engineered I-joists web burn-out and flange rupture.

Figure 163 Top chord rupture and internal hinge development at web member butt joint locations.

Figure 164 Exterior view of percentage of collapsed area.

7.6. Experiment 6 – Engineered I Joist

In this experiment all of the ventilation openings were open prior to ignition and the fire was ignited in the rear fuel package closest to the base of the stairs. The fire spread until the floor system collapsed and then was suppressed. The loading on the floor system was modified in this experiment to reflect the loading used on previous floor furnace experiments. Instead of having a uniform loading of 65 % of the design stress, the rear of the floor system was loaded with 40 lb/ft^2 on two walls and two 300 lb barrels were located at the mid span (See Section 6.3). The timeline of events is detailed in Table 30. The results for the experiment are presented in the following sections: observations, temperature, gas velocity, and deflection.

Table 30. Experiment 6 Timeline

Time (s, mm:ss)	Event
0 (0:00)	Ignition
180 (3:00)	Flames attach to the floor system
409 (6:49)	Collapse
475 (7:55)	End of experiment

7.6.1. Observations

The observations are presented as a series of images captured from eight camera locations, seven were video cameras and one was a thermal imaging camera. The views were captured at the start of the experiment (0:00, Figure 165), once flames attached to the floor system (3:00, Figure 166), when flames are seen exiting the doorway to the first floor (3:22, Figure 167), and 5 seconds before collapse (6:44, Figure 168).

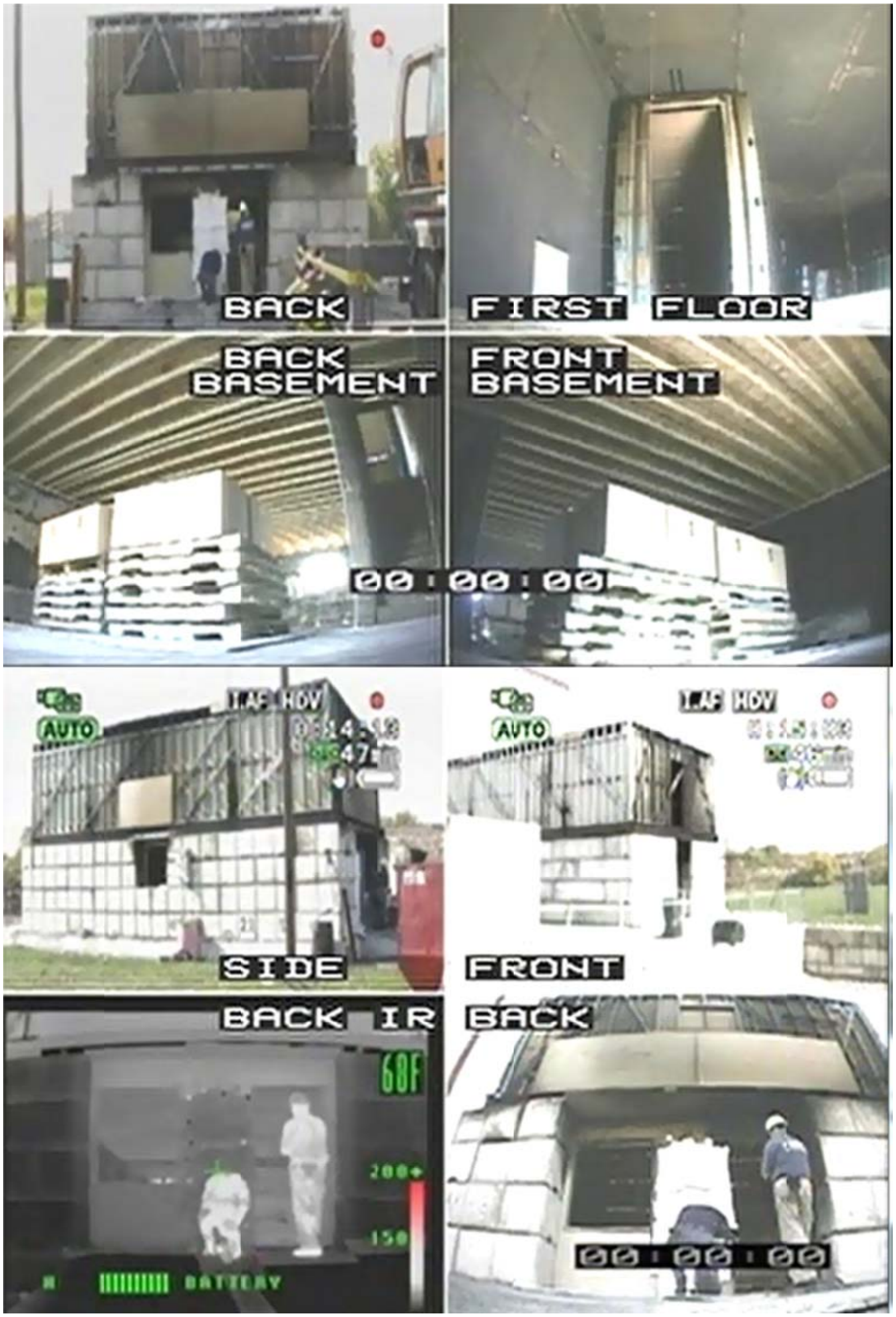

Figure 165. Experiment 6 video views at 0:00.

Figure 166. Experiment 6 video views at 3:00.

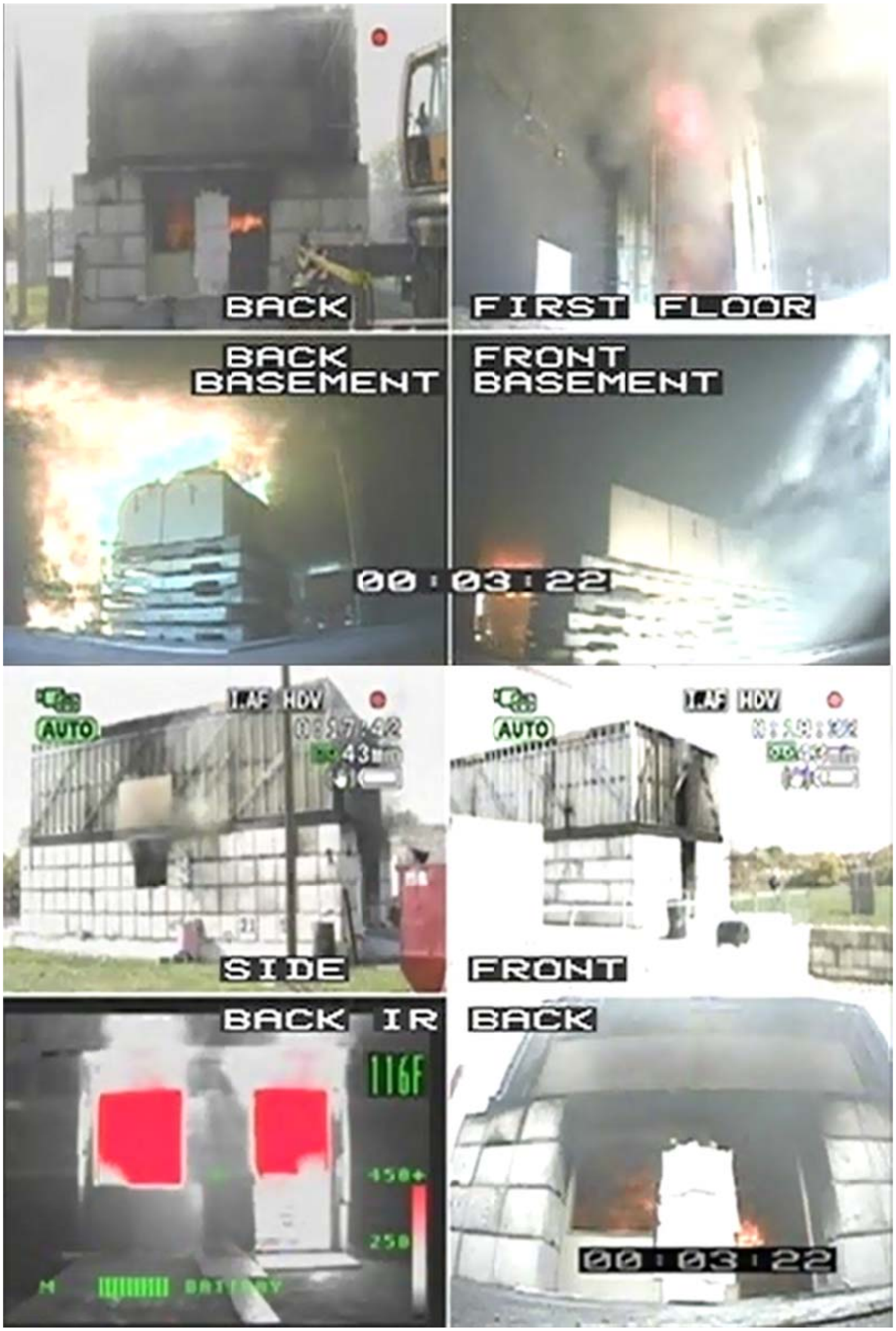

Figure 167. Experiment 6 video views at 3:22.

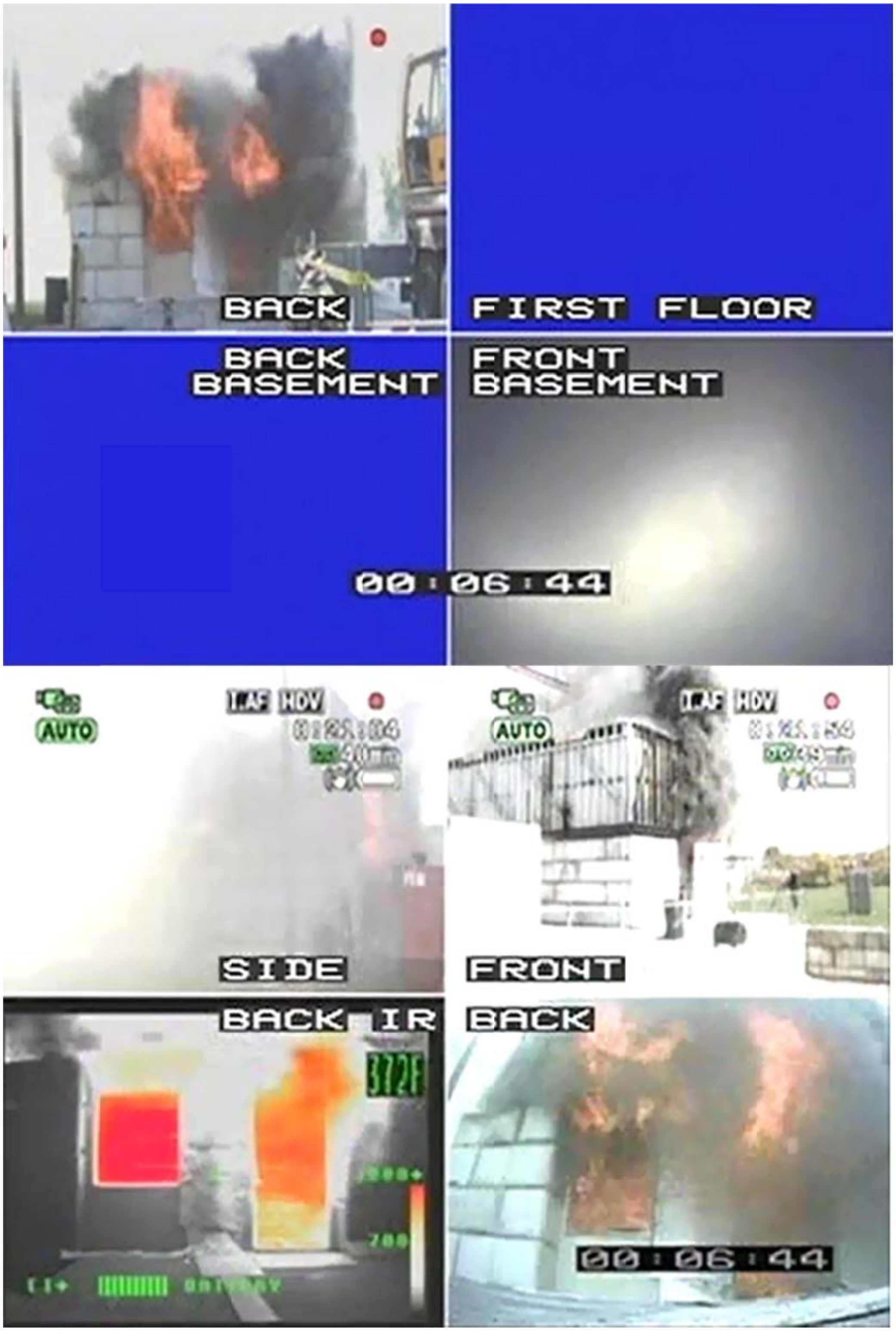

Figure 168. Experiment 6 video views at 6:44.

7.6.2. Temperature

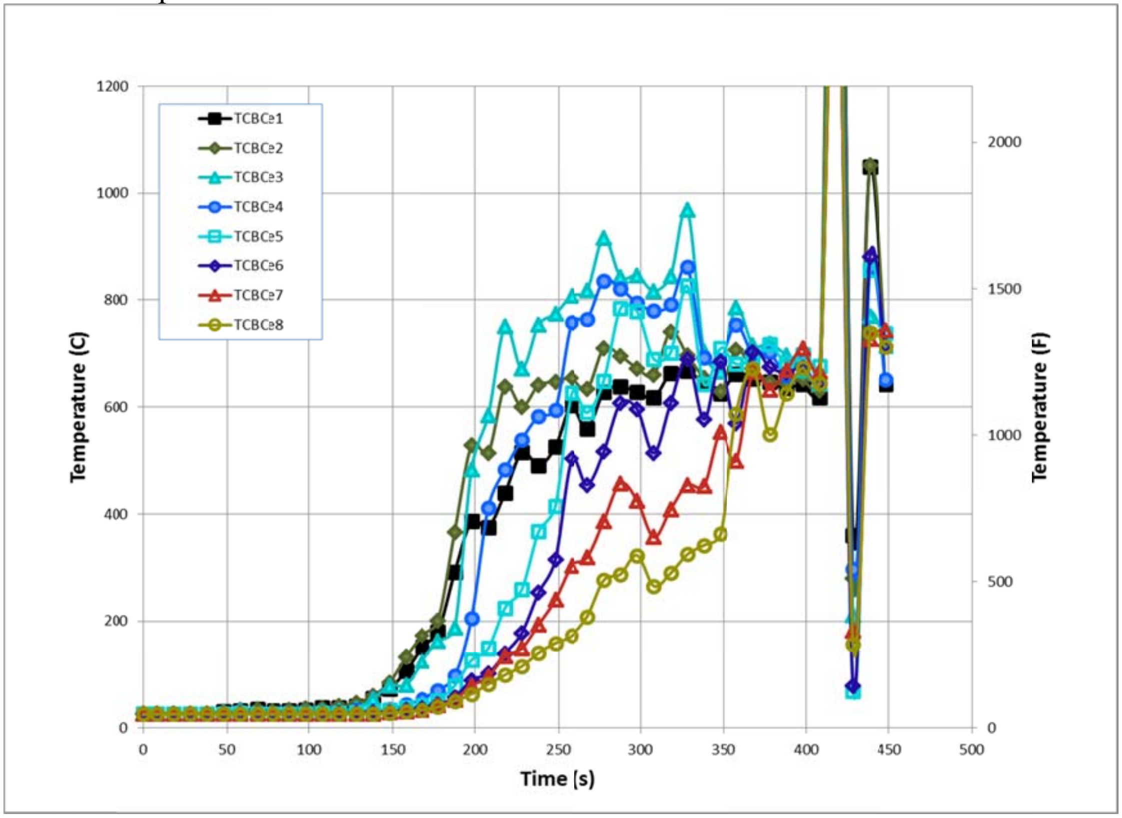

Figure 169. Experiment 6 - Basement Center Temperatures

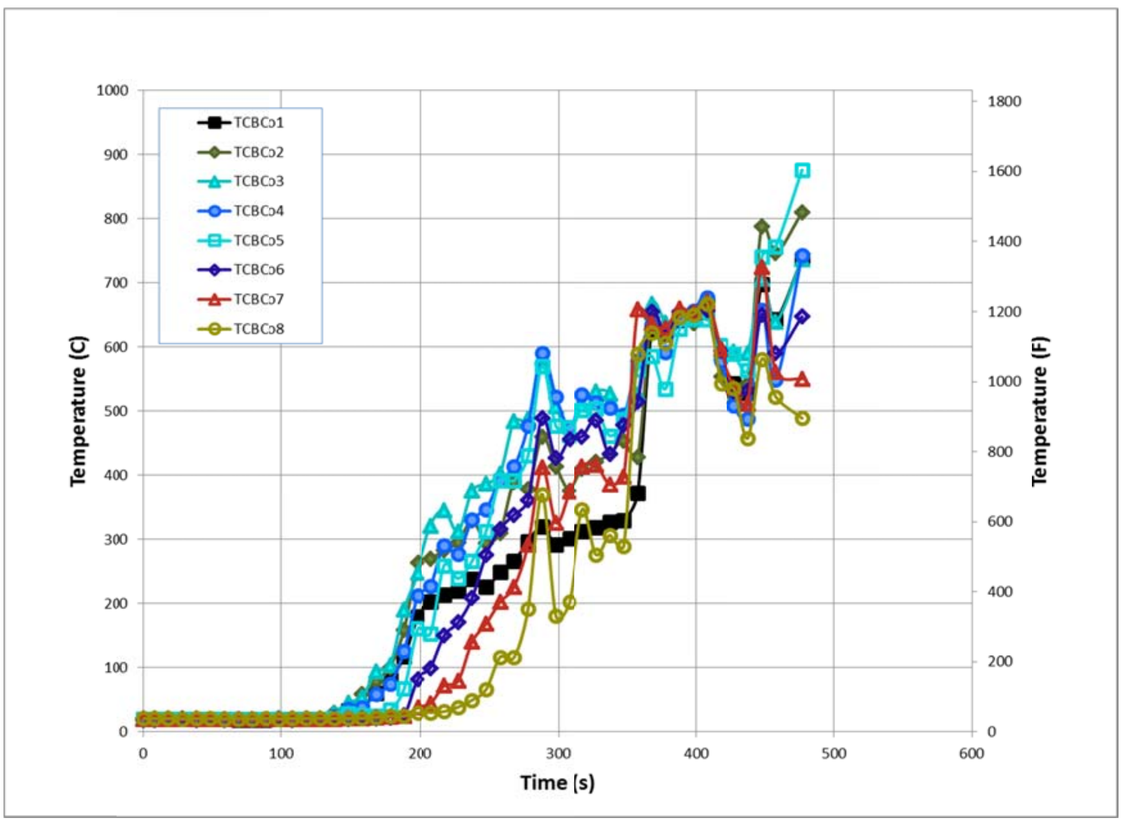

Figure 170. Experiment 6 - Basement Corner Temperatures

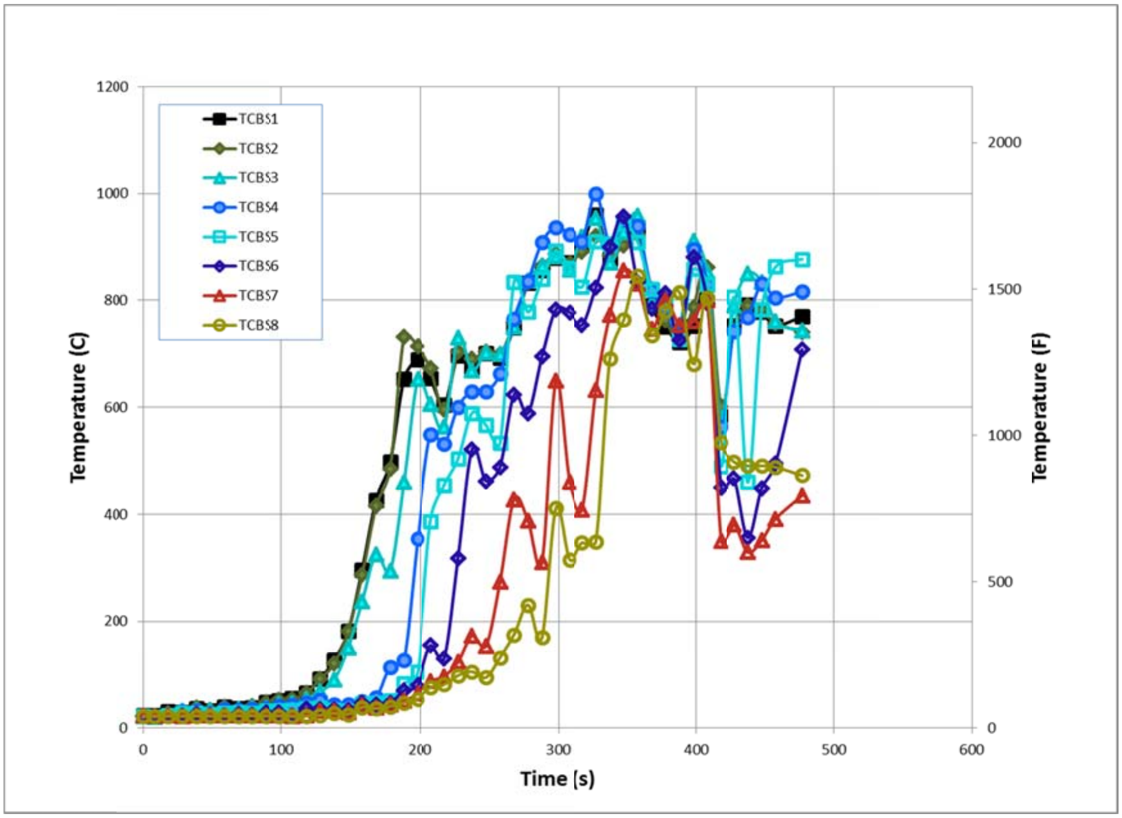

Figure 171. Experiment 6 - Basement Base of Stair Temperatures

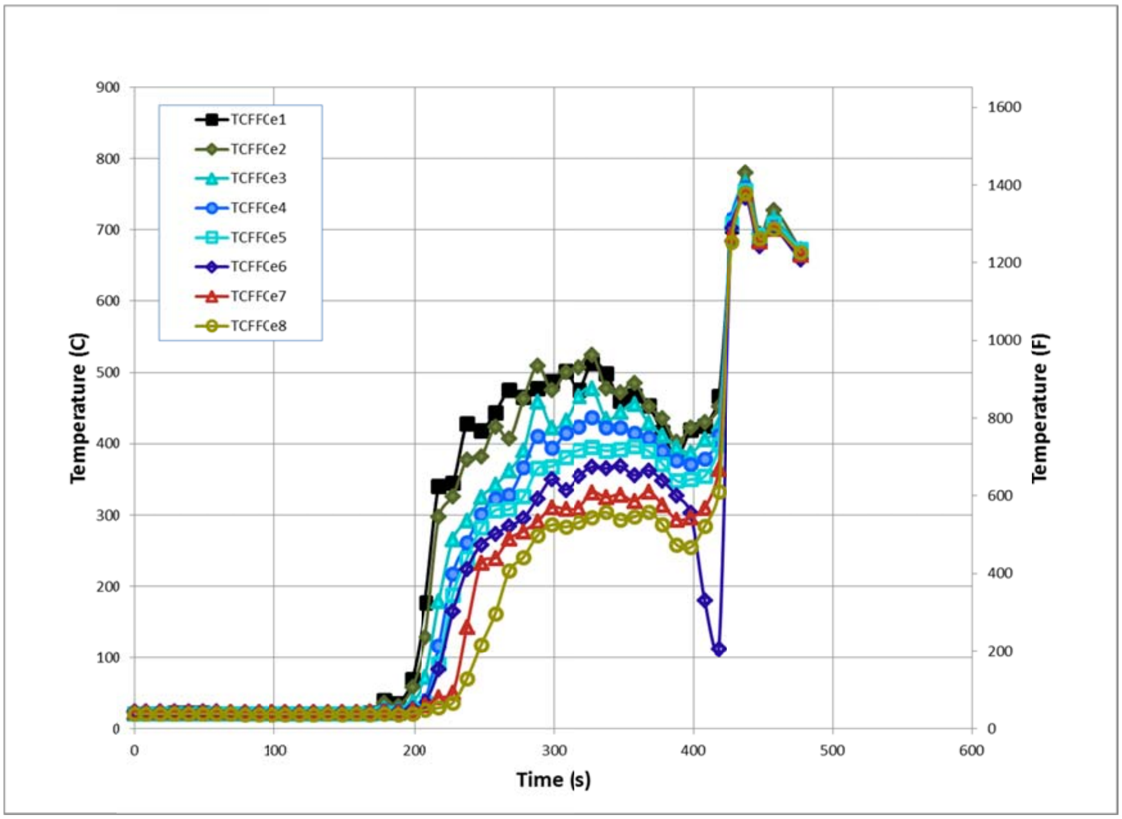

Figure 172. Experiment 6 - First Floor Center Temperatures

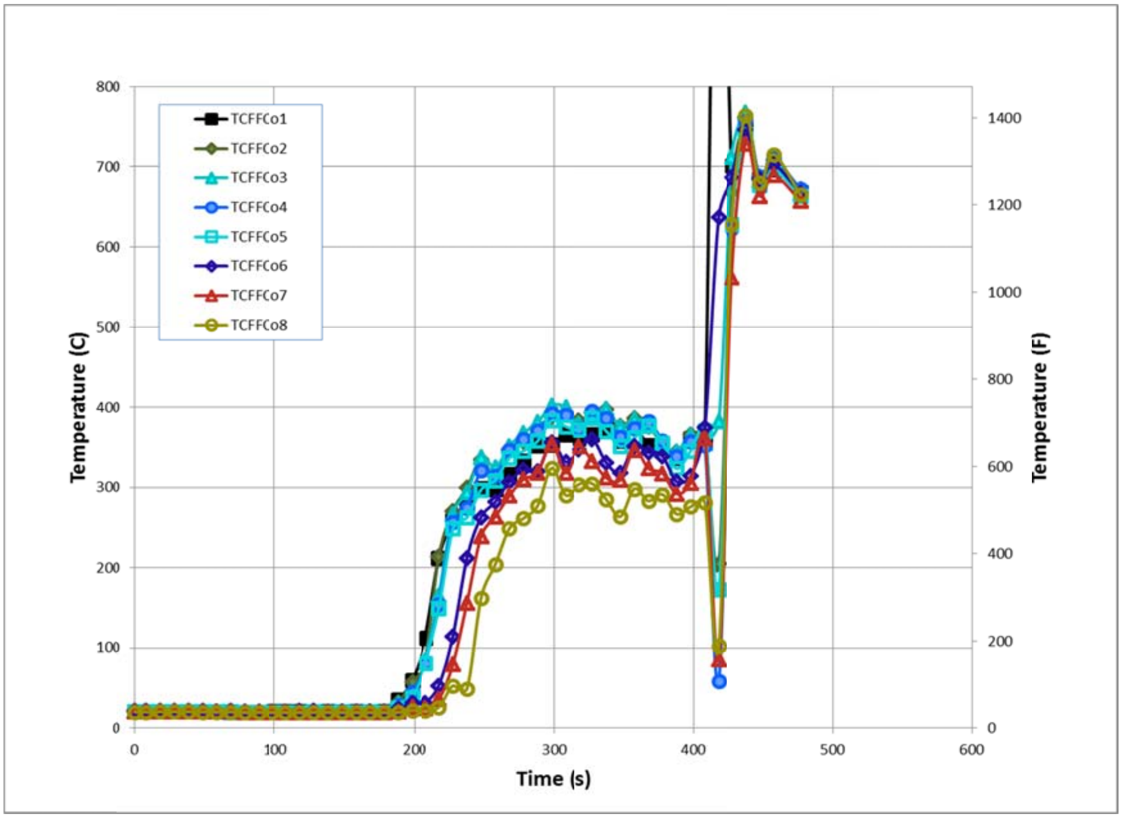

Figure 173. Experiment 6 - First Floor Corner Temperatures

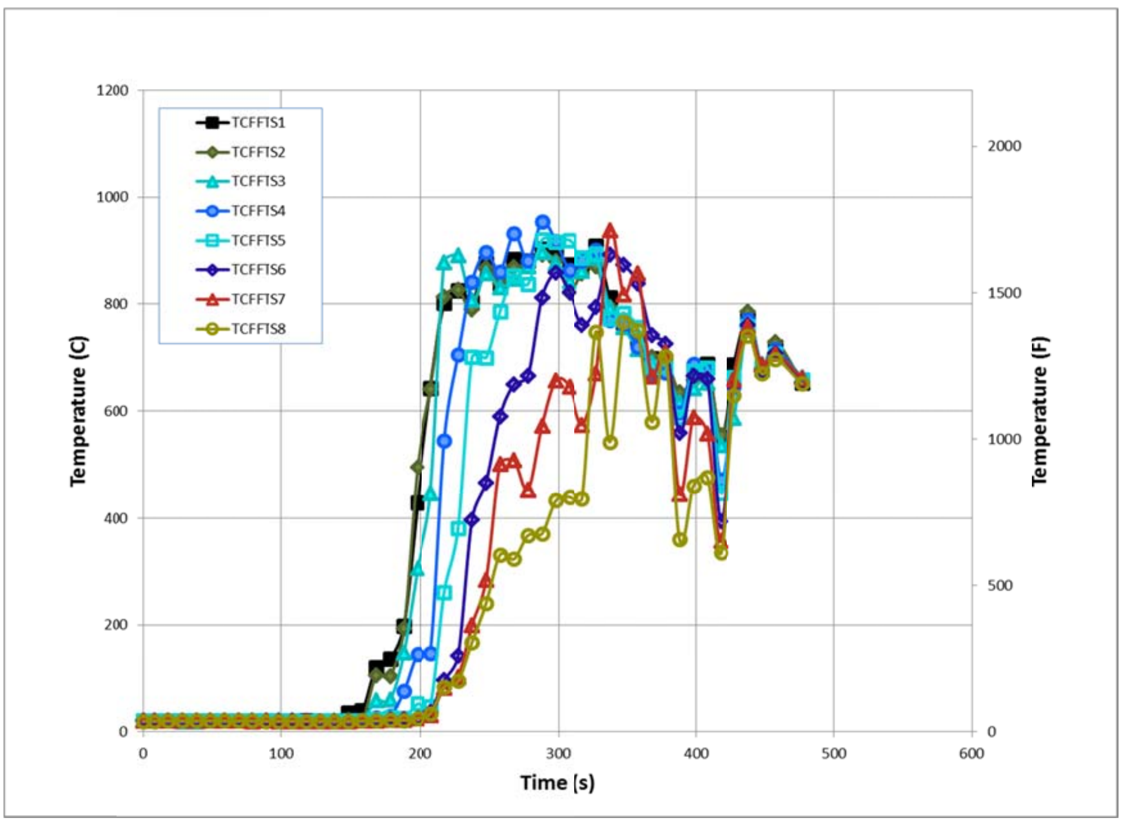

Figure 174. Experiment 6 - First Floor Top of Stair Temperatures

7.6.3. Gas Velocity

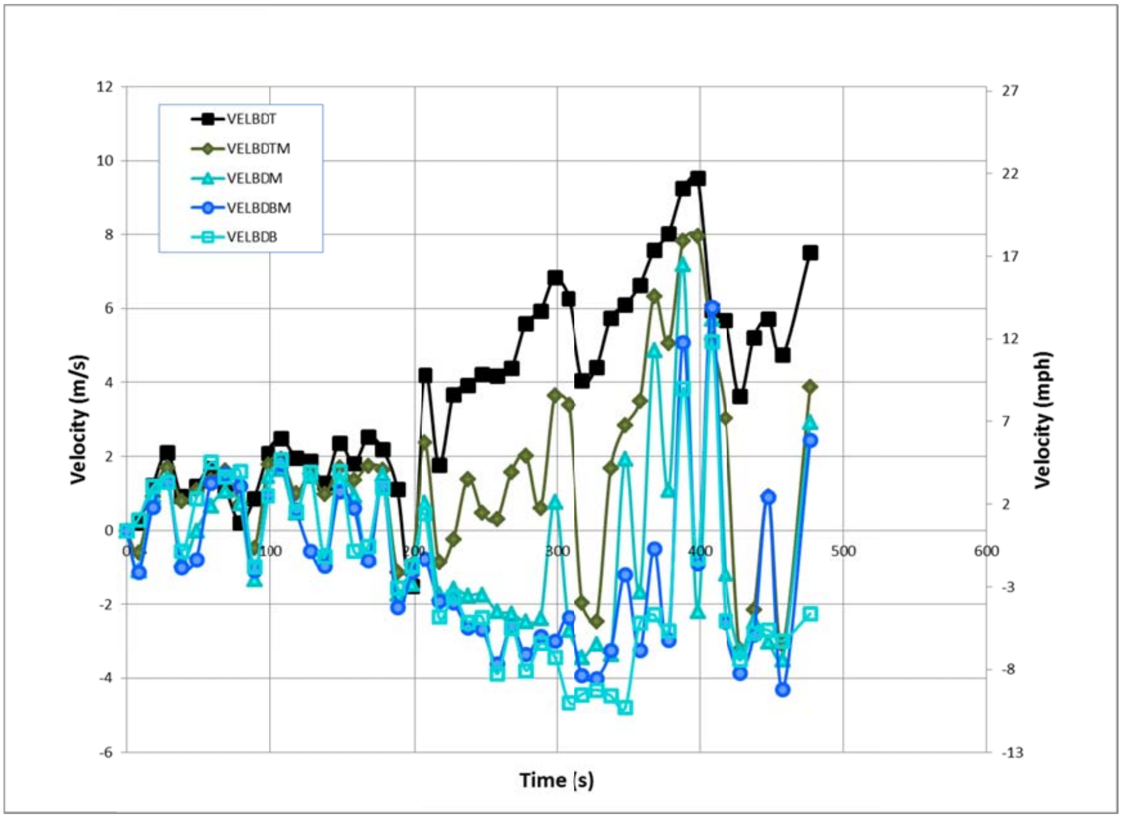

Figure 175. Experiment 6 - Basement Door Velocities

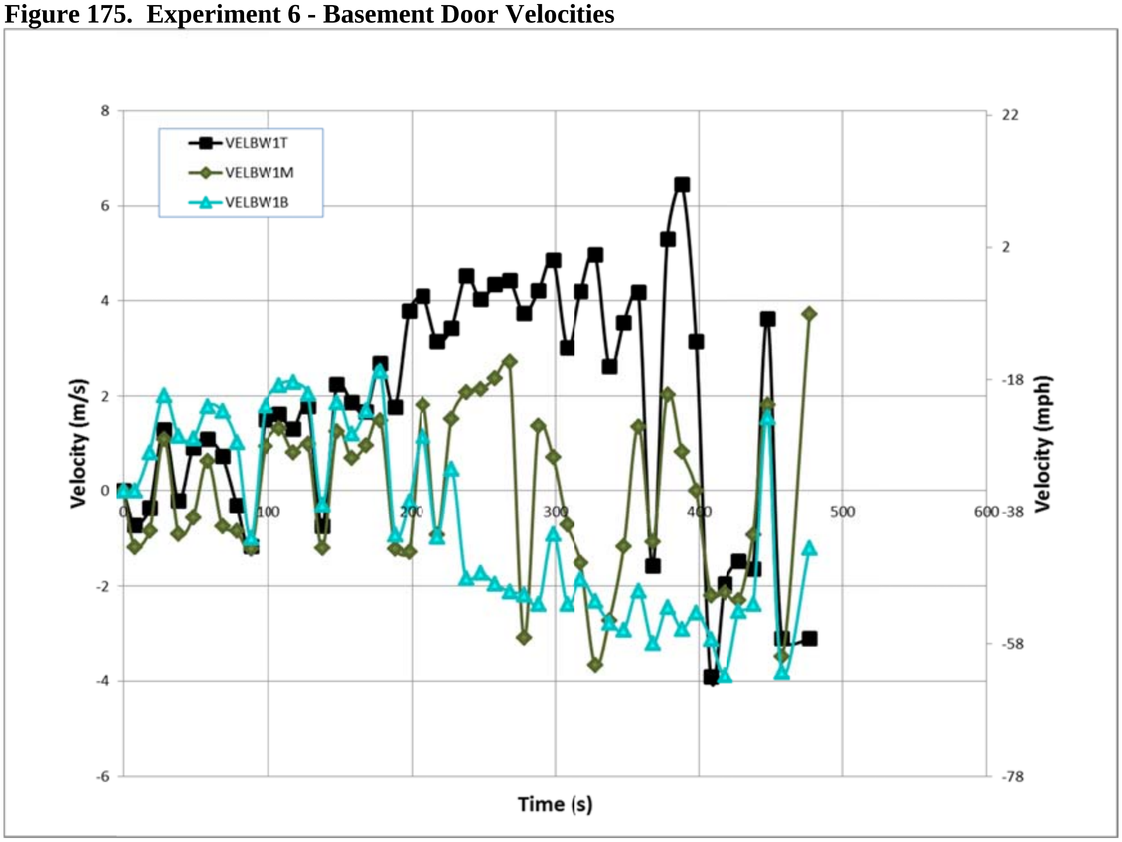

Figure 176. Experiment 6 - Basement Window 1 Velocities

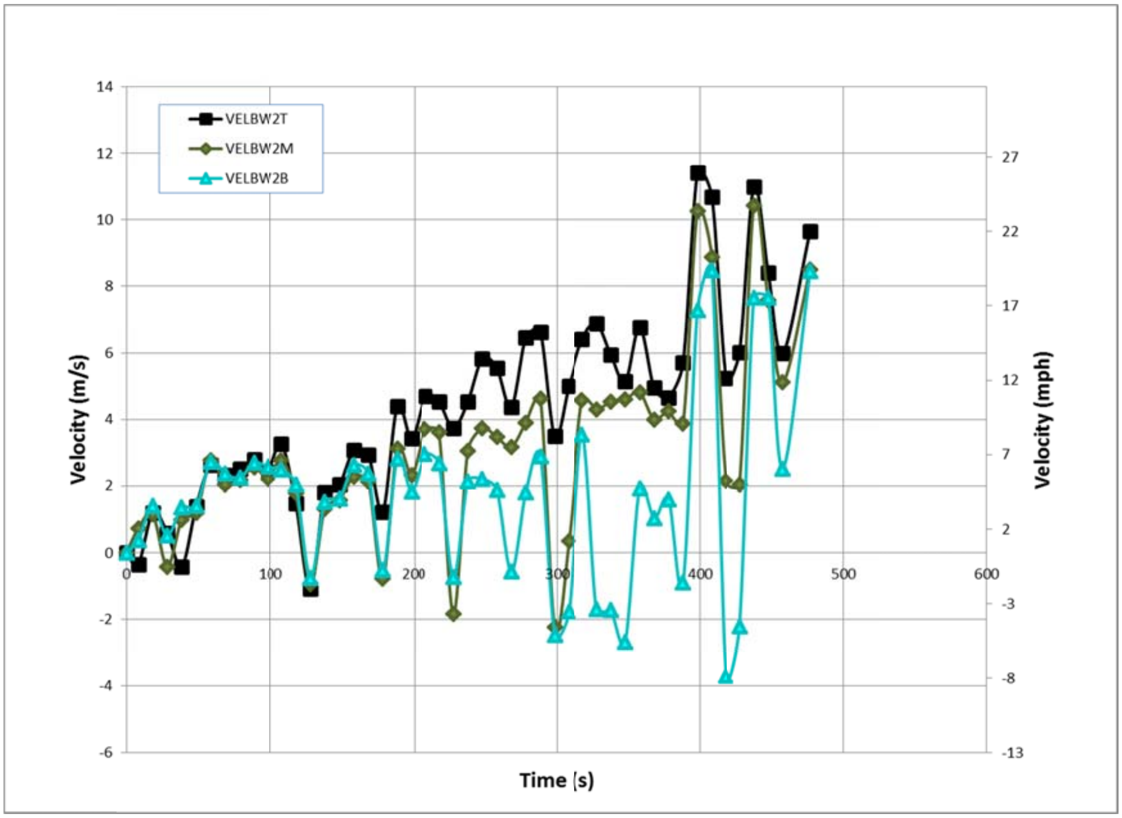

Figure 177. Experiment 6 - Basement Window 2 Velocities

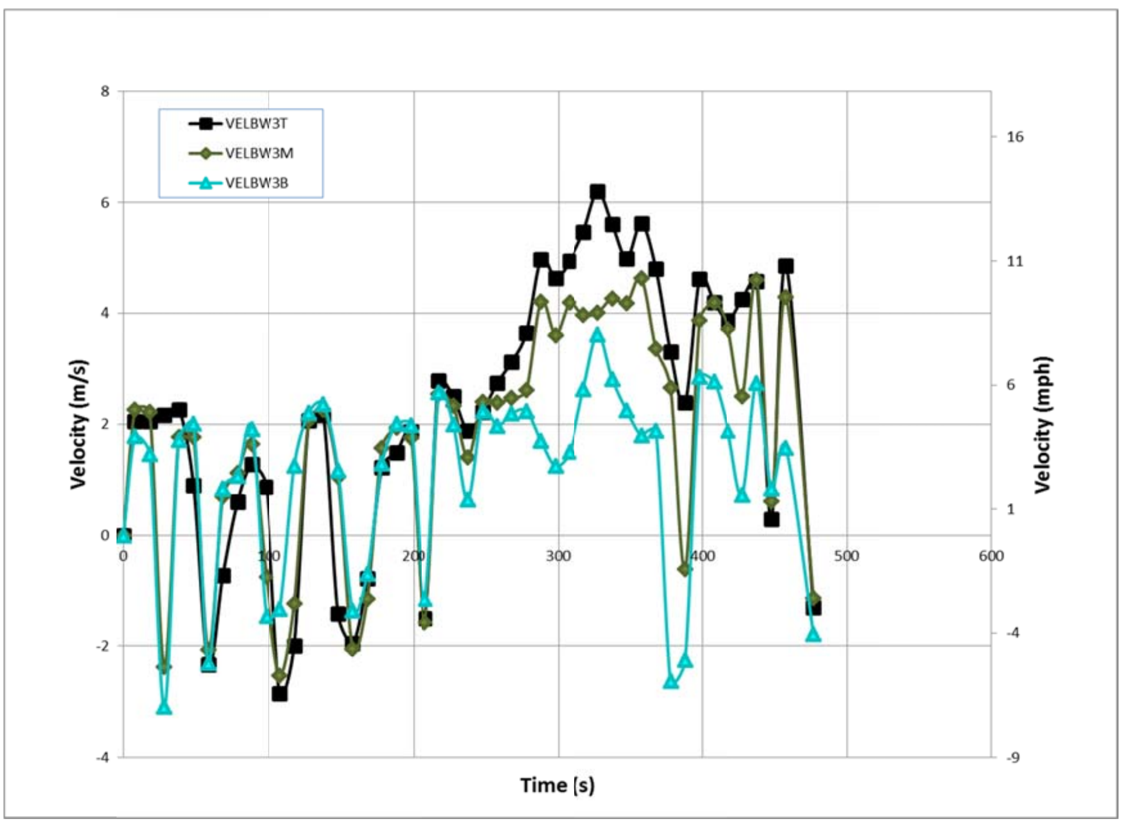

Figure 178. Experiment 6 - Basement Window 3 Velocities

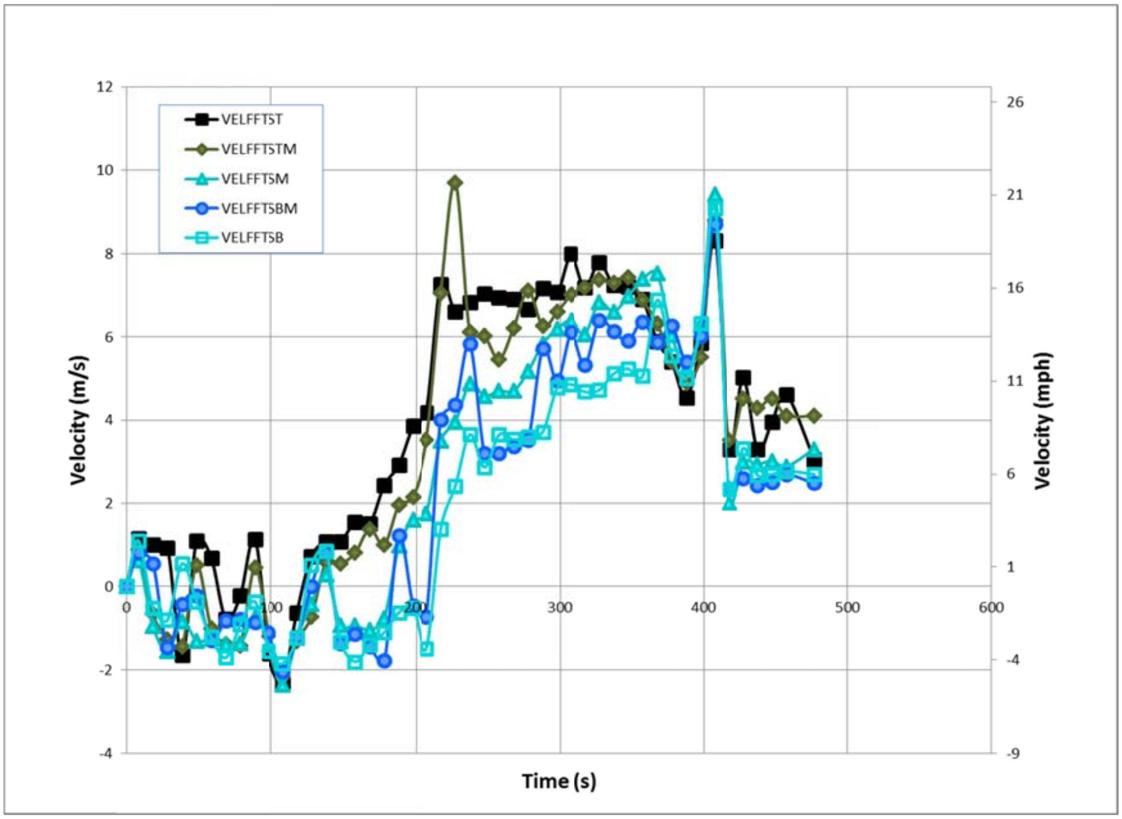

Figure 179. Experiment 6 - First Floor Stair Velocities

7.6.4. Deflection

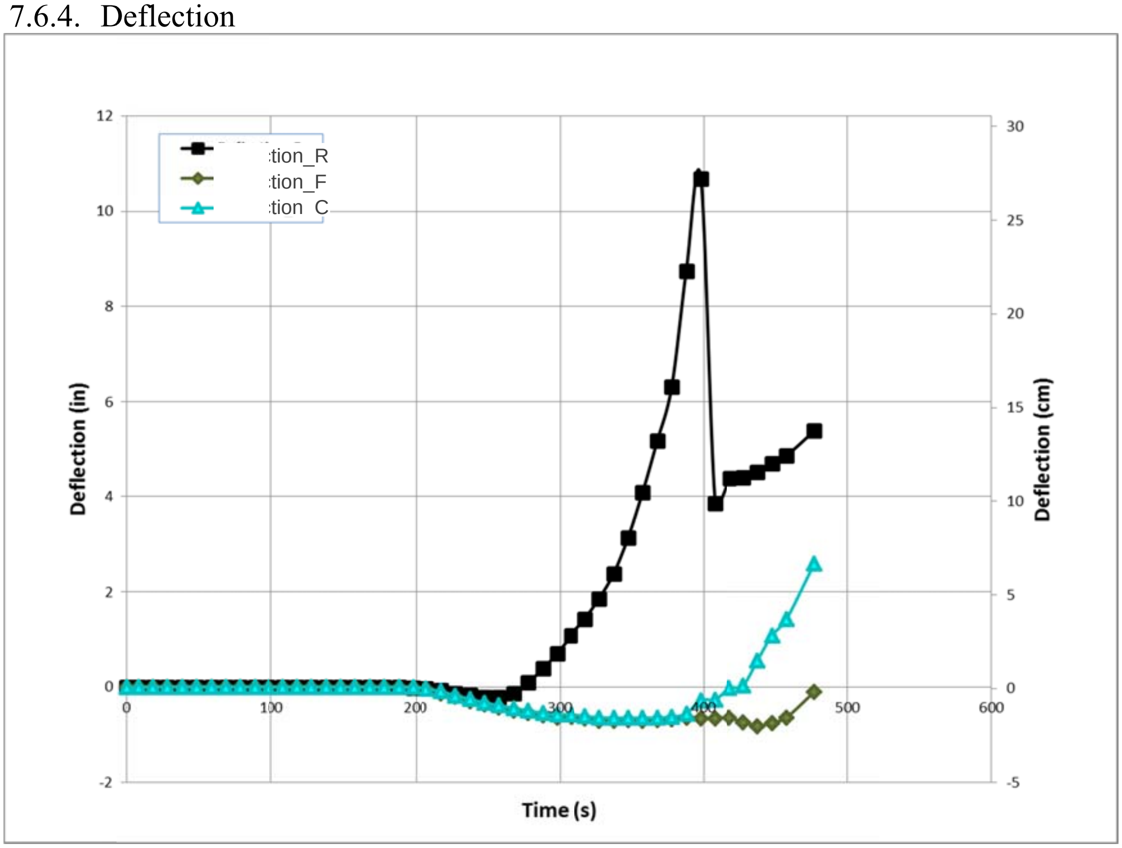

Figure 180. Experiment 6 - Floor System Deflections

7.6.5. Structural Response

Test number 6 utilized a modified applied load similar to the loading scheme produced for floor furnace testing for the Structural Stability of Engineered Lumber Project (UL 2006). The primary structural failure occurred at the rear and center sections of the floor system, local and adjacent to the initial fire location. The failure mode for the engineered I-joists was due to burn-out of the web members (Figure 181 and Figure 182). The web burn-out produced a significant reduction in the joist depth as the top and bottom chord members converged resulting in a loss of member stiffness (Figure 183). Excessive deflections were noted throughout the floor assembly, this precipitated a collapse of the rear and center sections of the floor system. Various locations of subflooring burn through were also documented (Figure 184). The floor system began to progressively deflect from approximately 250 seconds until the end of the test. Experiment 6 induced a collapse of approximately 65 % of the total floor structure and caused significant damage to the remainder of the floor structure (Figure 186). The collapse time for the Experiment 6 was 6:49 after ignition. The collapse time respective of the structural element fire involvement for Experiment 6 was 3:49.

Figure 181 Web burn-out of the engineered I-joist produced a significant reduction in the joist depth and excessive deflection.

Figure 182 Web burn-out of the engineered I-Joist produced a significant reduction in the joist depth and excessive deflection.


Figure 183 Comparison of original engineered I-joist joist depth to post experiment engineered I-joist depth at front section of floor system.


Figure 184 Area of subfloor burn through located at front section of floor system..


Figure 185 Engineered I-joist web burn-out at bearing condition at front floor section.


Figure 186 Exterior view of percentage of collapsed area.

7.7. Experiment 7 – Steel C Joist

In this experiment all of the ventilation openings were open prior to ignition and the fire was ignited in the rear fuel package closest to the base of the stairs. The fire spread until the floor system collapsed and then was suppressed. The timeline of events is detailed in Table 31. The results for the experiment are presented in the following sections: observations, temperature, gas velocity, and deflection.

Table 31. Experiment 7 Timeline

Time (s, mm:ss)	Event
0 (0:00)	Ignition
180 (3:00)	Flames attach to the OSB subfloor
495 (8:15)	Collapse
510 (8:30)	End of experiment

7.7.1. Observations

The observations are presented as a series of images captured from eight camera locations, seven were video cameras and one was a thermal imaging camera. The views were captured at the start of the experiment (0:00, Figure 187), once flames attached to the floor system (3:00, Figure 188), when flames are seen exiting the doorway to the first floor (4:10, Figure 189), and 5 seconds before collapse (8:10, Figure 190).

Figure 187. Experiment 7 video views at 0:00.

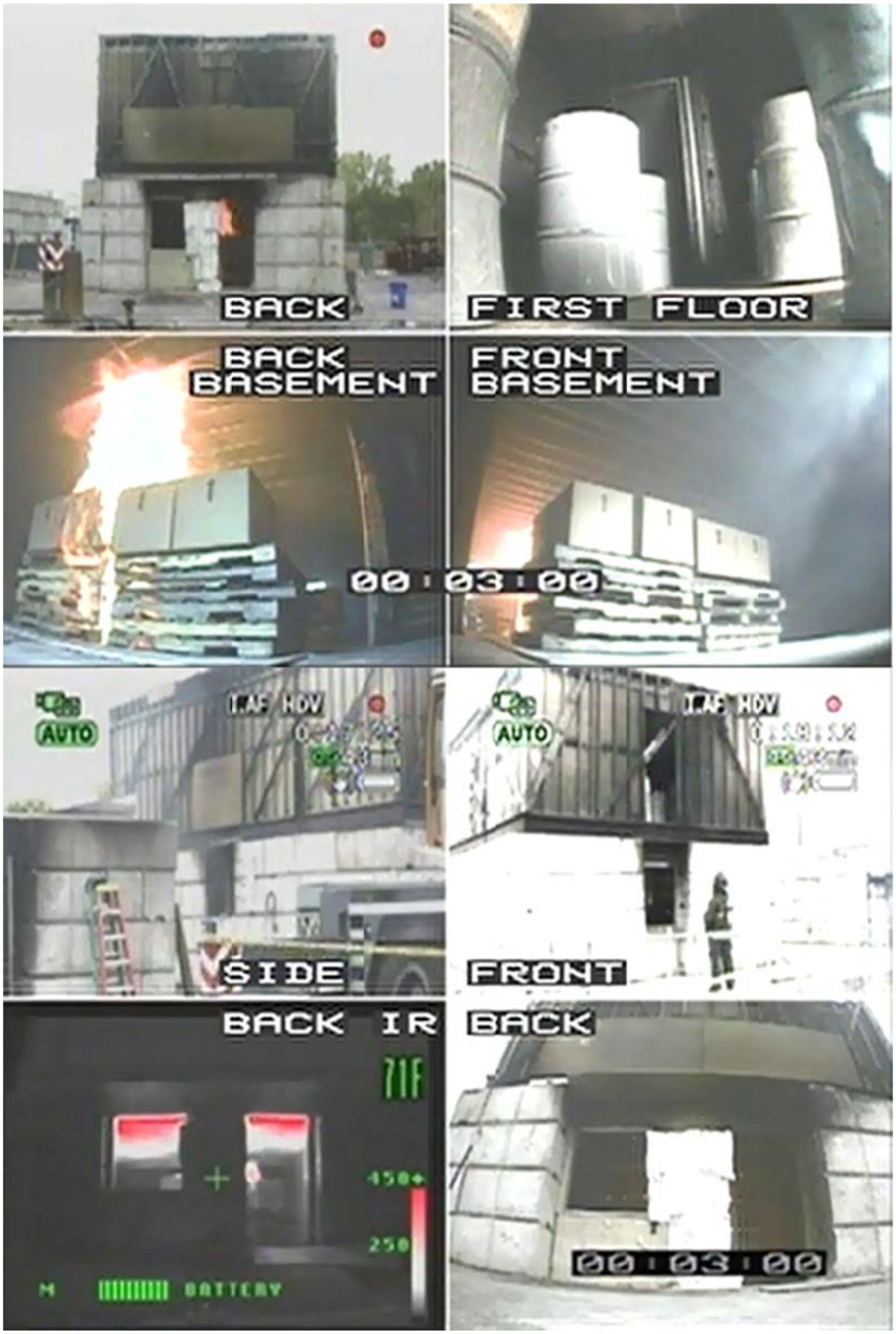

Figure 188. Experiment 7 video views at 3:00.

Figure 189. Experiment 7 video views at 4:10.

Figure 190. Experiment 7 video views at 8:10.

7.7.2. Temperature

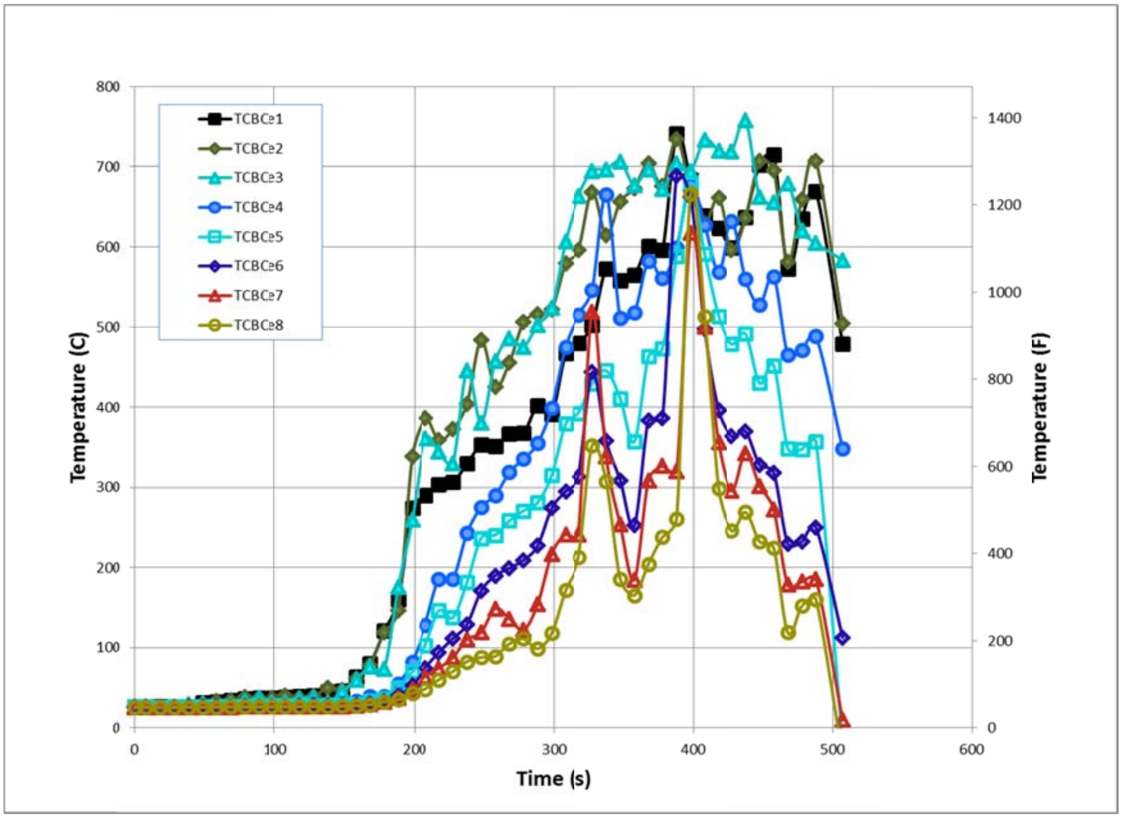

Figure 191. Experiment 7 - Basement Center Temperatures

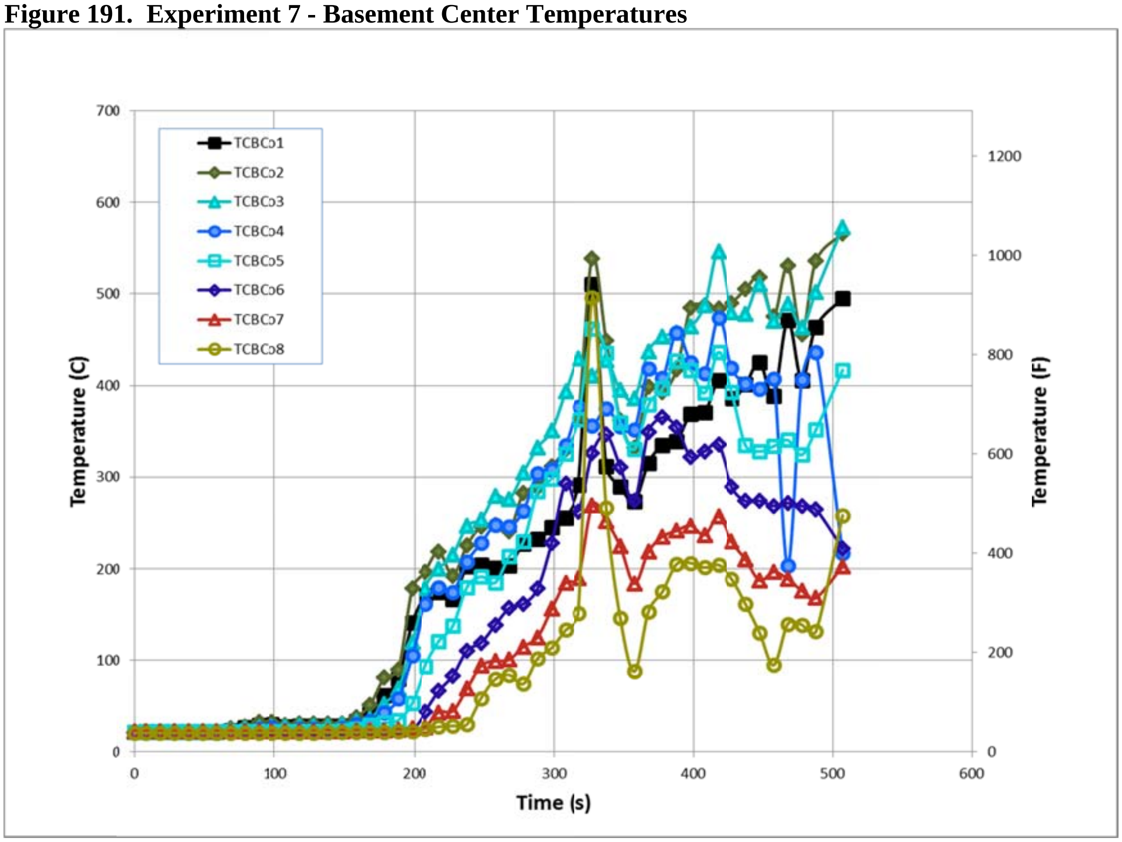

Figure 192. Experiment 7 - Basement Corner Temperatures

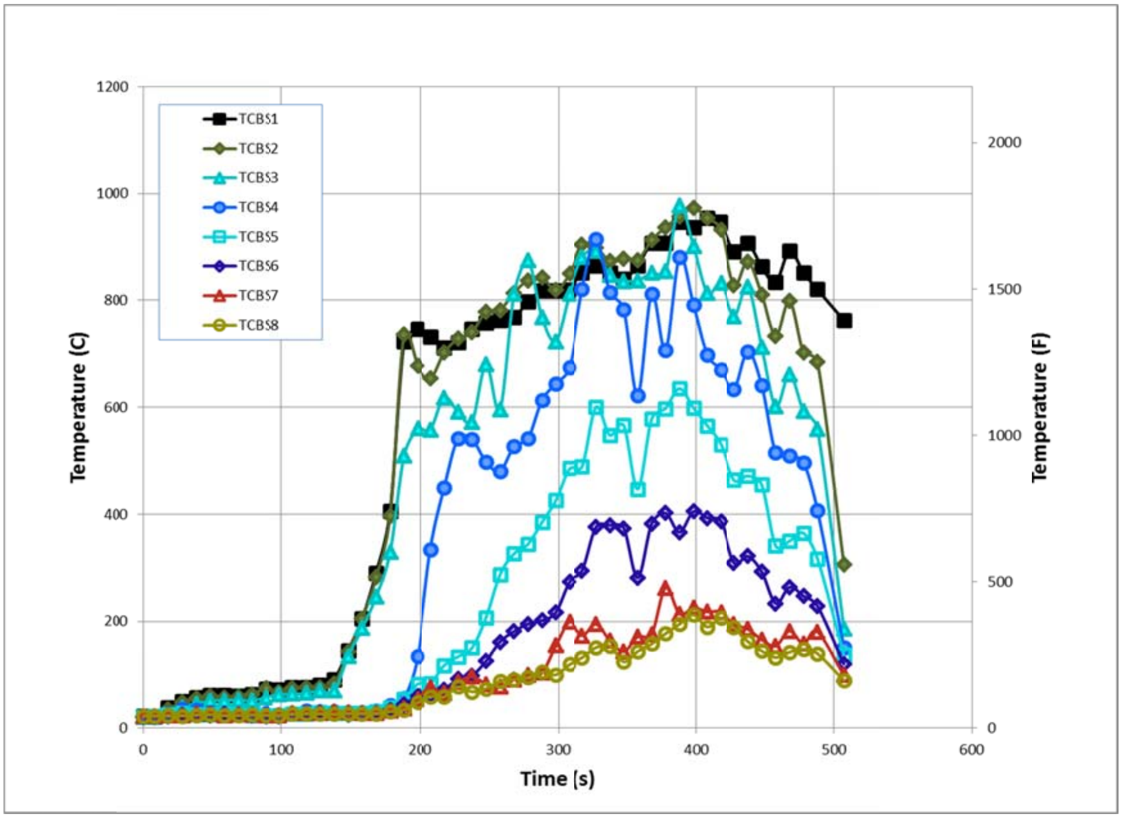

Figure 193. Experiment 7 - Basement Base of Stair Temperatures

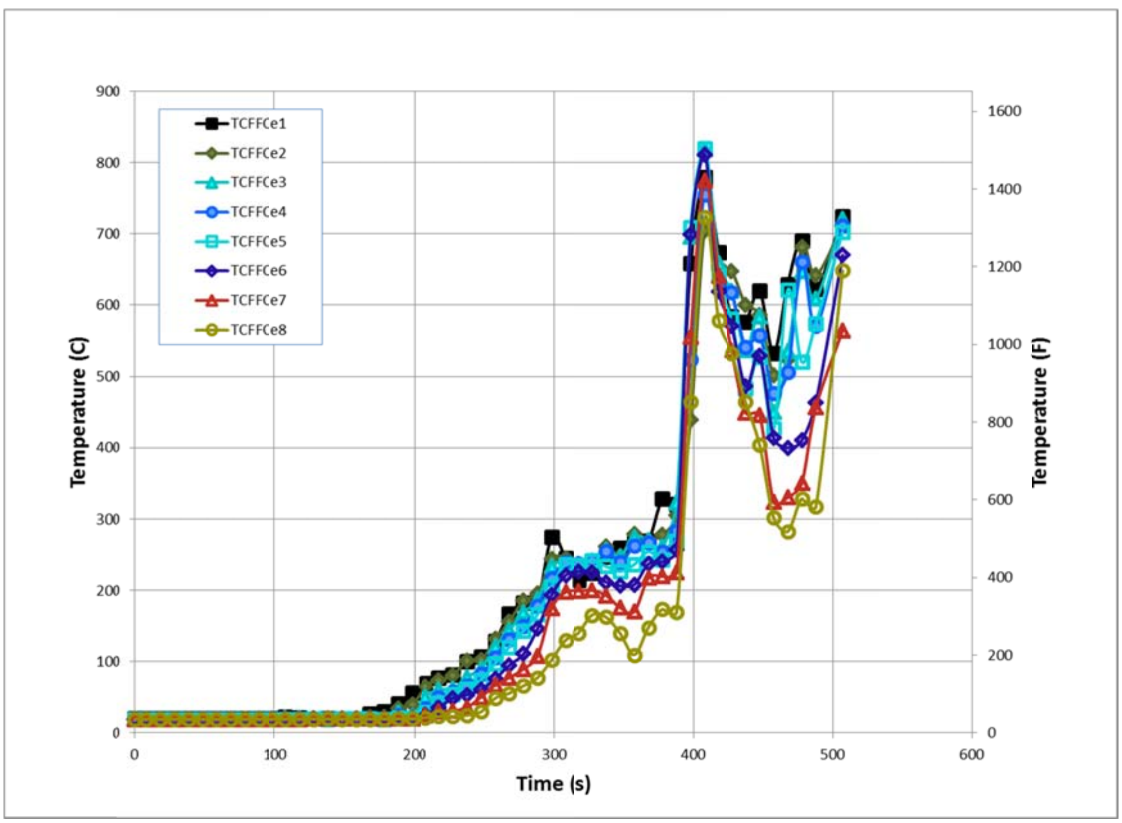

Figure 194. Experiment 7 - First Floor Center Temperatures

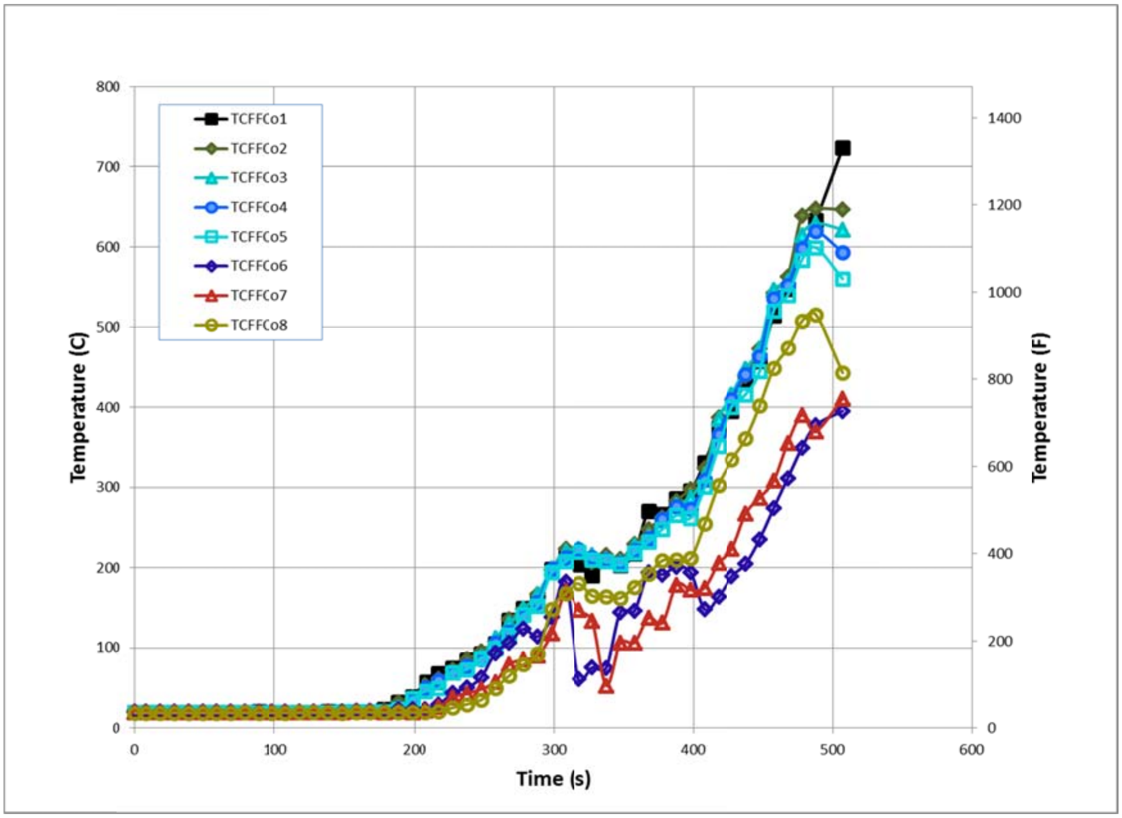

Figure 195. Experiment 7 - First Floor Corner Temperatures

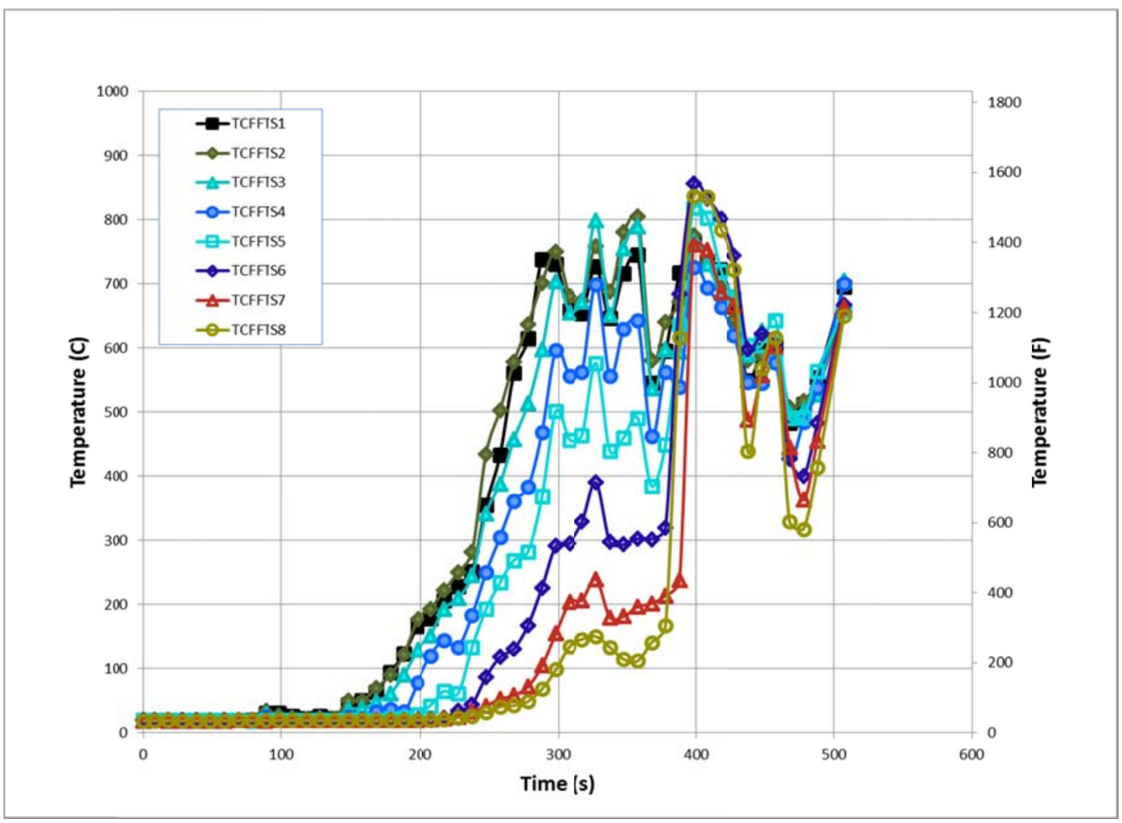

Figure 196. Experiment 7 - First Floor Top of Stair Temperatures

7.7.3. Gas Velocity

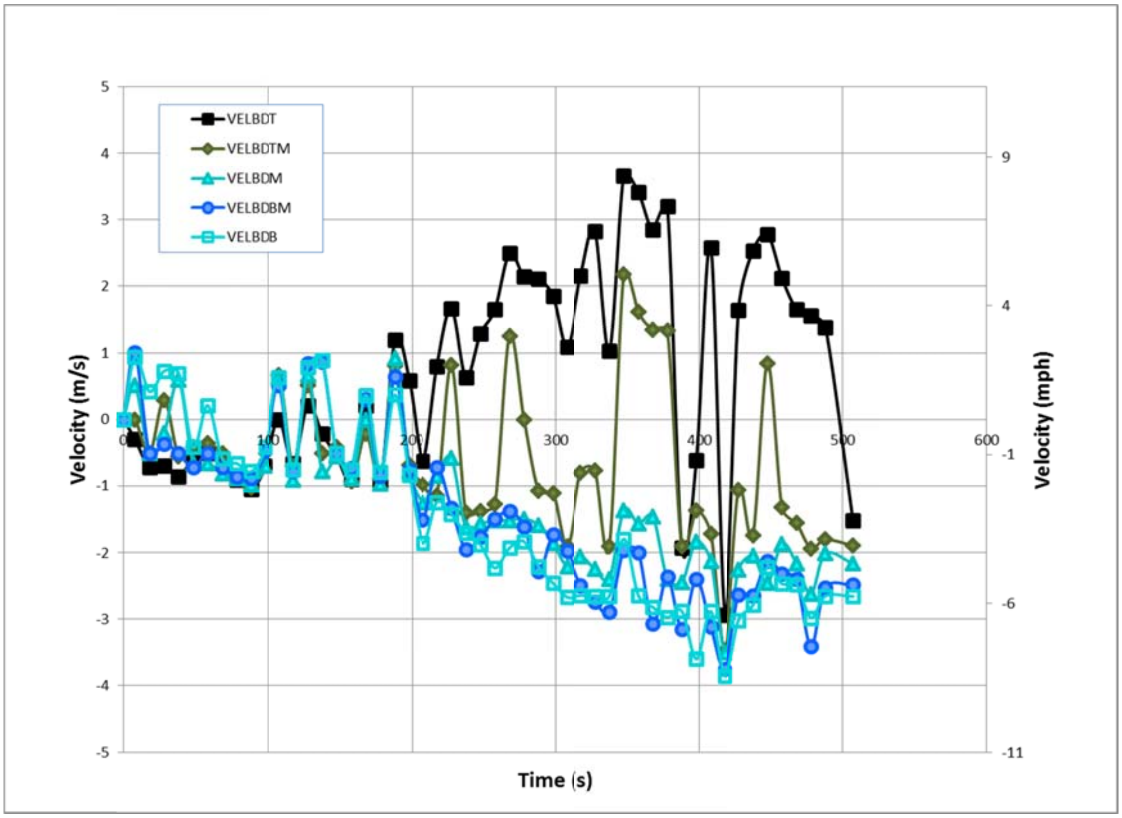

Figure 197. Experiment 7 - Basement Door Velocities

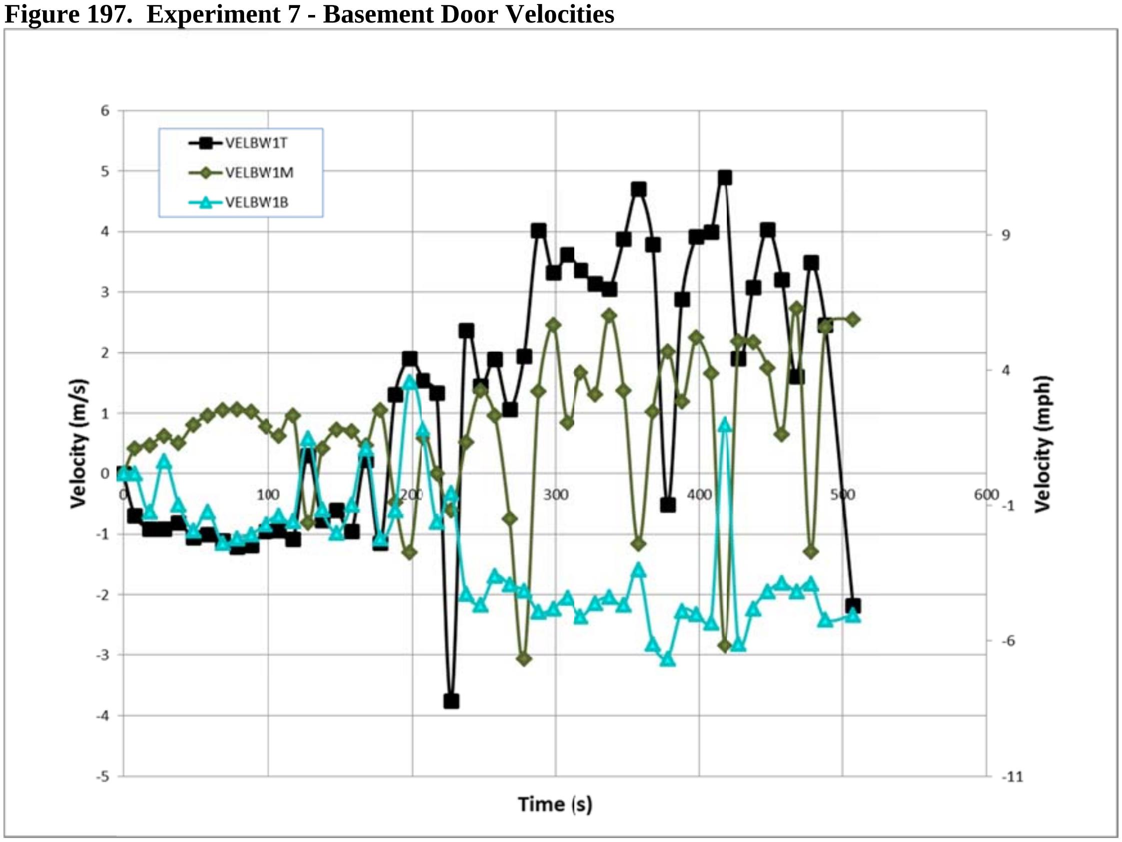

Figure 198. Experiment 7 - Basement Window 1 Velocities

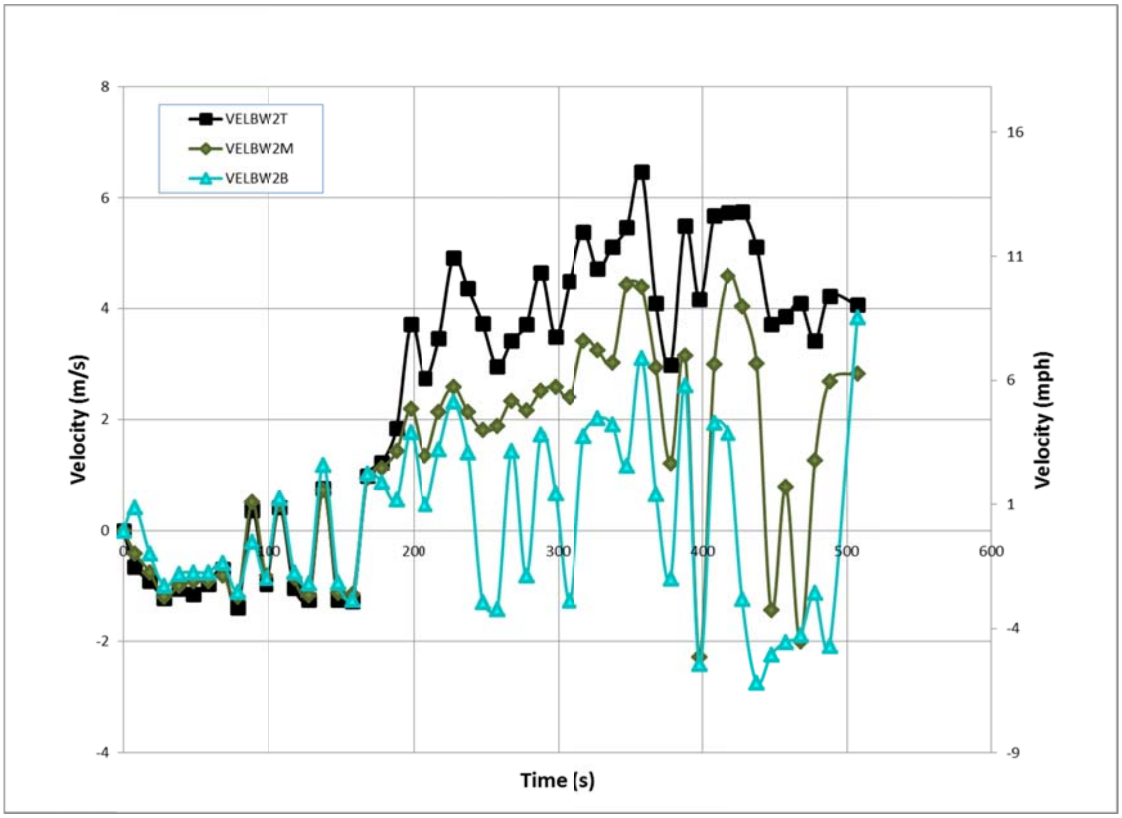

Figure 199. Experiment 7 - Basement Window 2 Velocities

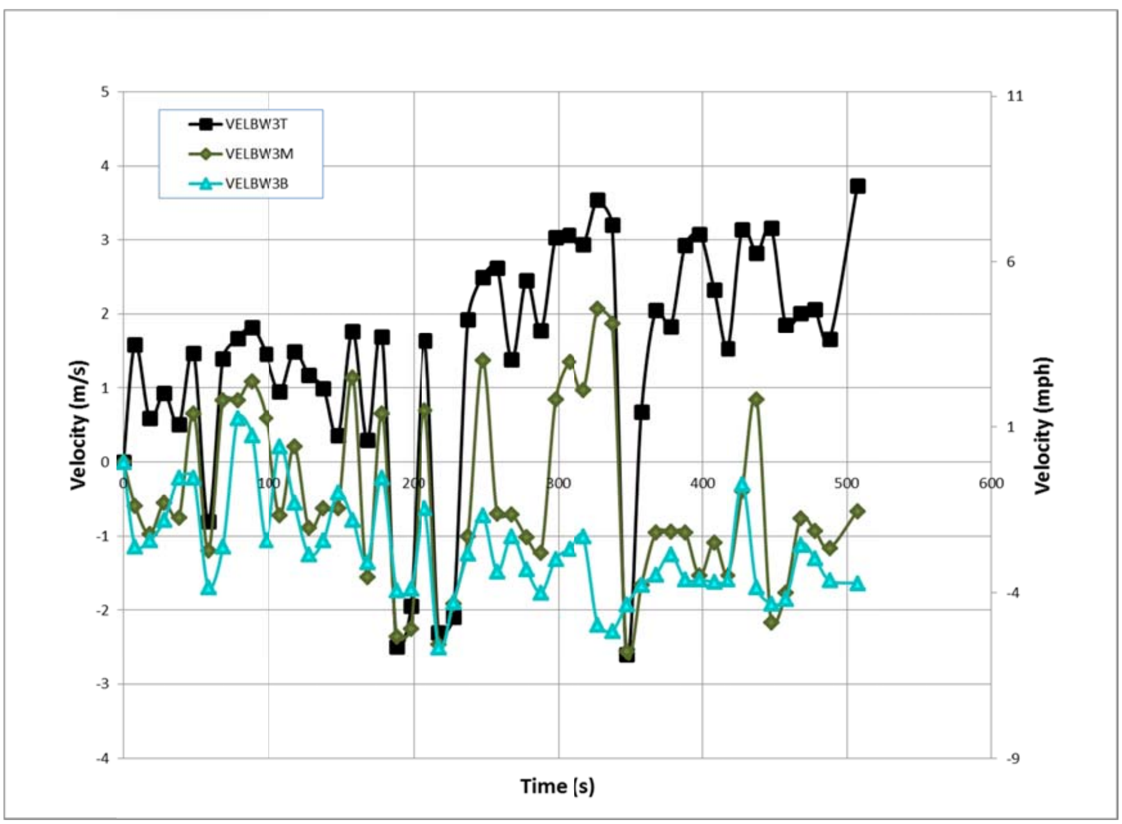

Figure 200. Experiment 7 - Basement Window 3 Velocities

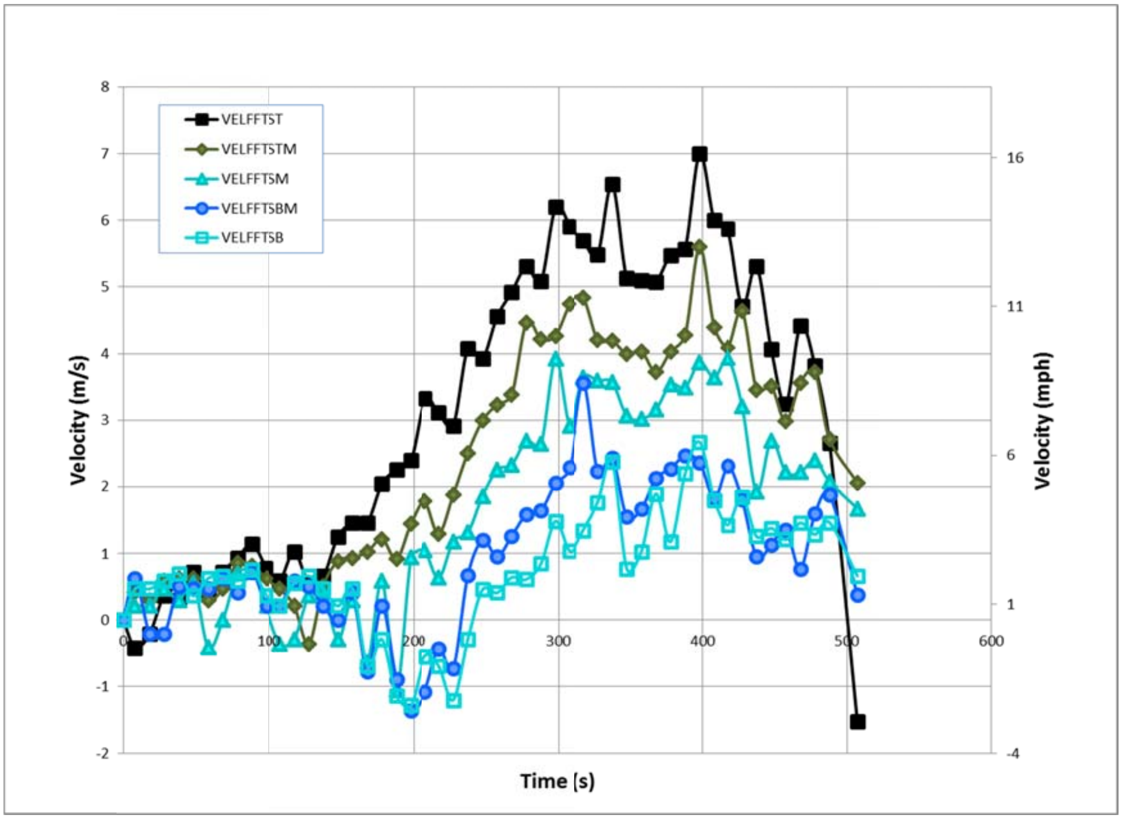

Figure 201. Experiment 7 - First Floor Stair Velocities

7.7.4. Deflection

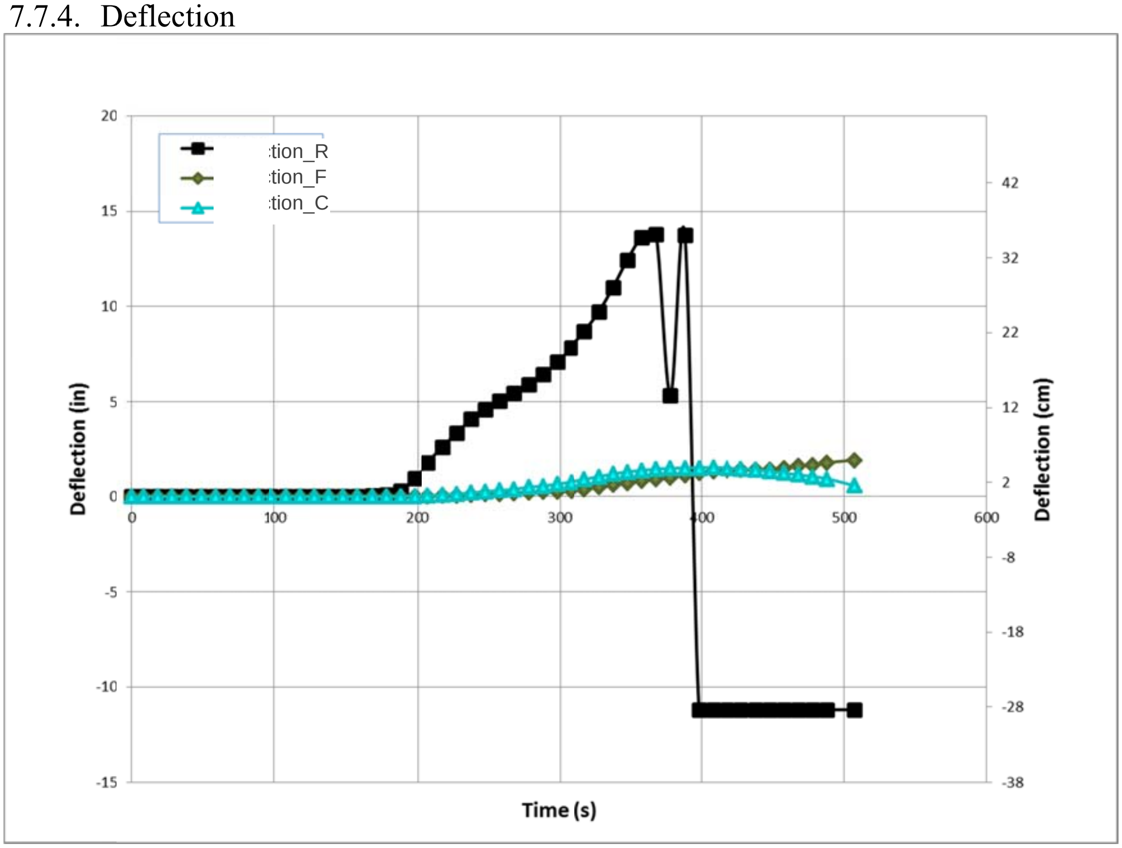

Figure 202. Experiment 7 - Floor System Deflections

7.7.5. Structural Response

The primary structural failure occurred at the rear section of the floor system; local to the initial fire location. Steel C-Joists experience a loss in strength when exposed to high temperatures (Figure 203). This loss of strength then induces progressive deformations, which lead to excessive deflection (Figure 204), flame passage through the gaps created in the floor sheathing, fastener mechanical separation of the floor sheathing, rupture of the lateral bracing (Figure 205), failure of joist blocking, and progressive torsional warping until the point of collapse (Figure 206). The rear section of the floor system began to progressively deflect at approximately 190 seconds until the end of the test. Experiment 7 induced a collapse of approximately 33 % of the total floor structure (Figure 207). The collapse time for the Experiment 7 was 8:15 after ignition which was defined as the barrels utilized for loading falling through the floor system. There was excessive deflection and flame passage seen prior to fall through of the barrels The collapse time respective of the fire involvement local to the structural elements for Experiment 7 was 5:15.

Figure 203 Steel C-Joists collapse.

Figure 204 Torsional warping of steel C-joists.

Figure 205 Burn through of sheathing, fastener mechanical separation of sheathing, rupture of lateral bracing strap, and torsional warping of steel C-joists.

Figure 206 Tearing failure of joist blocking, rupture of lateral bracing strap at underside of floor structure and torsional warping of steel C-joists.

Figure 207 Exterior view of percentage of collapsed area from above.

7.8. Experiment 8 – Steel C Joist

In this experiment all of the ventilation openings were closed prior to ignition and the fire was ignited in the rear fuel package closest to the base of the stairs. The ventilation openings were opened sequentially to simulate fire department operations. At 11:10 after ignition the floor had deflected to the point where barrels on the first floor tipped over and water was poured onto the fuel load, suppressing the fire. The experiment was allowed to continue until collapse and was terminated at the onset of manual suppression. The timeline of events is detailed in Table 32. The results for the experiment are presented in the following sections: observations, temperature, gas velocity, and deflection.

Table 32. Experiment 8 Timeline

Time (s, mm:ss)	Event
0 (0:00)	Ignition
212 (3:32)	Flames attach to the floor system
480 (8:00)	First floor door opened
600 (10:00)	Back basement door opened
630 (10:30)	Back basement window opened
660 (11:00)	Side basement window opened
670 (11:10)	Water from overturned barrels suppresses fire
690 (11:30)	Front basement window opened
844 (14:04)	Collapse
850 (14:10)	End of experiment

7.8.1. Observations

The observations are presented as a series of images captured from eight camera locations, seven were video cameras and one was a thermal imaging camera. The views were captured at the start of the experiment (0:00, Figure 208), once flames attached to the floor system (3:32, Figure 209), when visibility was lost on the first floor (4:20, Figure 210), when water can be seen pouring from an overturned barrel (11:10, Figure 211), and 5 seconds before collapse (13:59, Figure 212).

Figure 208. Experiment 8 video views at 0:00.

Figure 209. Experiment 8 video views at 3:32.

Figure 210. Experiment 8 video views at 4:20.

Figure 211. Experiment 8 video views at 11:10.

Figure 212. Experiment 8 video views at 13:59.

7.8.2. Temperature

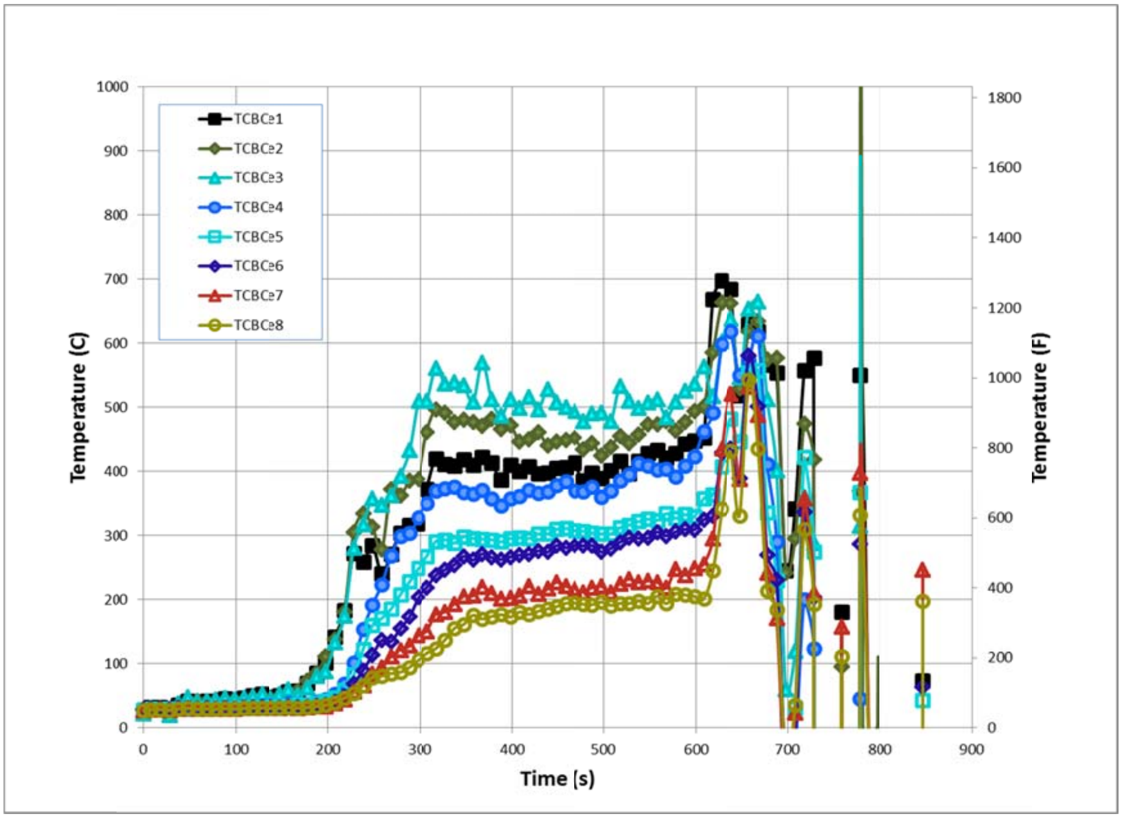

Figure 213. Experiment 8 - Basement Center Temperatures

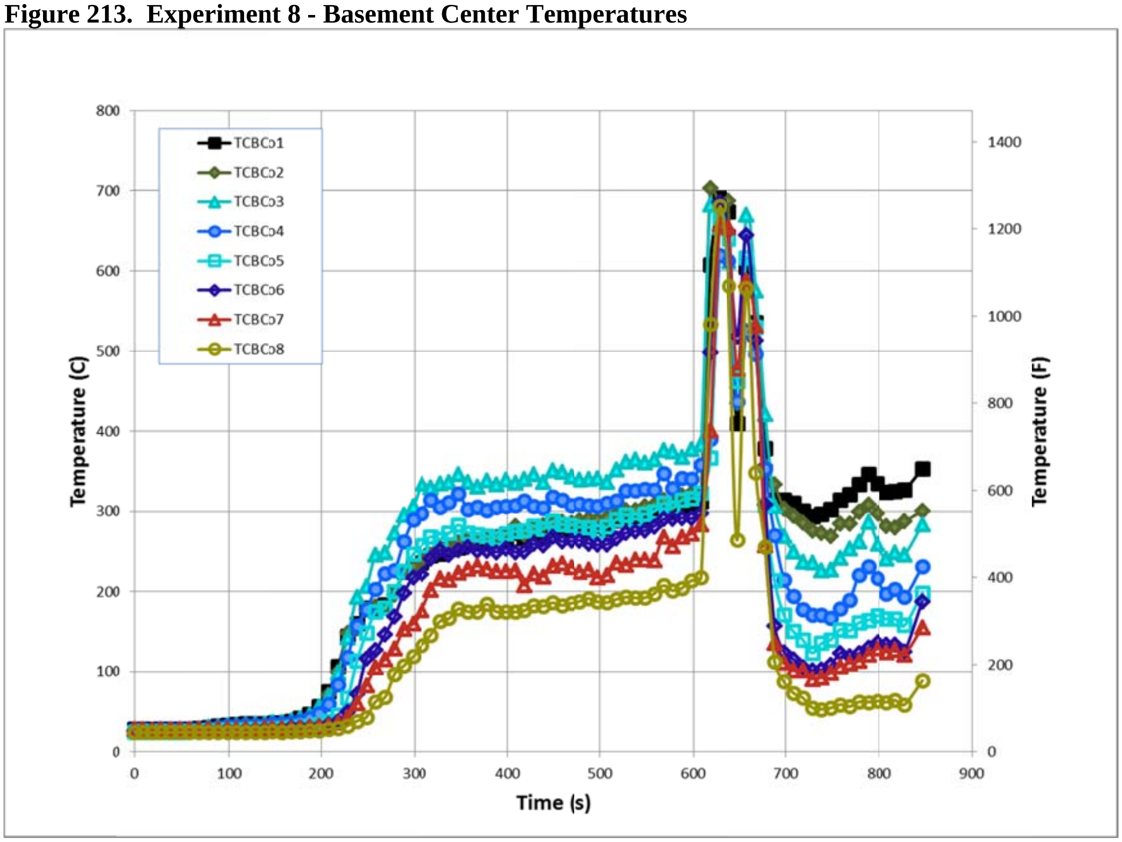

Figure 214. Experiment 8 - Basement Corner Temperatures

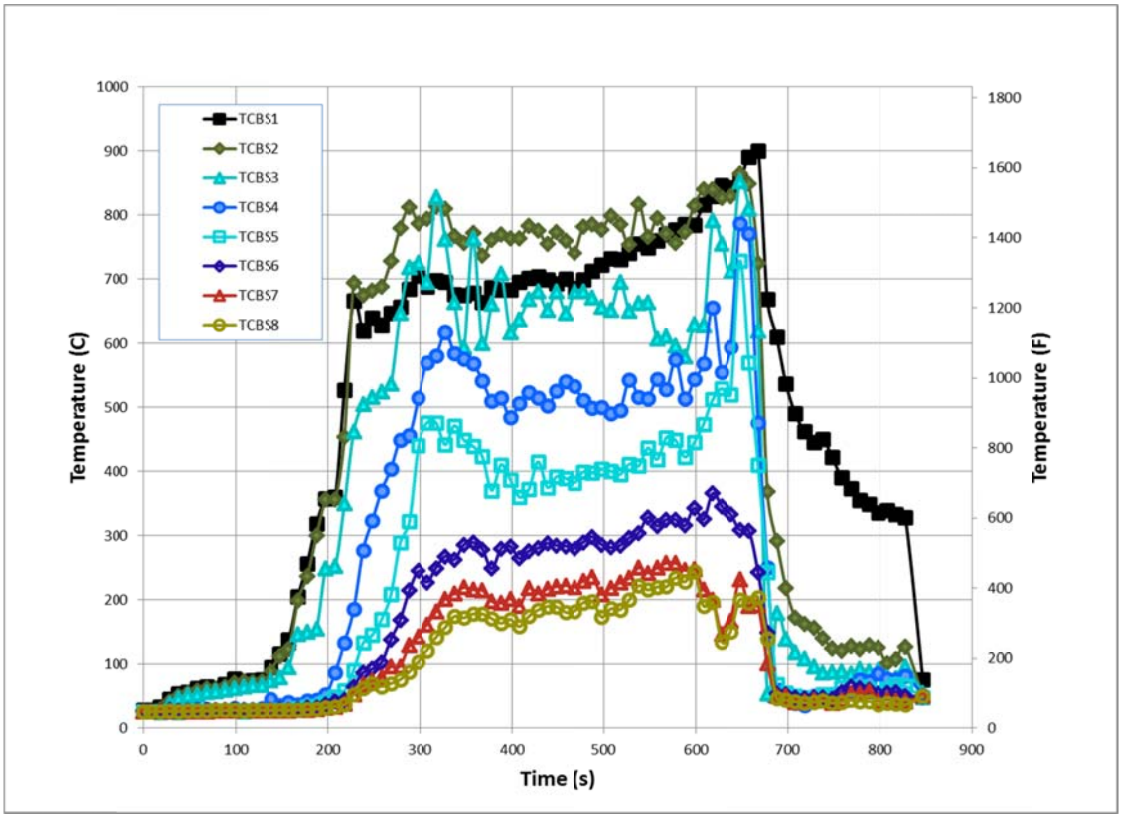

Figure 215. Experiment 8 - Basement Base of Stair Temperatures

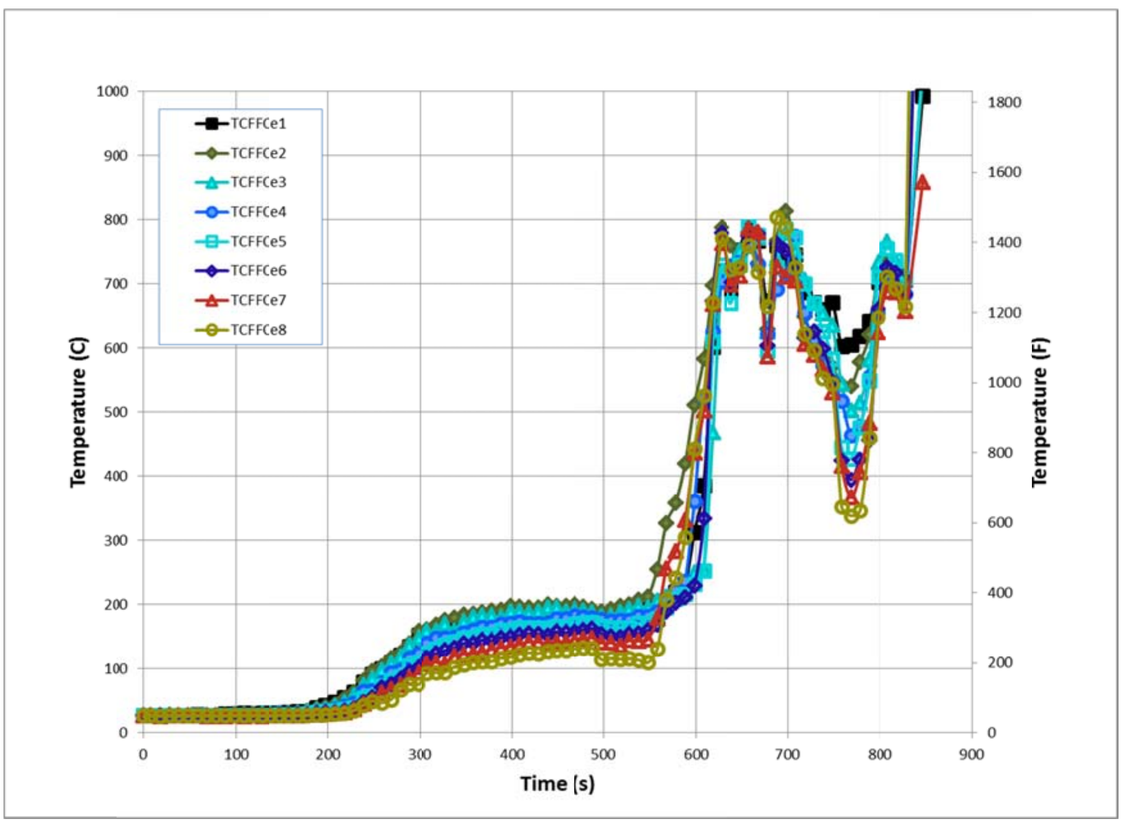

Figure 216. Experiment 8 - First Floor Center Temperatures

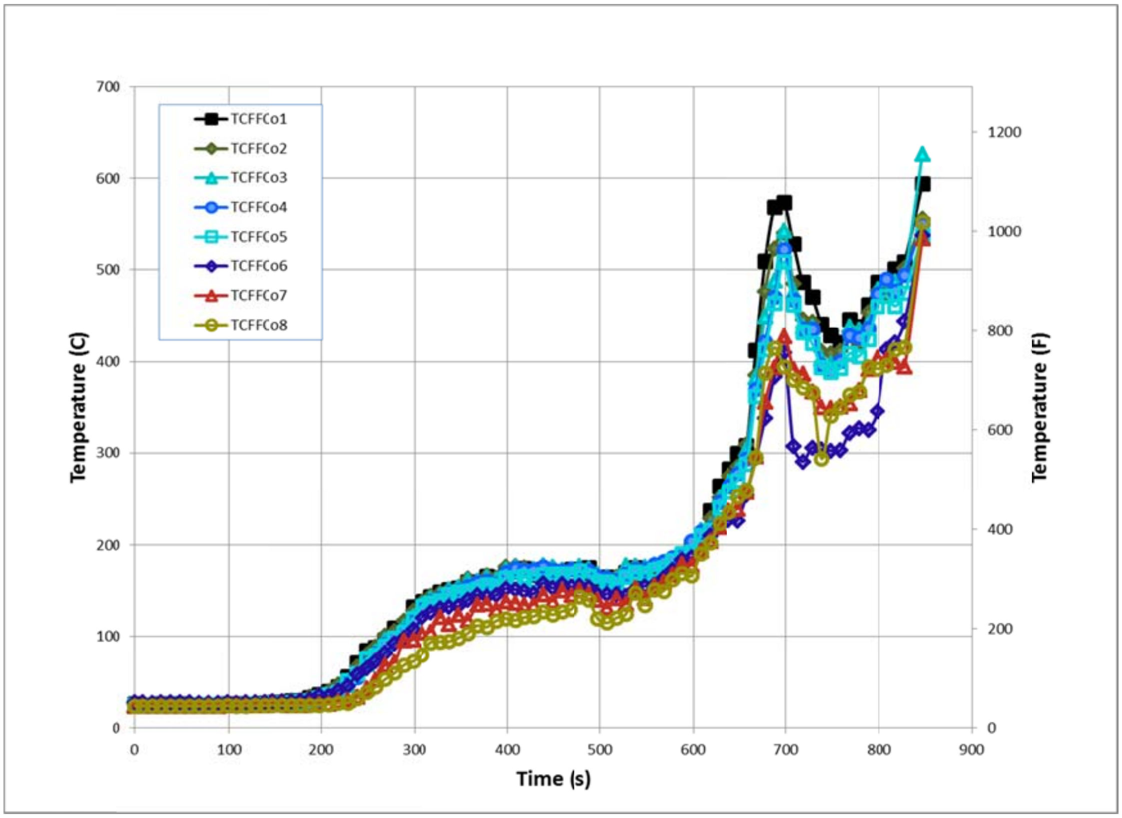

Figure 217. Experiment 8 - First Floor Corner Temperatures

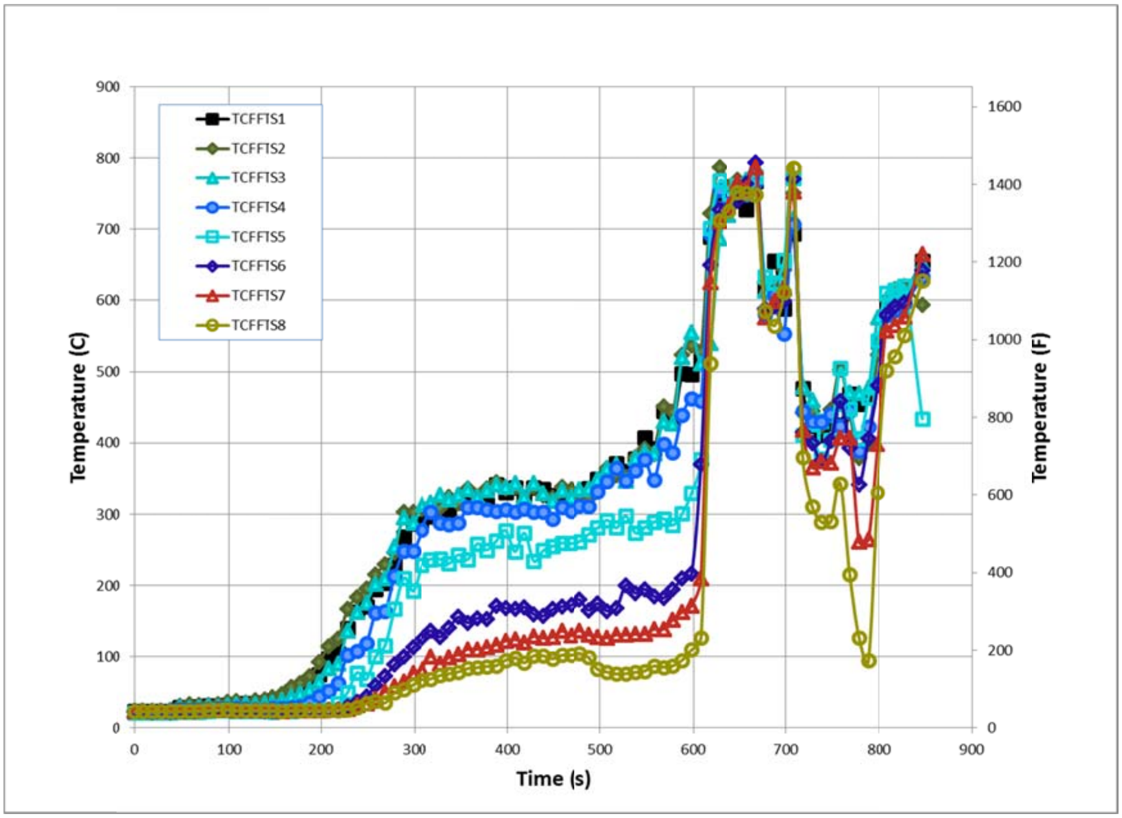

Figure 218. Experiment 8 - First Floor Top of Stair Temperatures

7.8.3. Gas Velocity

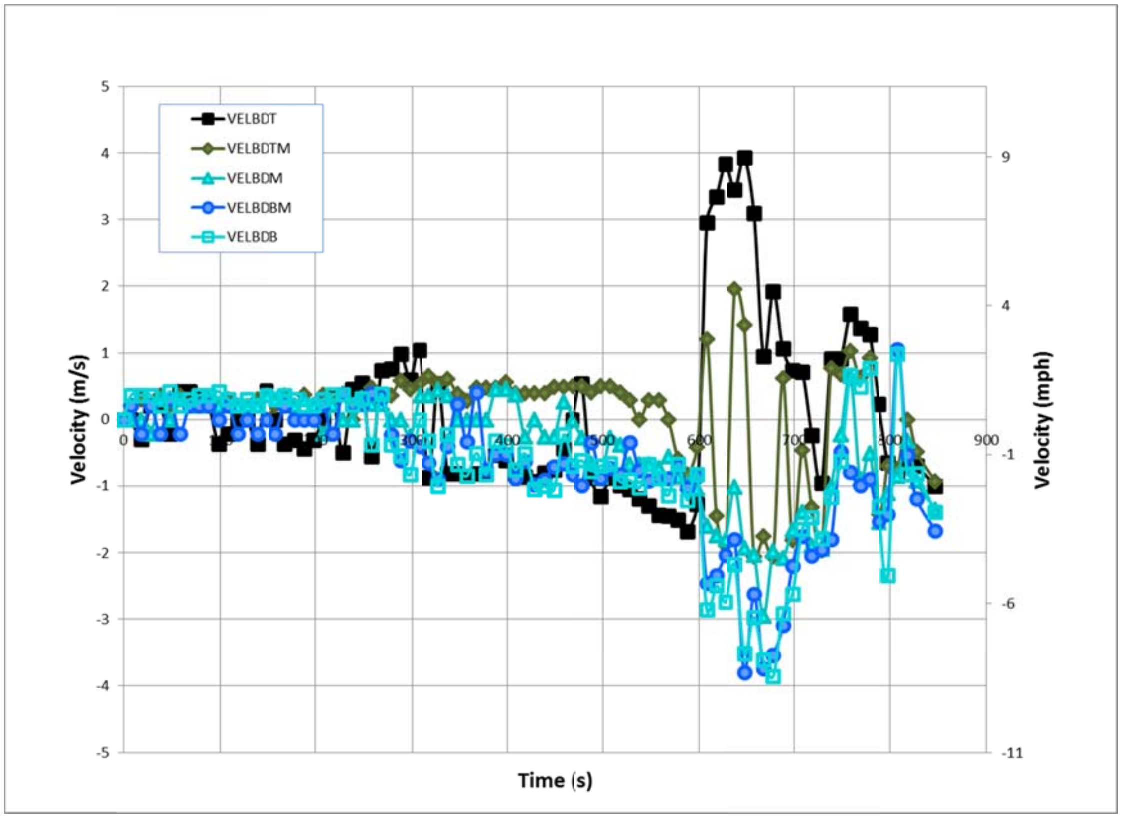

Figure 219. Experiment 8 - Basement Door Velocities

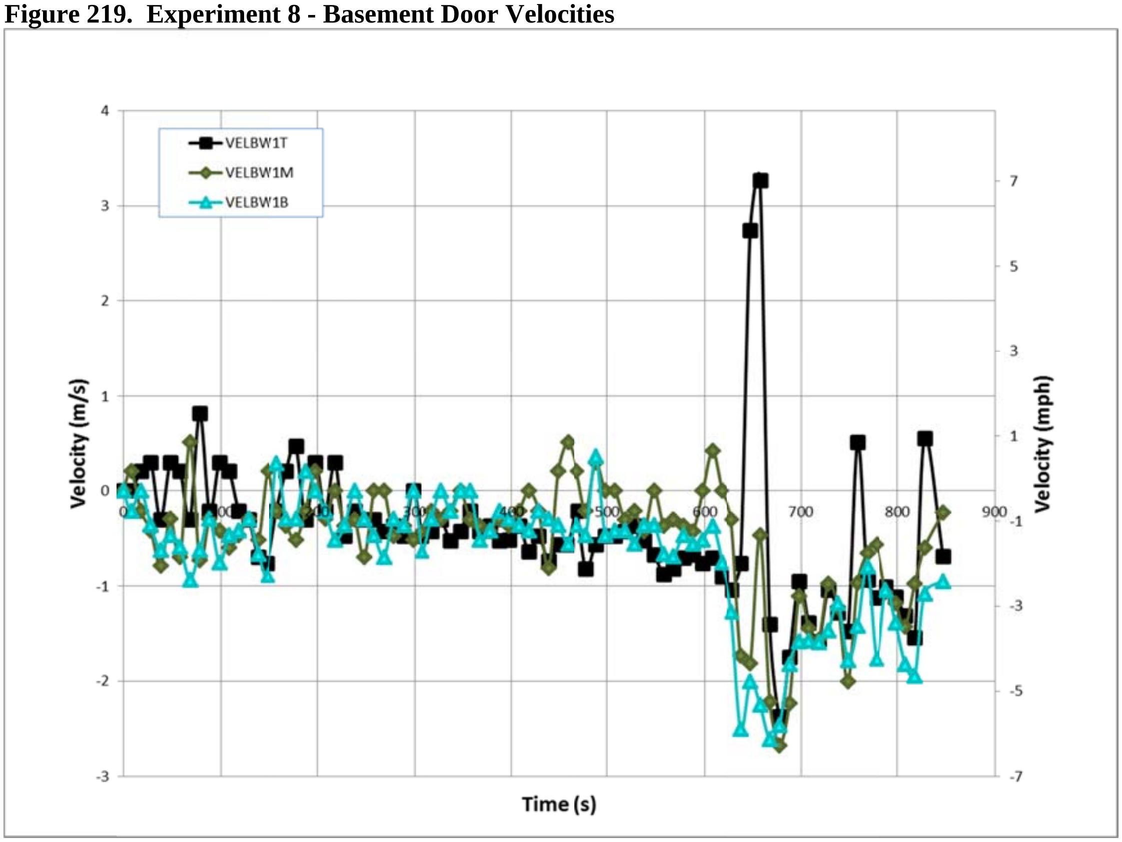

Figure 220. Experiment 8 - Basement Window 1 Velocities

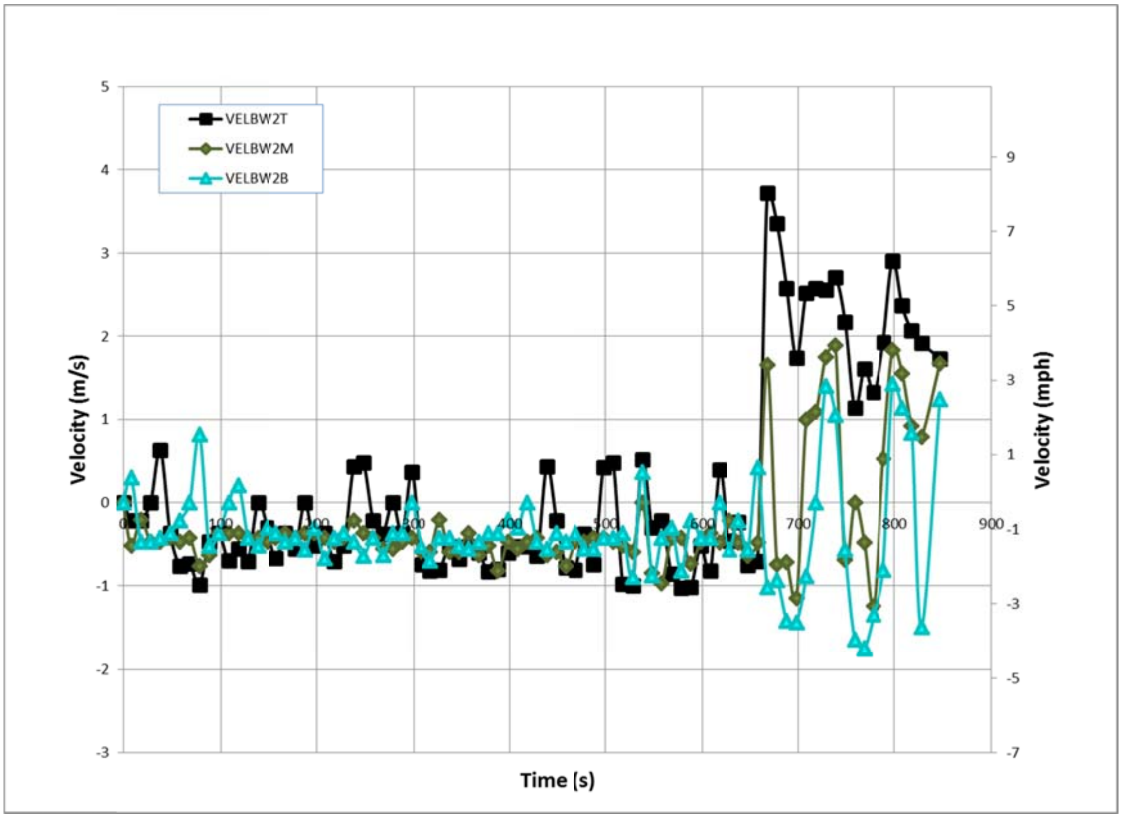

Figure 221. Experiment 8 - Basement Window 2 Velocities

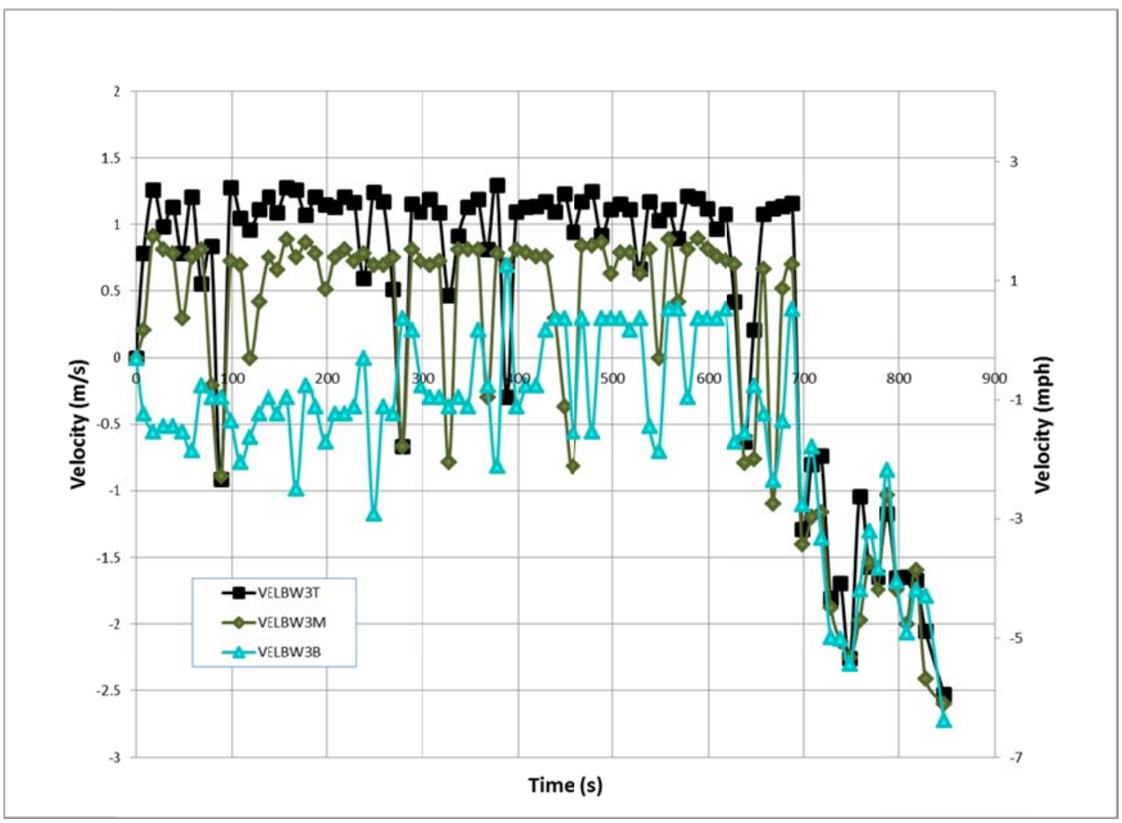

Figure 222. Experiment 8 - Basement Window 3 Velocities

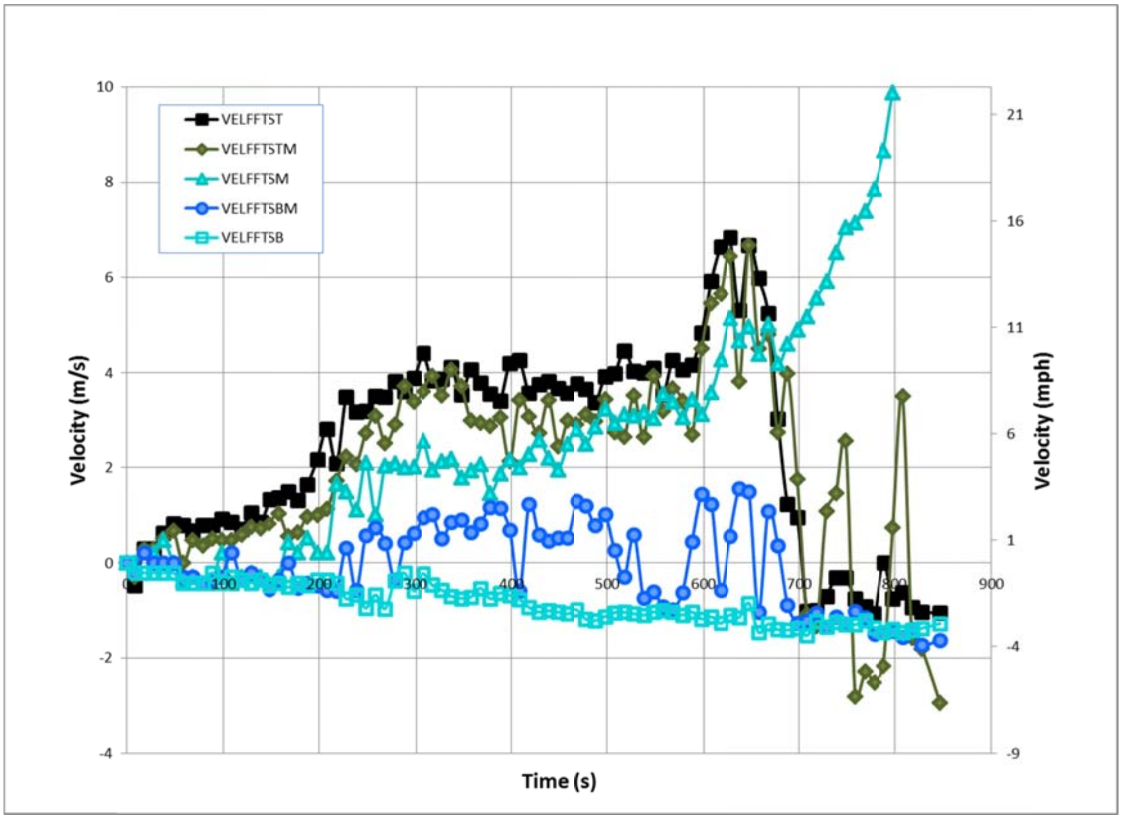

Figure 223. Experimentv8 - First Floor Stair Velocities

7.8.4. Deflection

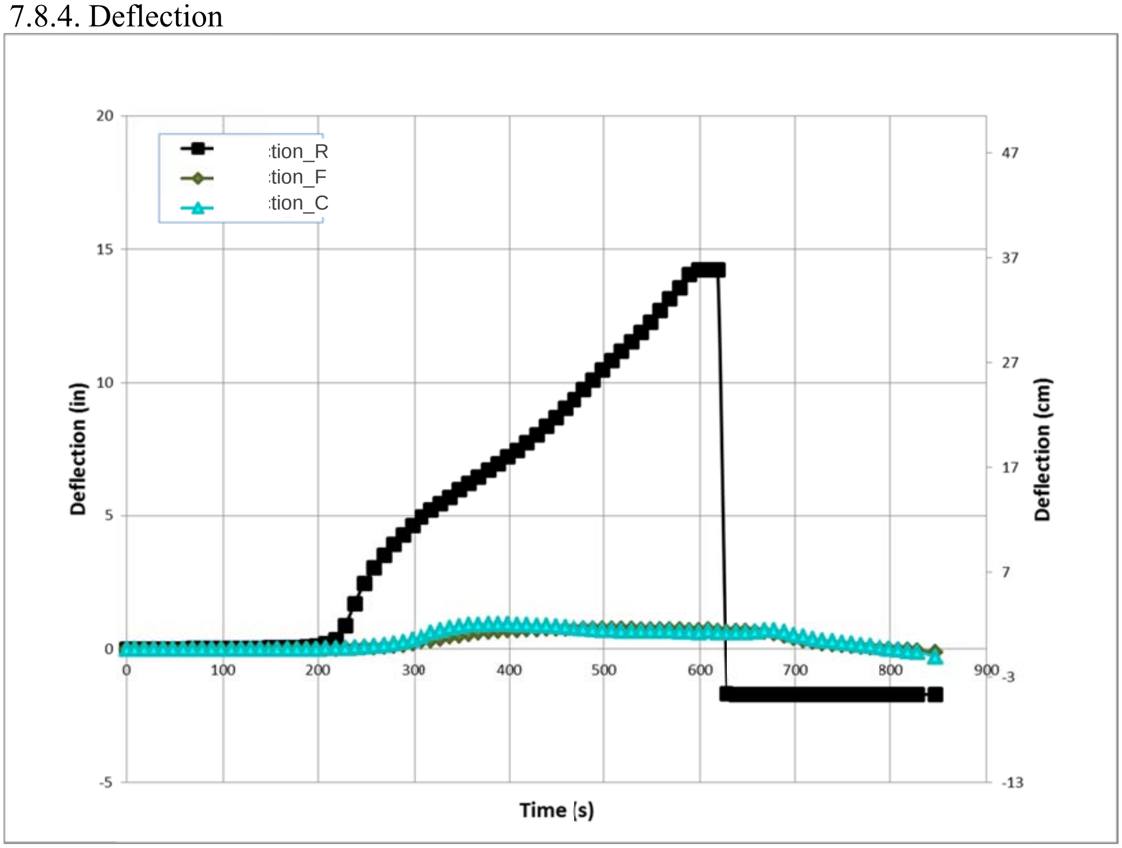

Figure 224. Experiment 8 - Floor System Deflections

7.8.5. Structural Response

The primary structural failure occurred at the rear section of the floor system; local to the initial fire location. Steel C-Joists experience a loss in strength when exposed to high temperatures. This loss of strength then induces progressive deformations, which lead to excessive deflection (Figure 204), flame passage through the gaps created in the floor sheathing, fastener mechanical separation of the floor sheathing, rupture of the lateral bracing (Figure 226), failure of joist blocking, and progressive torsional warping until the point of collapse (Figure 227 and Figure 228). The collapse also produced a collapse local to the C-joist bearing condition (Figure 230). The rear section of the floor system began to progressively deflect at approximately 190 seconds until the end of the test. Experiment 8 induced a collapse of approximately 33 % of the total floor structure (Figure 230). The collapse time for the Experiment 8 was 14:04 after ignition which was defined as the barrels utilized for loading falling through the floor system. There was excessive deflection and flame passage seen prior to fall through of the barrels. The collapse time respective of the fire involvement of the subflooring local to the structural elements for Experiment 8 was 10:32.

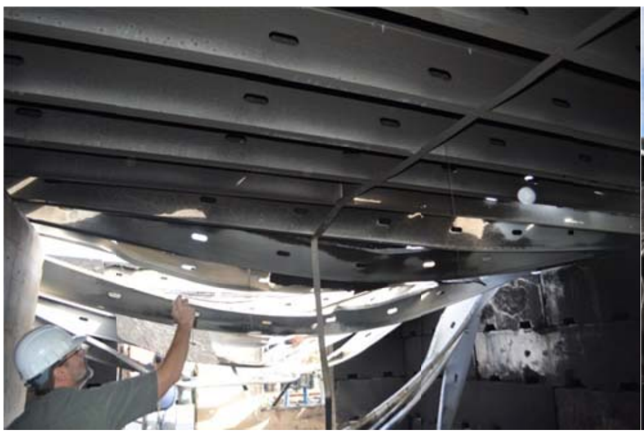

Figure 225 Steel C-Joists collapse.

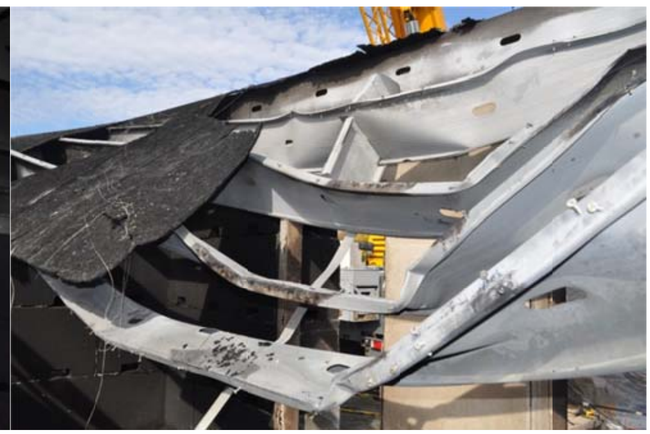

Figure 226 Burn through of floor sheathing and torsional warping of steel C-joists.

Figure 227 Torsional warping of steel C-joists and collapse local to C-joist support bearing.

Figure 228 Torsional warping of steel C-joists.

Figure 229. Exterior view of collapsed area of joist bearing condition from above.

Figure 230. Exterior view of percentage of collapsed area from above.

7.9. Experiment 9 – Parallel Chord Truss

In this experiment all of the ventilation openings were closed prior to ignition and the fire was ignited in the rear fuel package closest to the base of the stairs. The floor collapsed prior to a ventilation opening being made however; the ventilation openings were still opened sequentially to simulate fire department operations. The experiment was terminated at the onset of suppression. The timeline of events is detailed in Table 33. The results for the experiment are presented in the following sections: observations, temperature, gas velocity, and deflection.

Table 33. Experiment 9 Timeline

Time (s, mm:ss)	Event
0 (0:00)	Ignition
146 (2:26)	Flames attach to the floor system
368 (6:08)	Collapse
480 (8:00)	First floor door opened
603 (10:03)	Back basement door opened
638 (10:38)	Back basement window opened
660 (11:00)	Side basement window opened
690 (11:30)	Front basement window opened
750 (12:30)	End of experiment

7.9.1. Observations

The observations are presented as a series of images captured from eight camera locations, seven were video cameras and one was a thermal imaging camera. The views were captured at the start of the experiment (0:00, Figure 231), once flames attached to the floor system (2:26, Figure 232), when flames are seen exiting the doorway to the first floor (3:02, Figure 233), and 5 seconds before collapse (6:03, Figure 234).

Figure 231. Experiment 9 video views at 0:00.

Figure 232. Experiment 9 video views at 2:26.

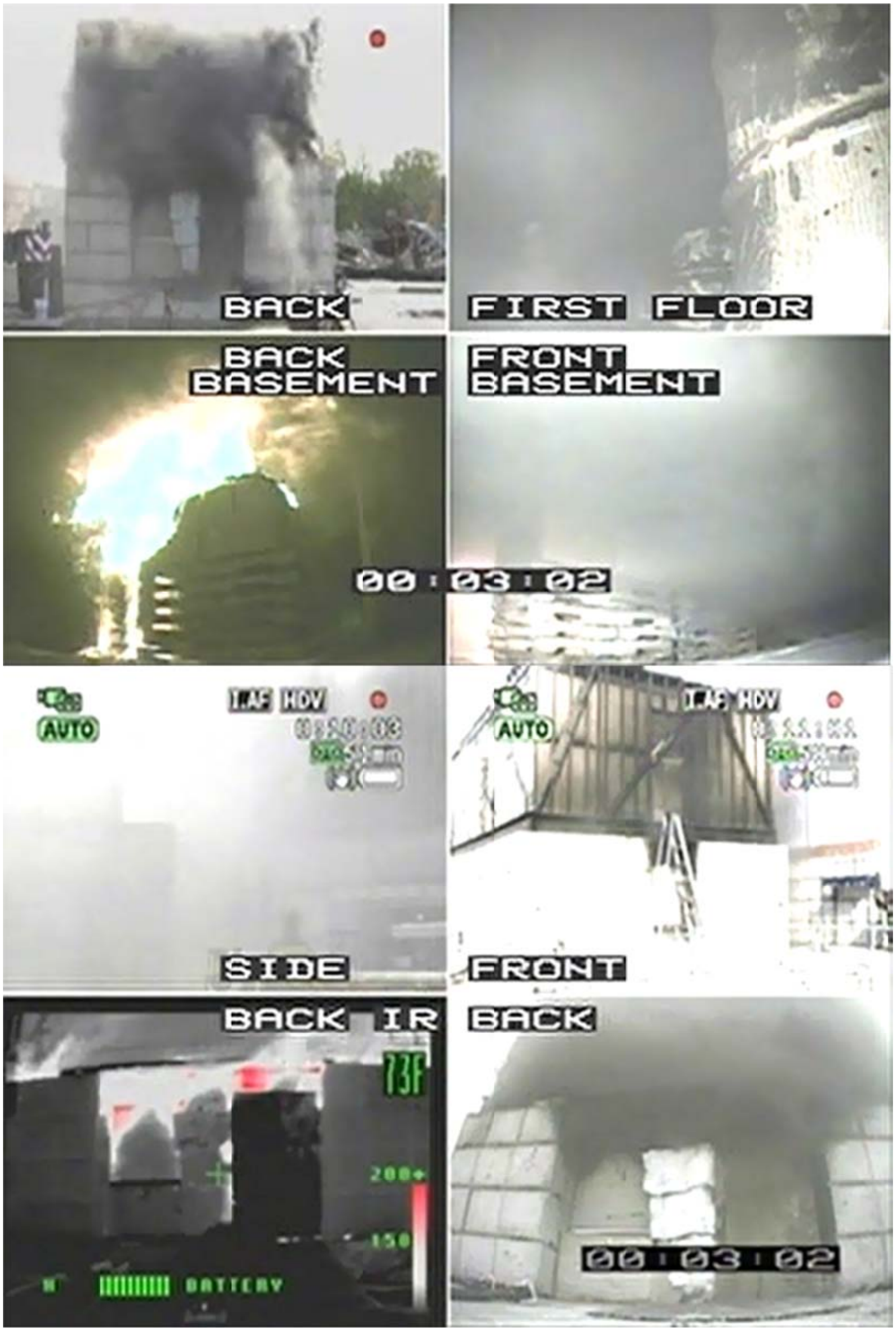

Figure 233. Experiment 9 video views at 3:02.

Figure 234. Experiment 9 video views at 6:03.

7.9.2. Temperature

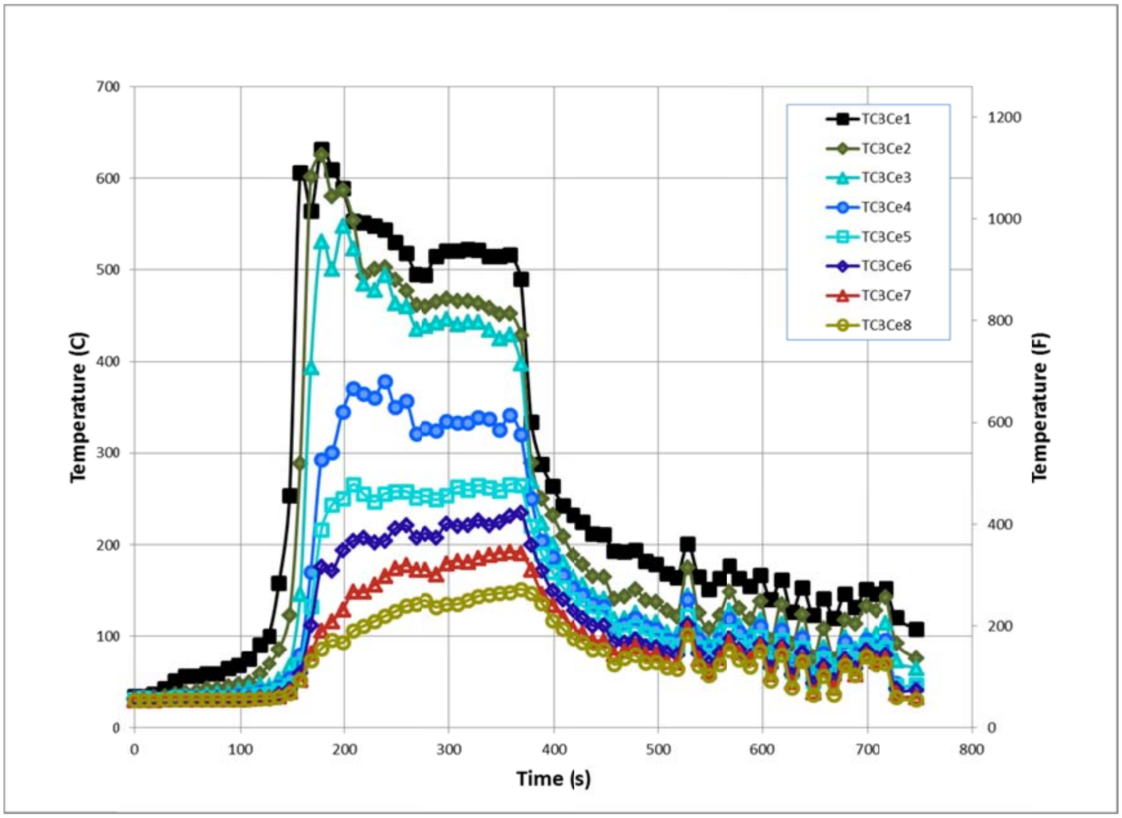

Figure 235. Experiment 9 - Basement Center Temperatures

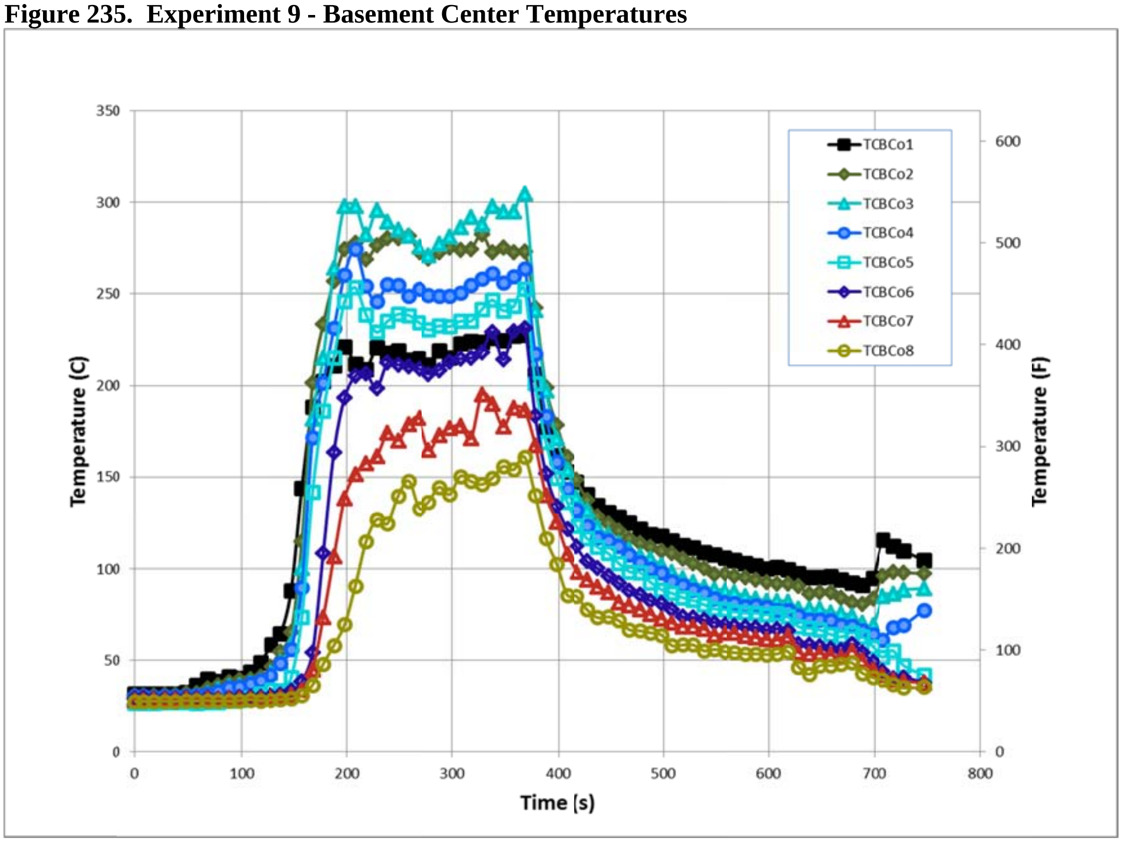

Figure 236. Experiment 9 - Basement Corner Temperatures

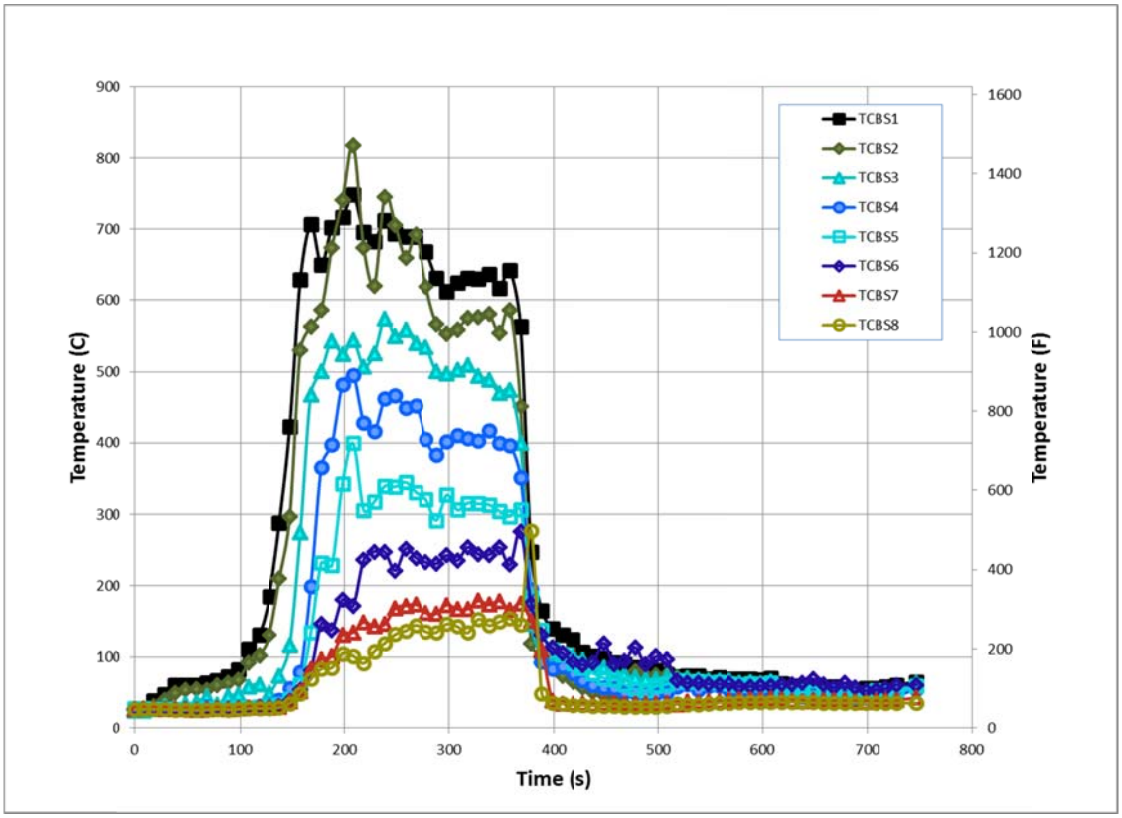

Figure 237. Experiment 9 - Basement Base of Stair Temperatures

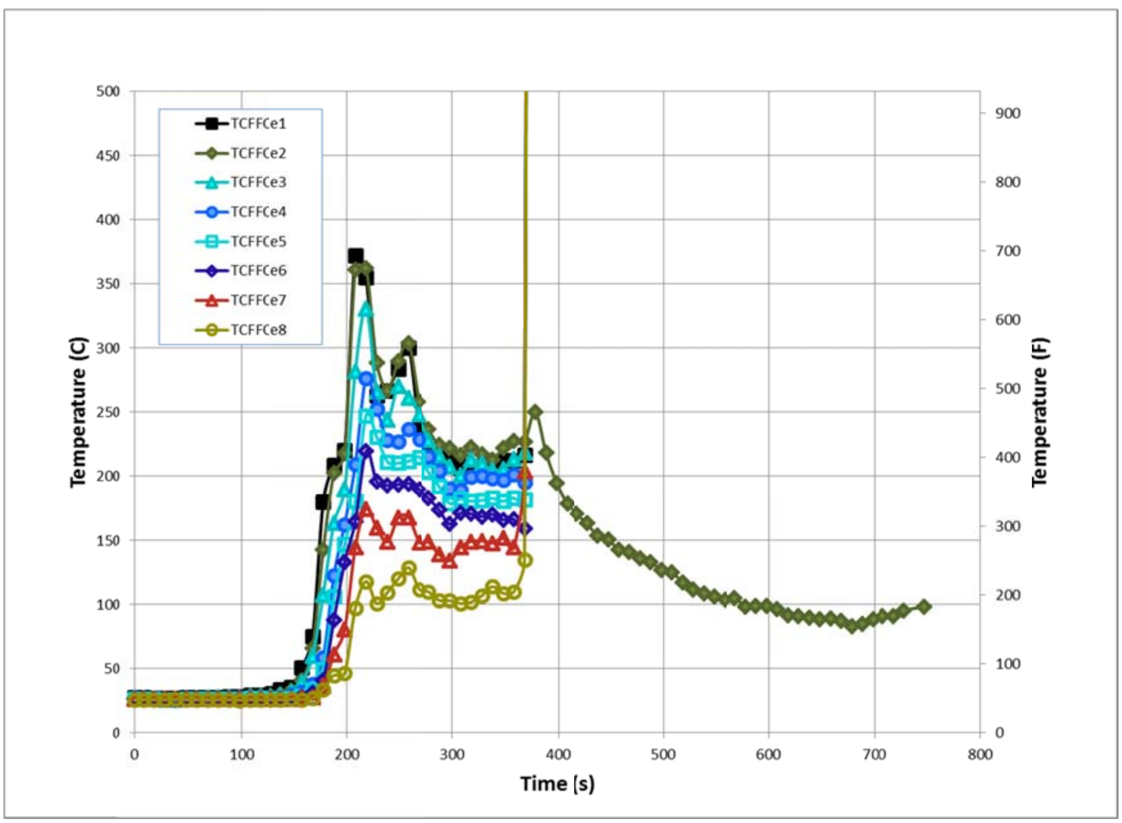

Figure 238. Experiment 9 - First Floor Center Temperatures

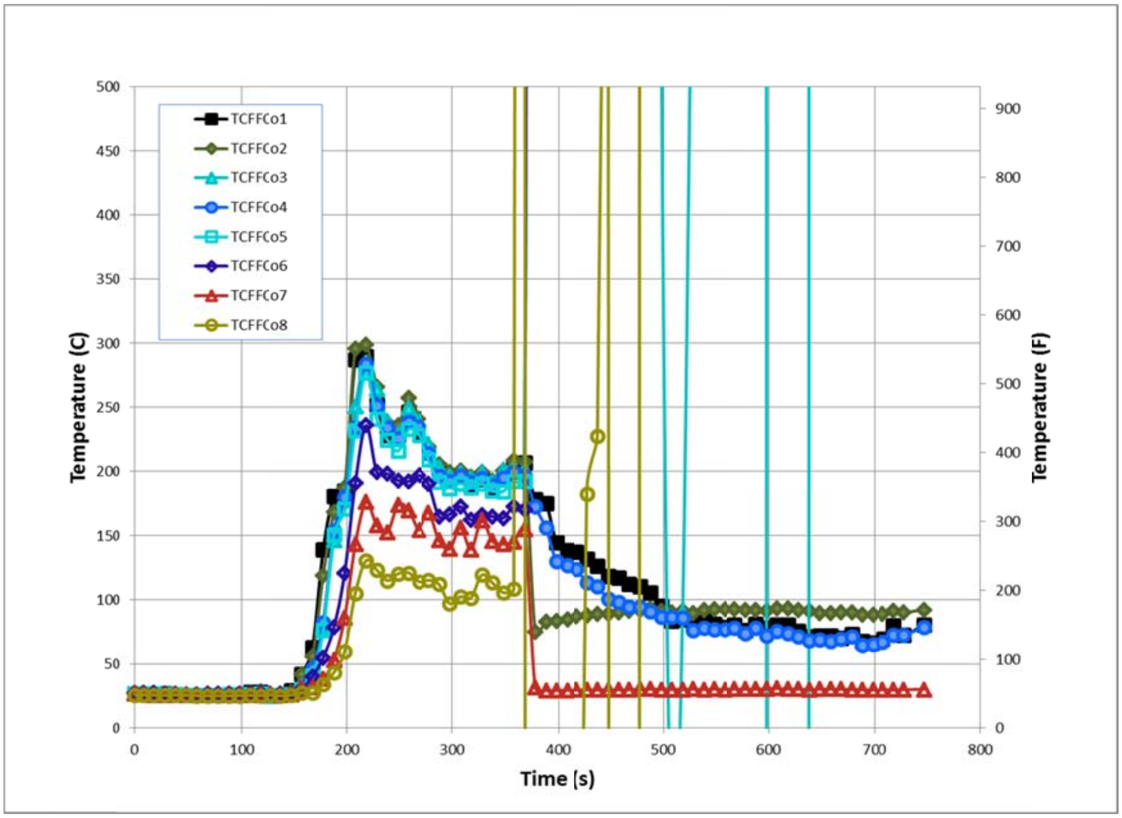

Figure 239. Experiment 9 - First Floor Corner Temperatures

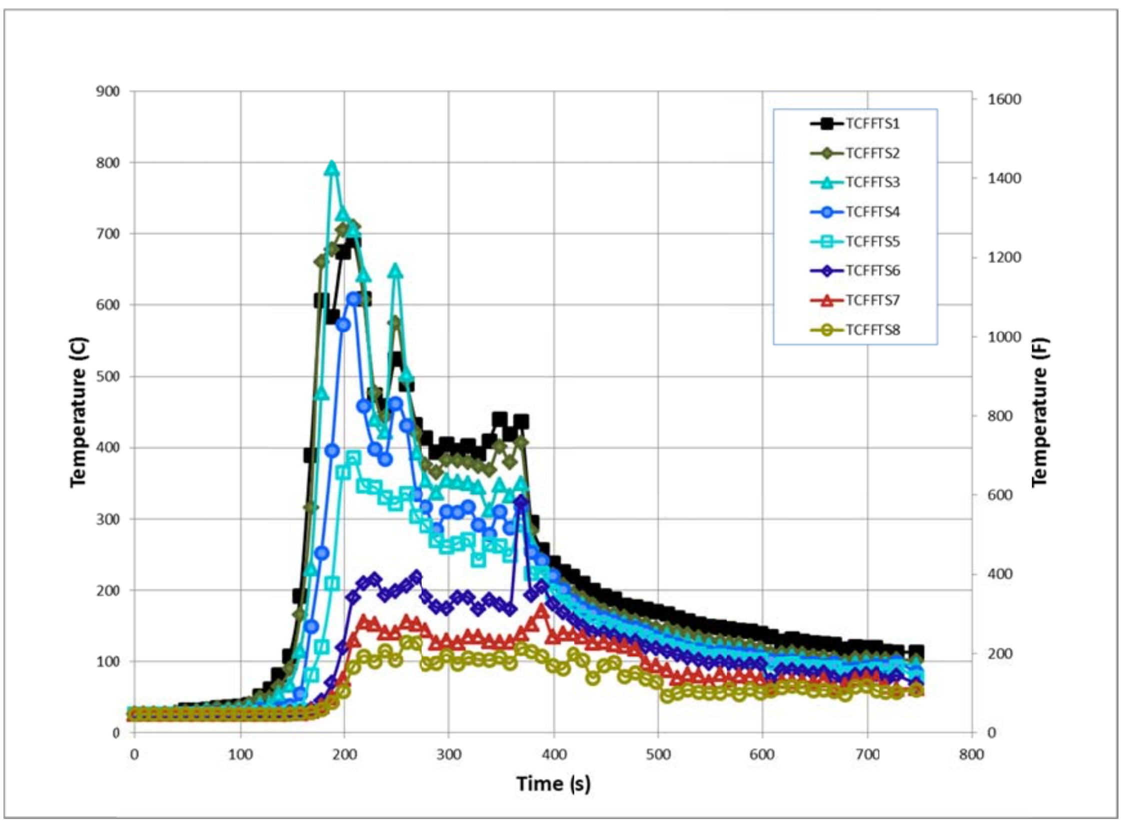

Figure 240. Experiment 9 - First Floor Top of Stair Temperatures

7.9.3. Gas Velocity

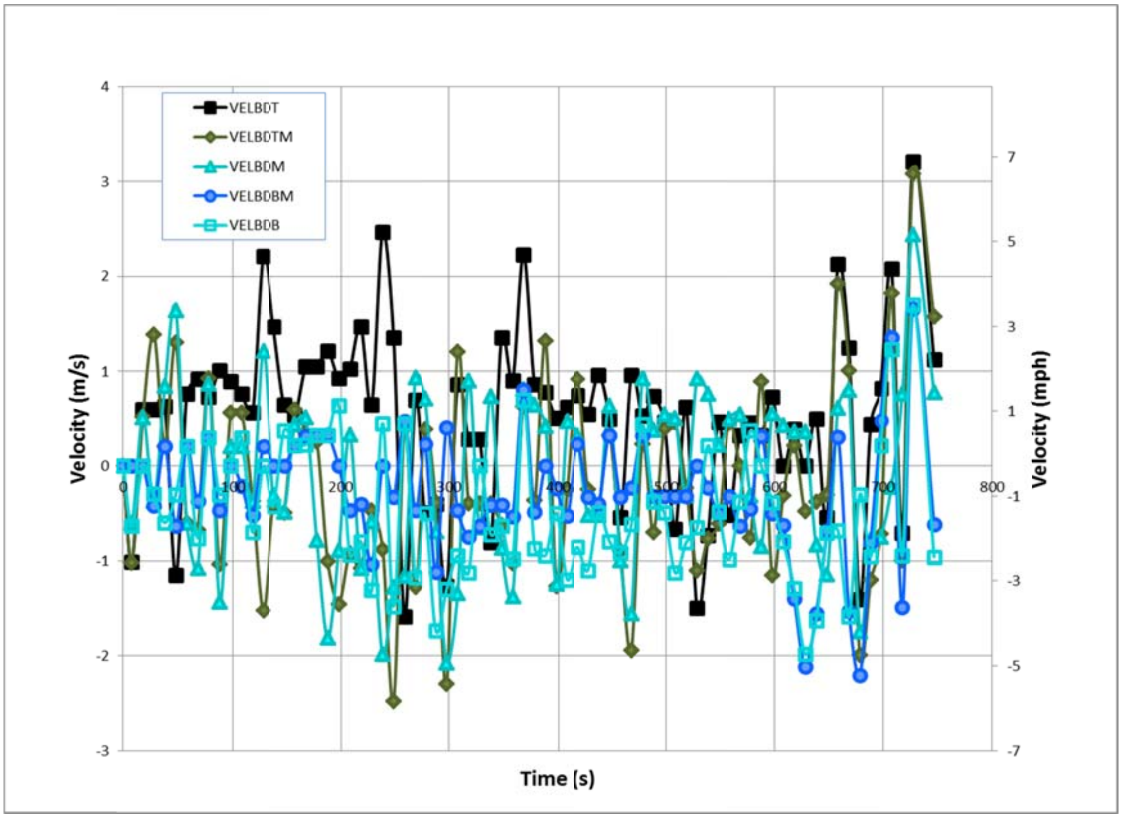

Figure 241. Experiment 9 - Basement Door Velocities

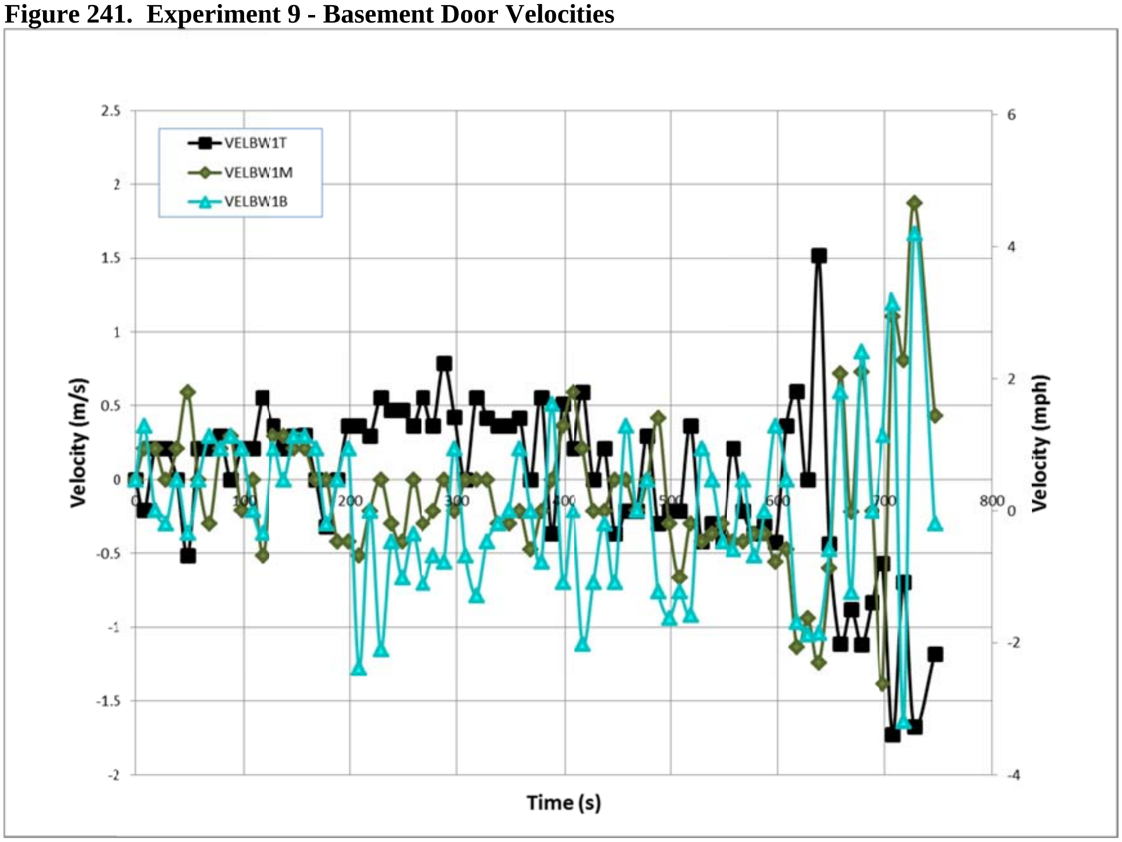

Figure 242. Experiment 9 - Basement Window 1 Velocities

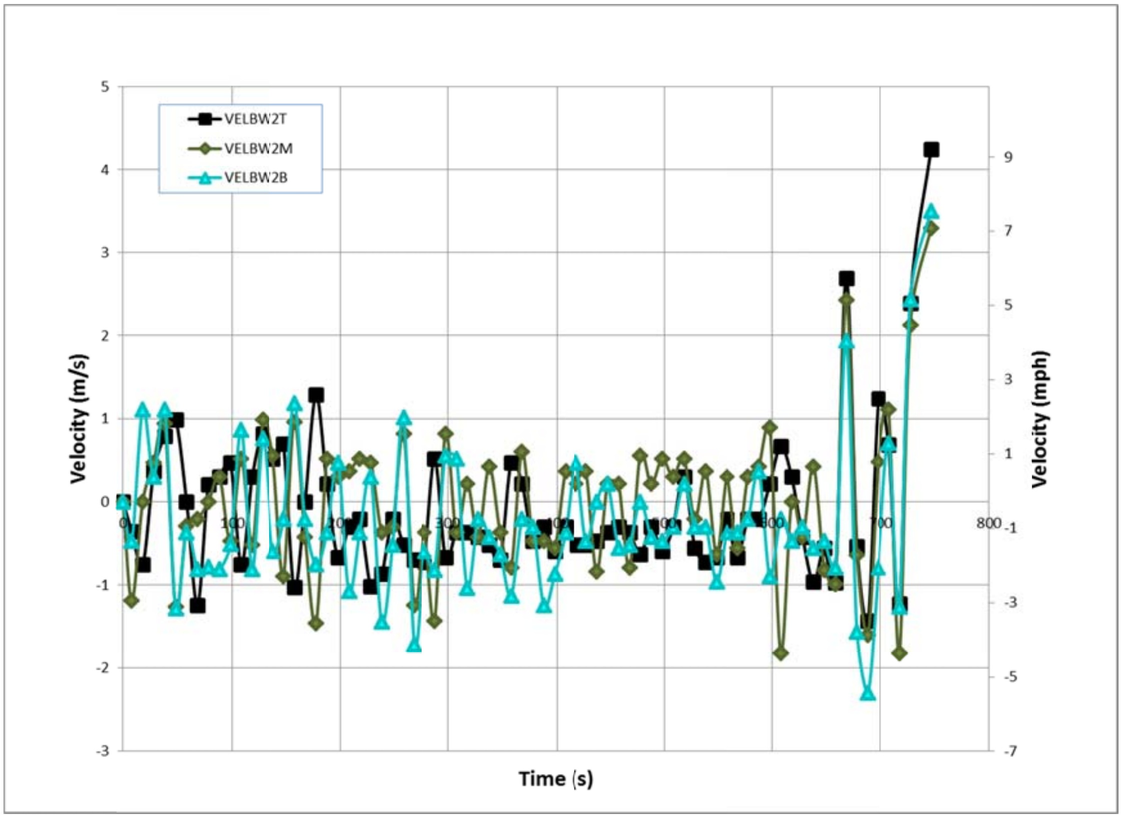

Figure 243. Experiment 9 - Basement Window 2 Velocities

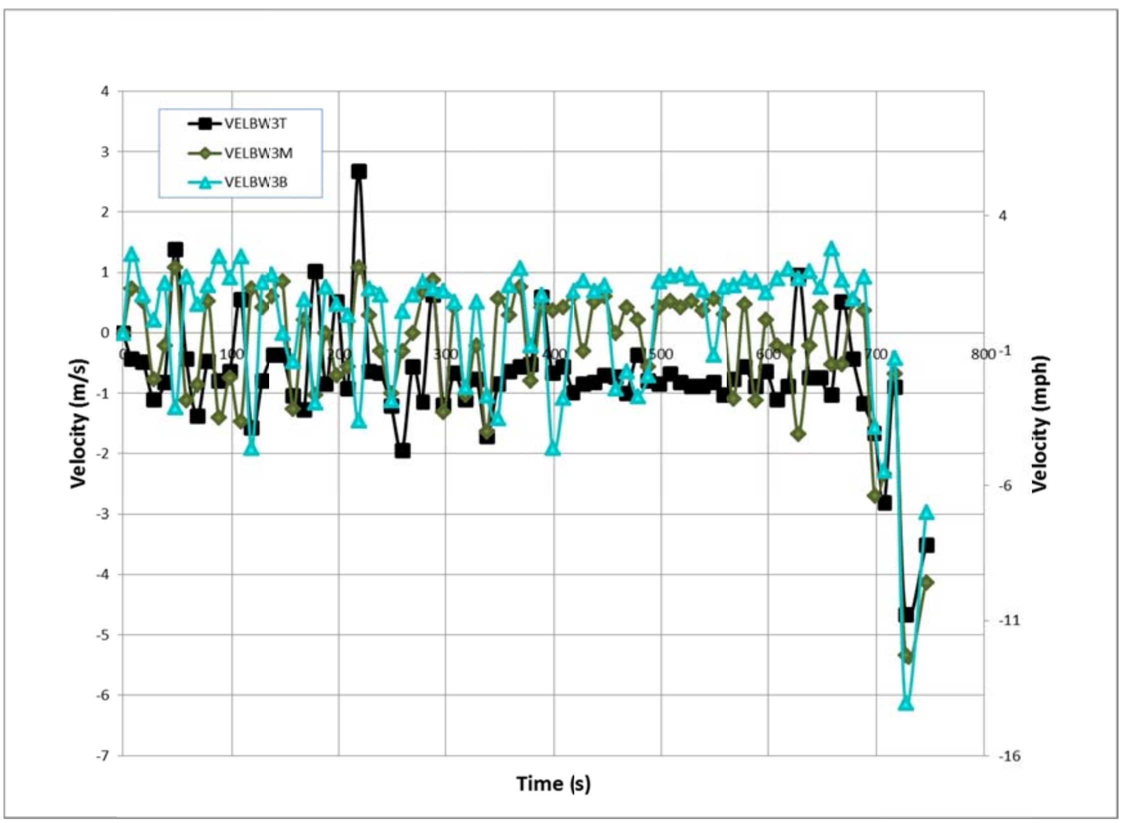

Figure 244. Experiment 9 - Basement Window 3 Velocities

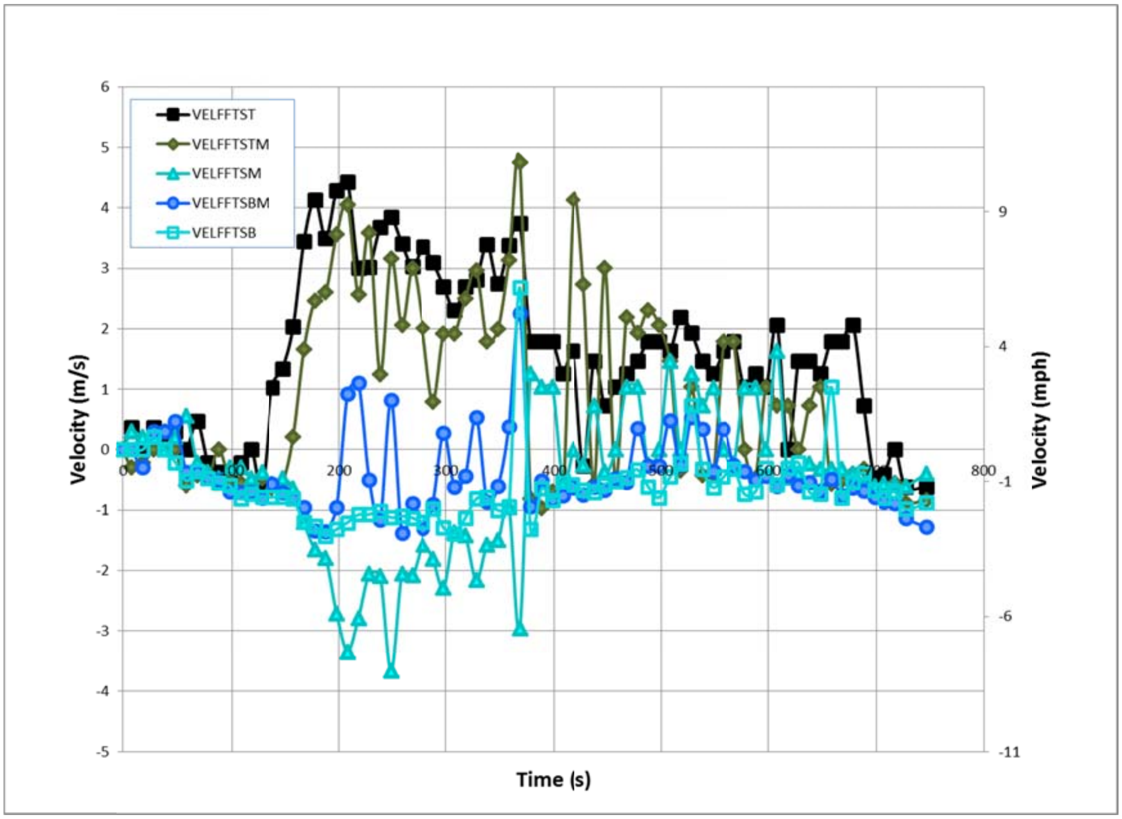

Figure 245. Experiment 9 - First Floor Stair Velocities

7.9.4. Deflection

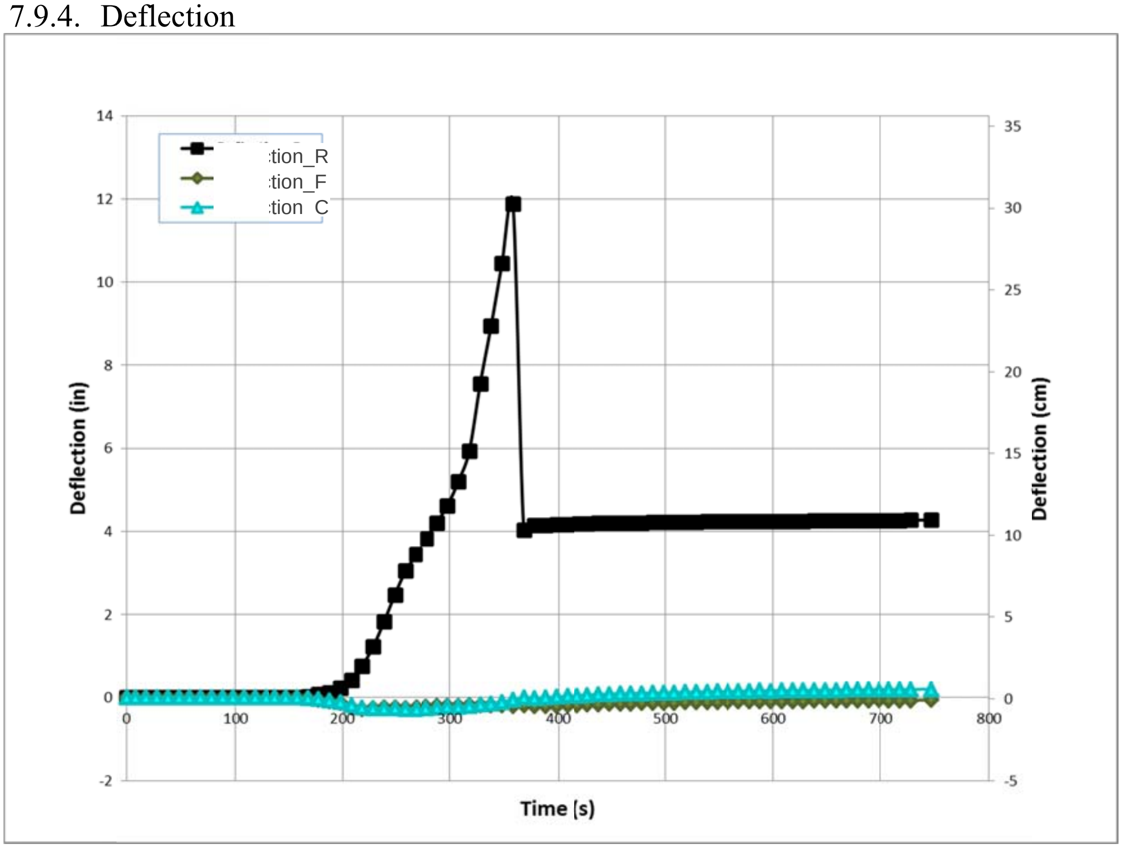

Figure 246. Experiment 9 - Floor System Deflections

7.9.5. Structural Response

The primary structural failure occurred at the rear section of the floor system; local to the initial fire location. The failure mode of the parallel chord metal plate connected trusses was due to steel/wood connection failures (Figure 248). Connection failures were noted at various truss panel points (Figure 249 and Figure 250) and tension splice locations (Figure 251 and Figure 252). The floor system began to progressively deflect from 190 seconds until the end of the test. Experiment 9 induced a collapse of approximately 50 % of the total floor structure. The collapse time for the Experiment 9 was 6:08 after ignition. The collapse time respective of the structural element fire involvement for Experiment 9 was 3:42.

Figure 247 Interior view of percentage of collapsed area from underside of floor.

Figure 248 Interior view of collapsed floor area.

Figure 249 Connection failure at truss panel point.

Figure 250 Connection failure at truss panel point.

Figure 251 Connection failure at truss panel points and at bottom chord tension splice.

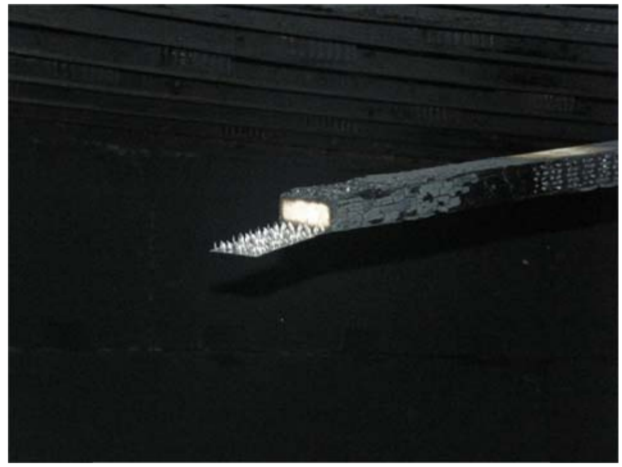

Figure 252 Connection failure of bottom chord tension splice.

7.10. Experiment 10 – Parallel Chord Truss

In this experiment all of the ventilation openings were open prior to ignition and the fire was ignited in the rear fuel package closest to the base of the stairs. The fire spread until the floor system collapsed and then was suppressed. The timeline of events is detailed in Table 34. The results for the experiment are presented in the following sections: observations, temperature, gas velocity, and deflection.

Table 34. Experiment 10 Timeline

Time (s, mm:ss)	Event
0 (0:00)	Ignition
98 (1:38)	Flames attach to the floor system
208 (3:28)	Collapse
260 (4:20)	End of experiment

7.10.1. Observations

The observations are presented as a series of images captured from eight camera locations, seven were video cameras and one was a thermal imaging camera. The views were captured at the start of the experiment (0:00, Figure 253), once flames attached to the floor system (1:38, Figure 254), when flames are seen exiting the doorway to the first floor (1:59, Figure 255), and 5 seconds before collapse (3:23, Figure 256).

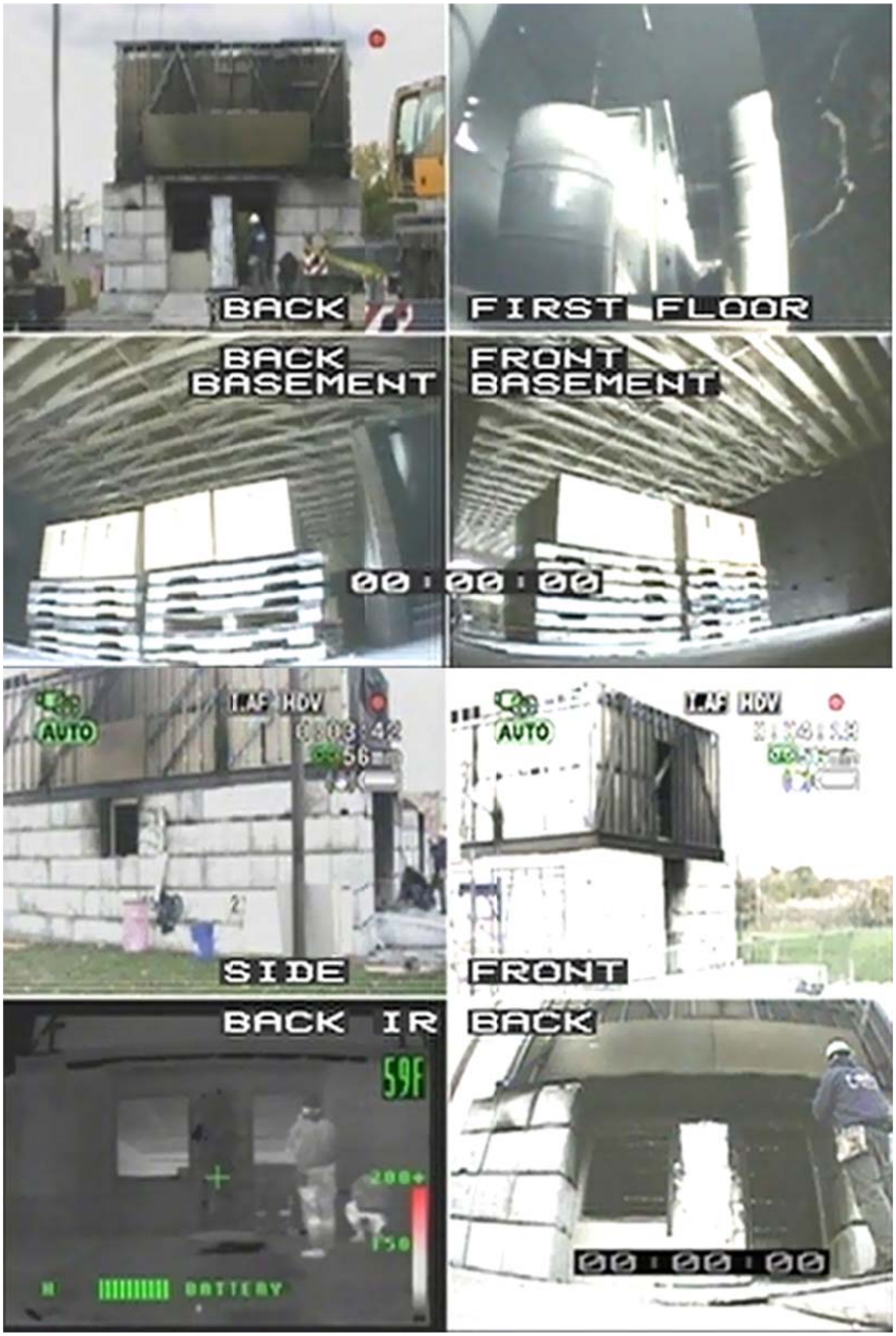

Figure 253. Experiment 10 video views at 0:00.

Figure 254. Experiment 10 video views at 1:38.

Figure 255. Experiment 10 video views at 1:59.

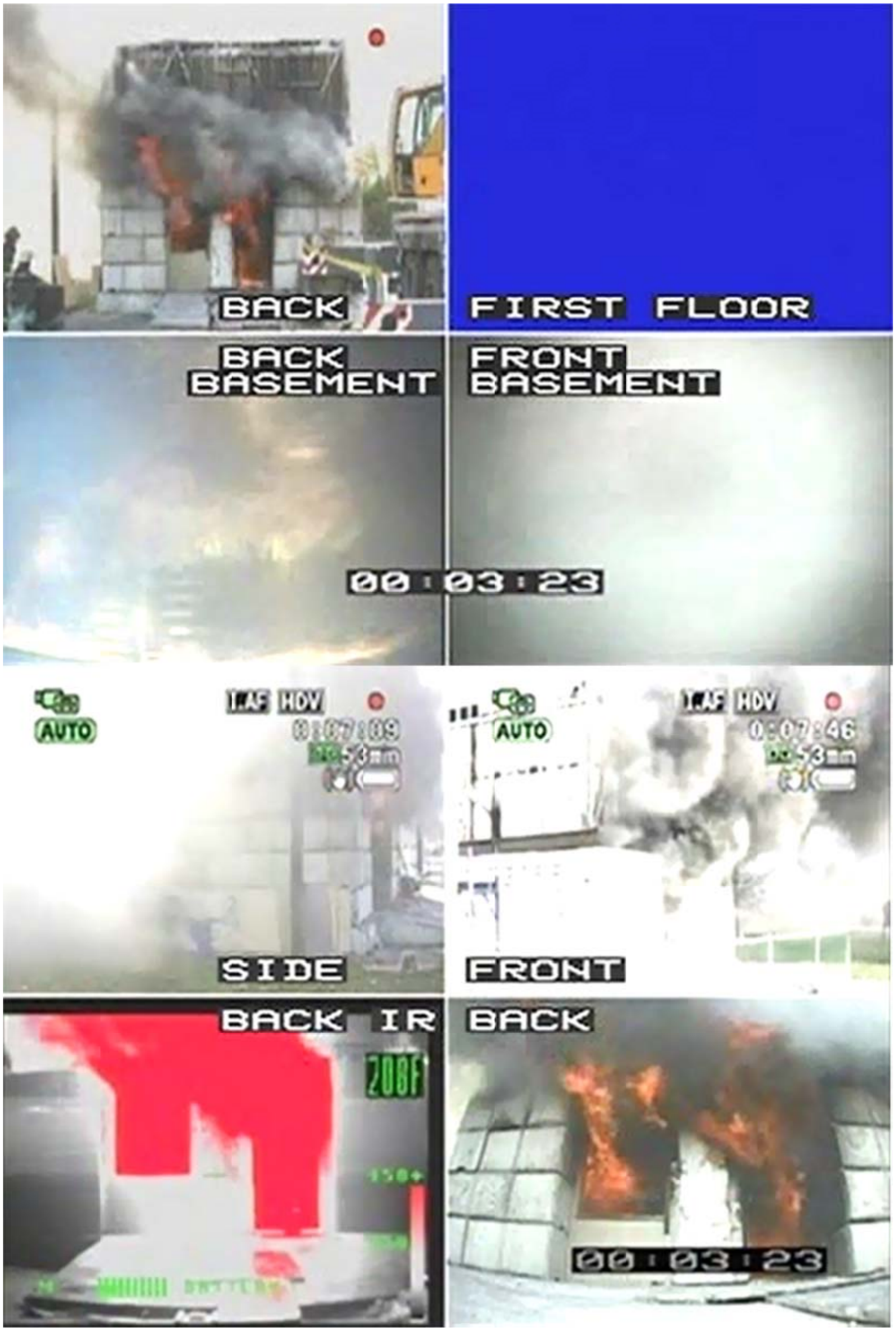

Figure 256. Experiment 10 video views at 3:23.

7.10.2. Temperature

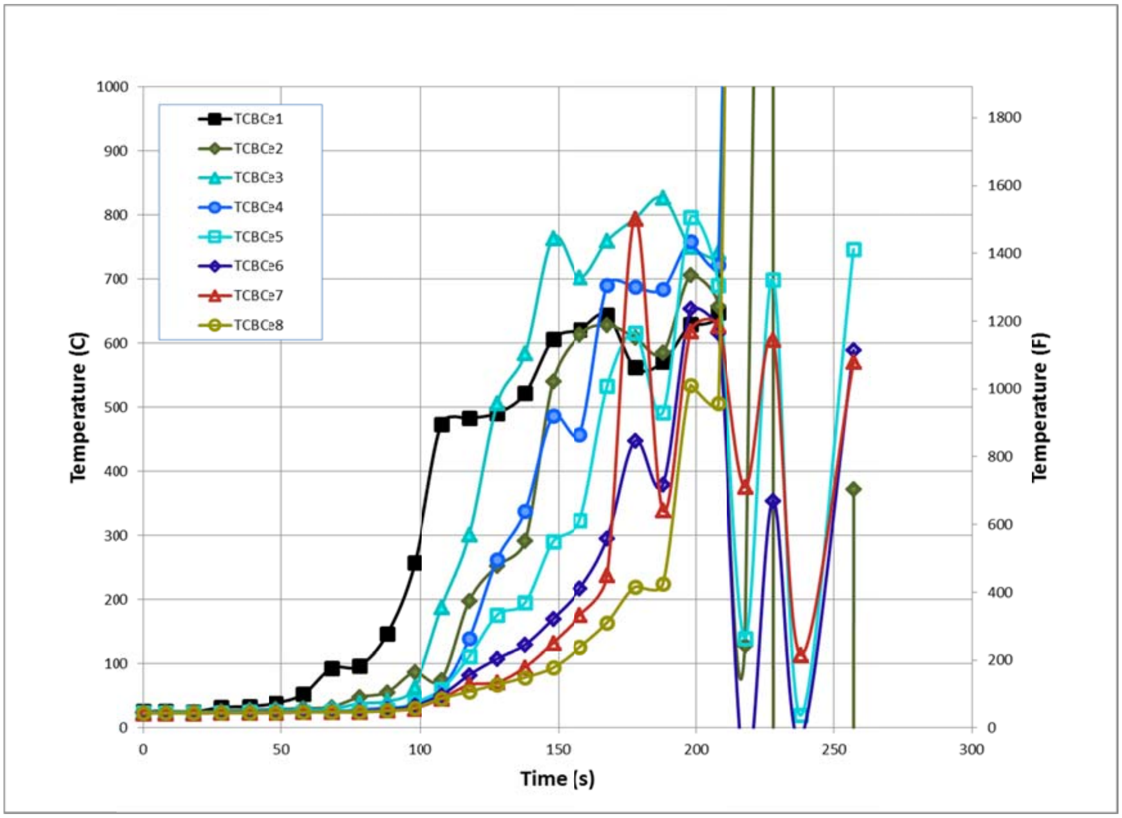

Figure 257. Experiment 10 - Basement Center Temperatures

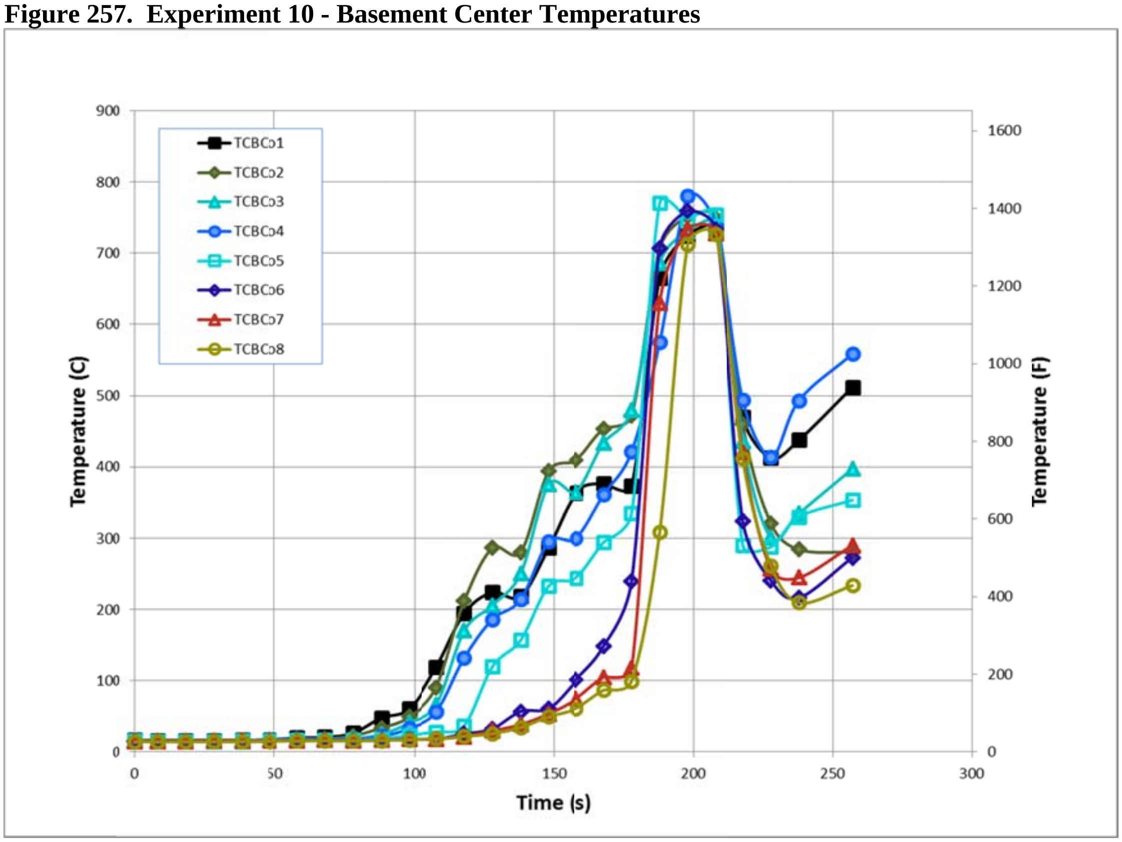

Figure 258. Experiment 10 - Basement Corner Temperatures

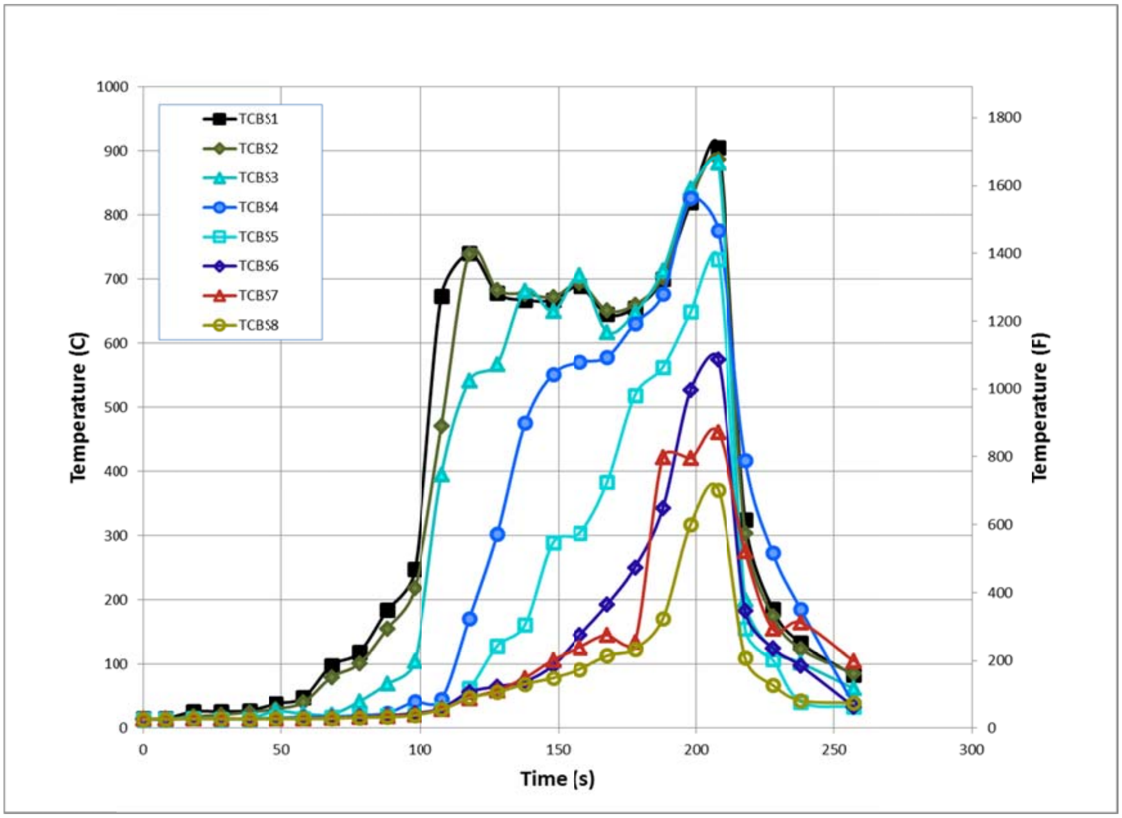

Figure 259. Experiment 10 - Basement Base of Stair Temperatures

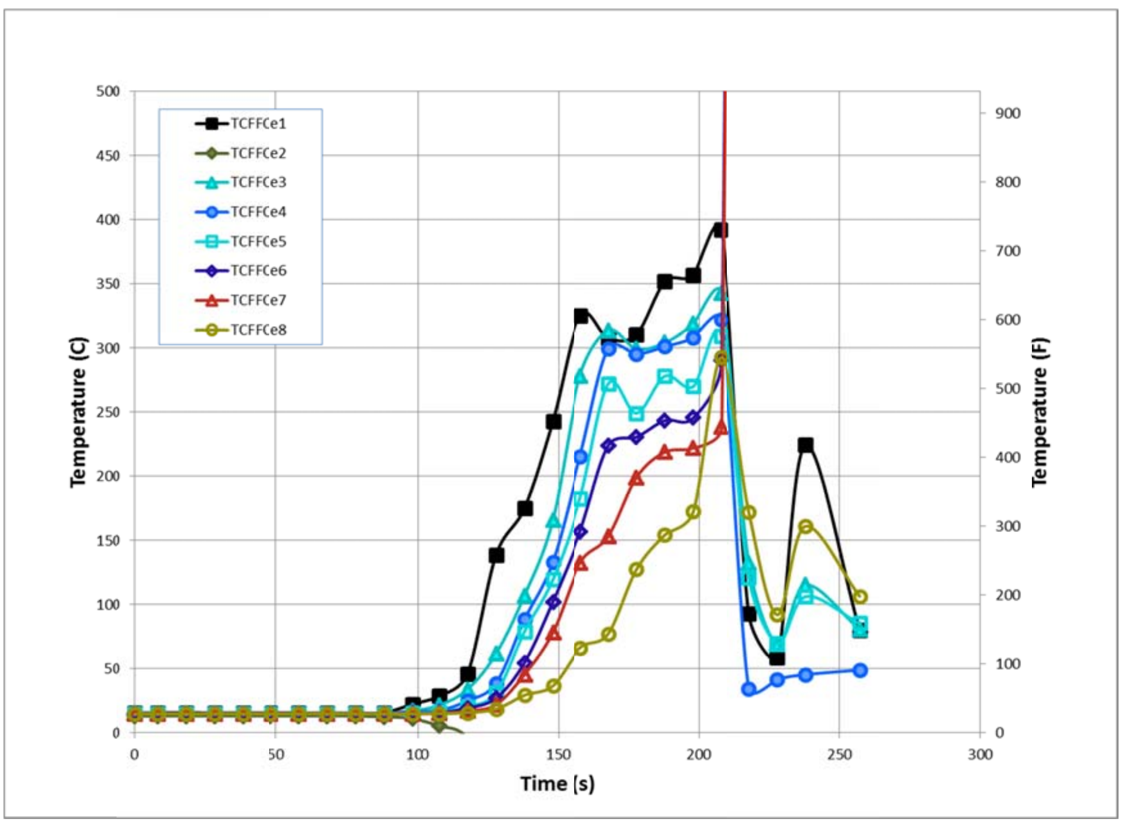

Figure 260. Experiment 10 - First Floor Center Temperatures

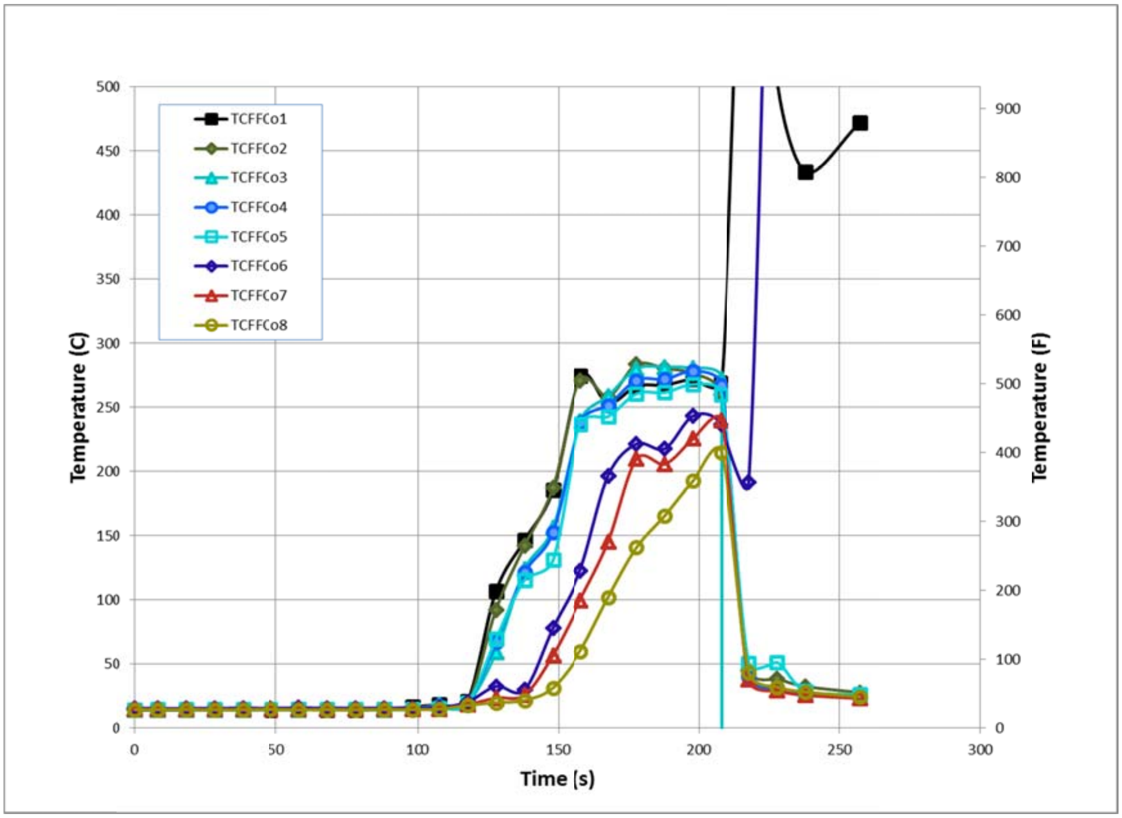

Figure 261. Experiment 10 - First Floor Corner Temperatures

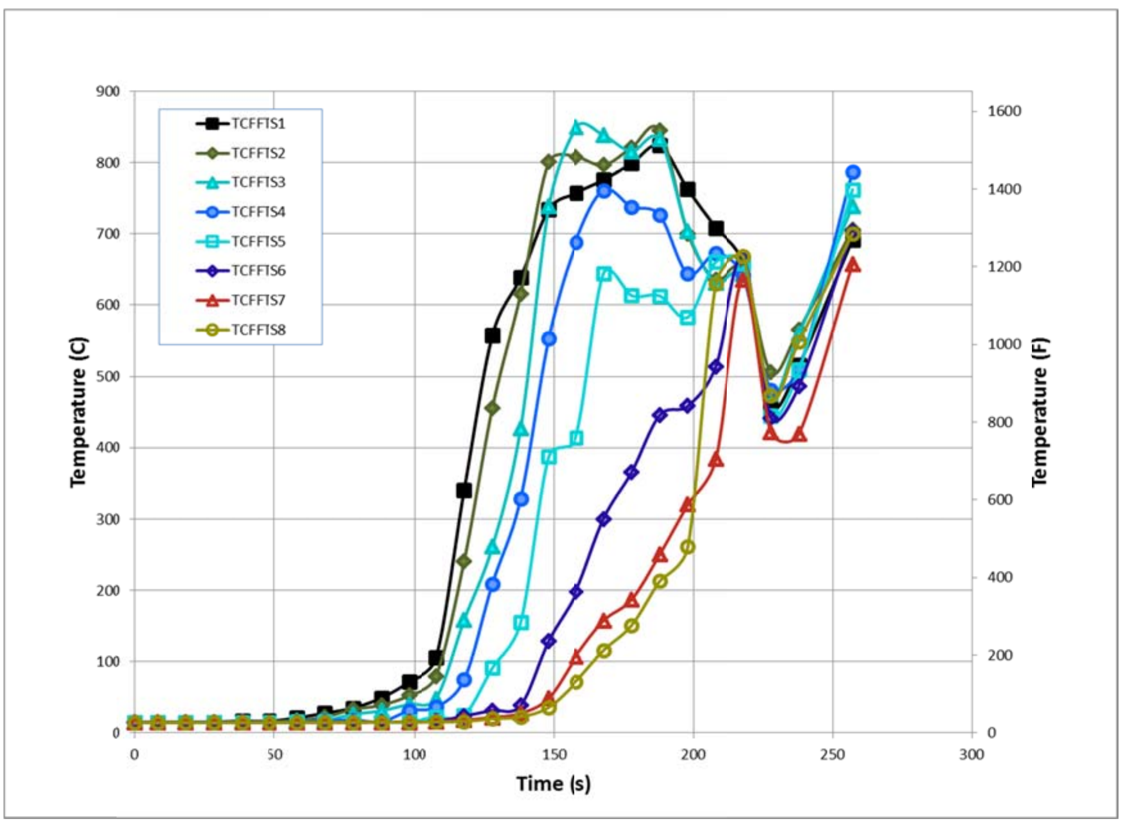

Figure 262. Experiment 10 - First Floor Top of Stair Temperatures

7.10.3. Gas Velocity

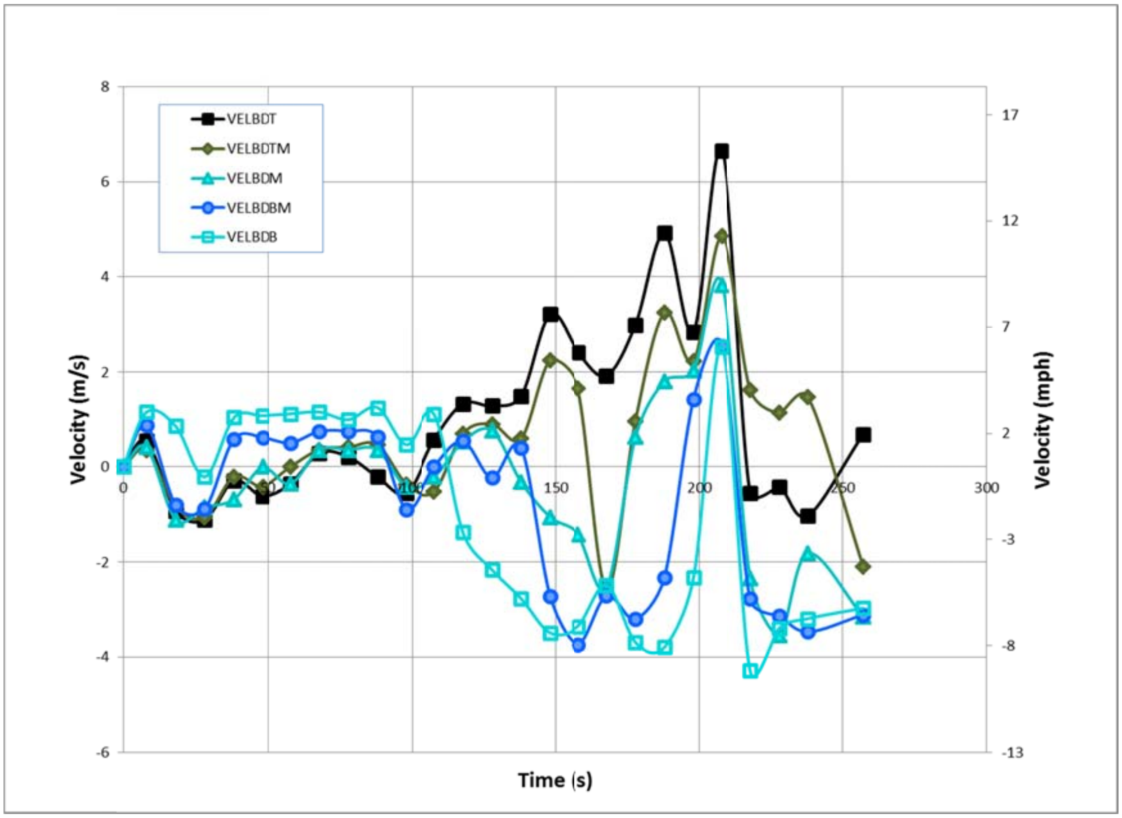

Figure 263. Experiment 10 - Basement Door Velocities

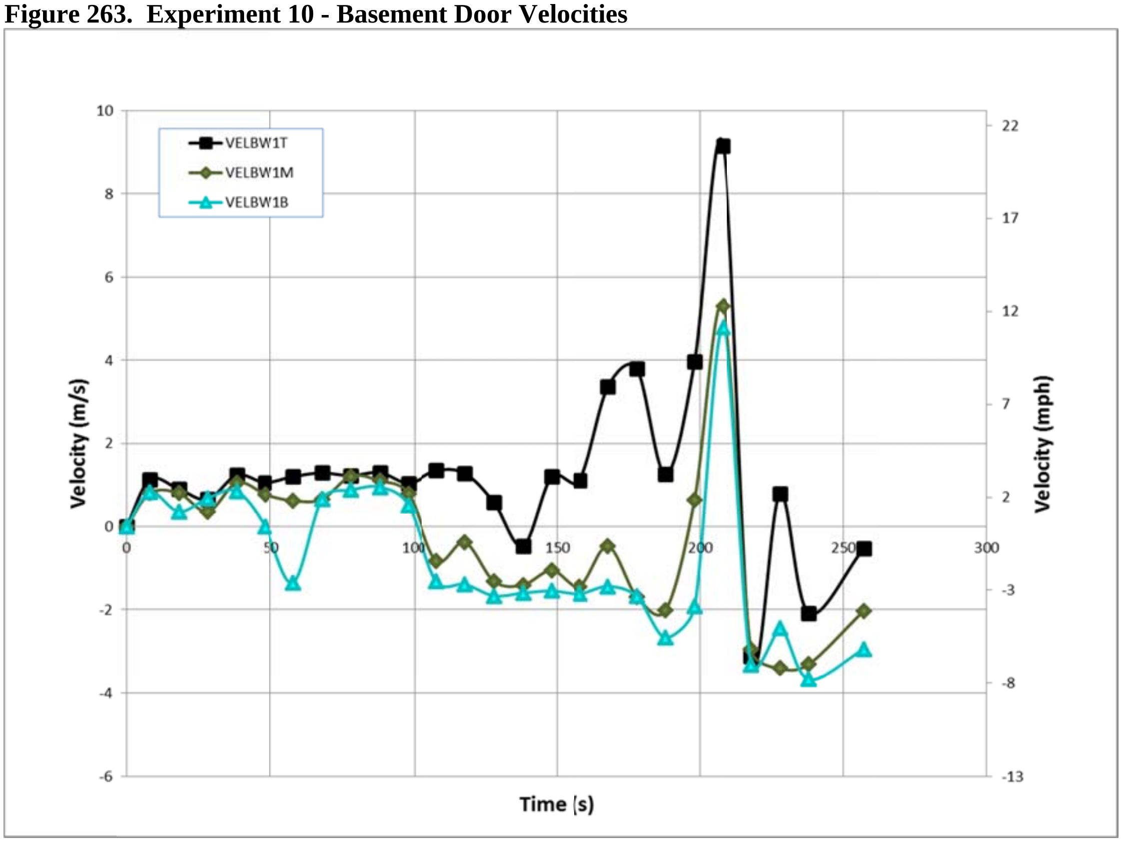

Figure 264. Experiment 10 - Basement Window 1 Velocities

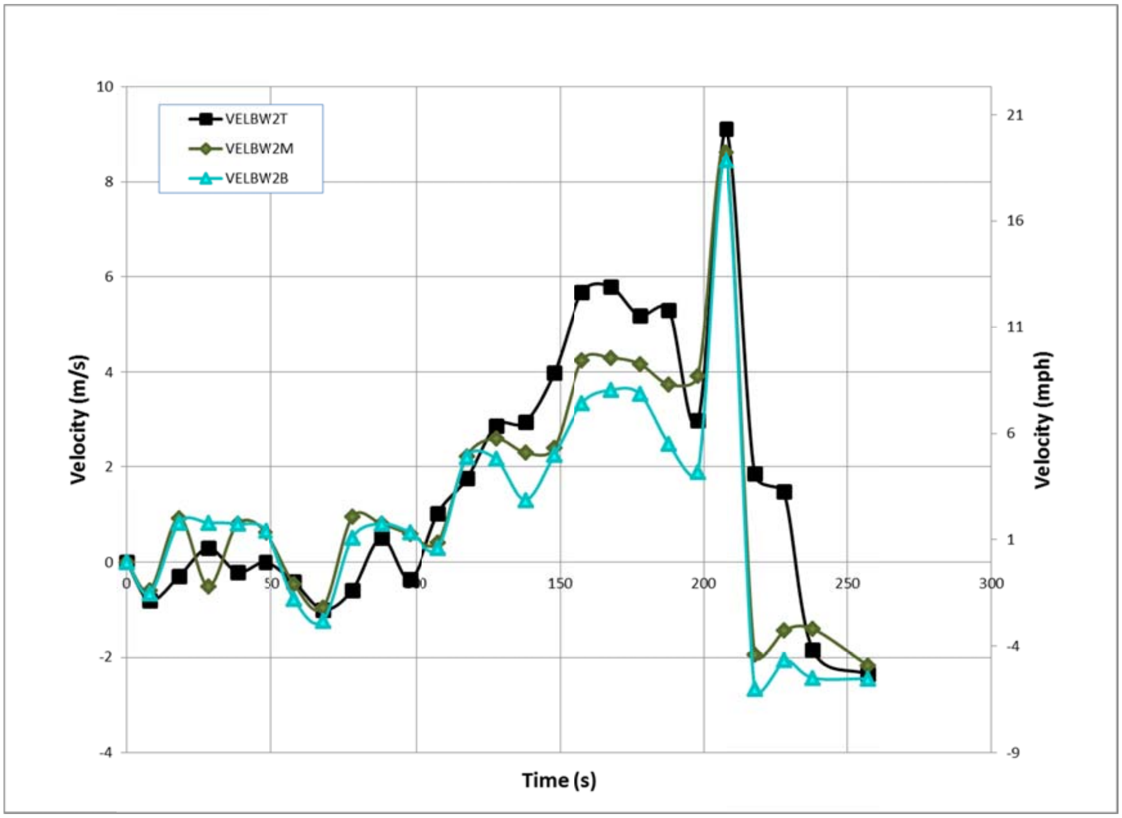

Figure 265. Experiment 10 - Basement Window 2 Velocities

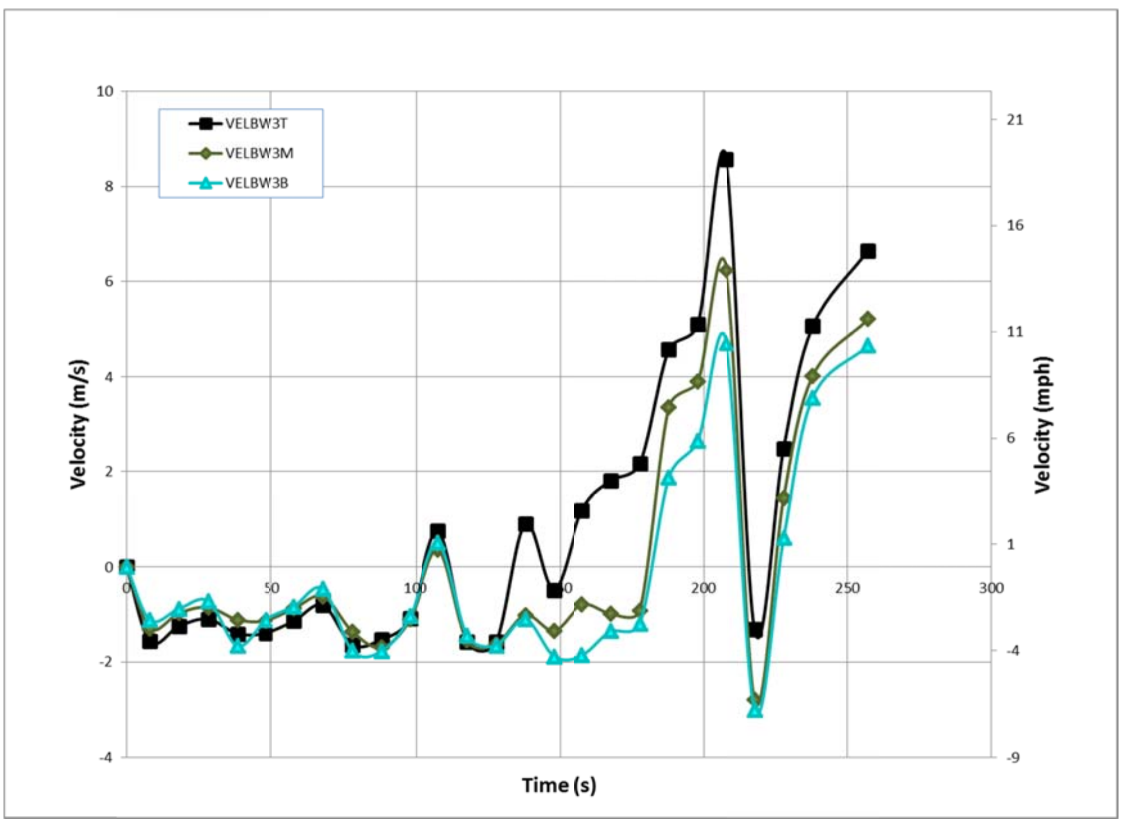

Figure 266. Experiment 10 - Basement Window 3 Velocities

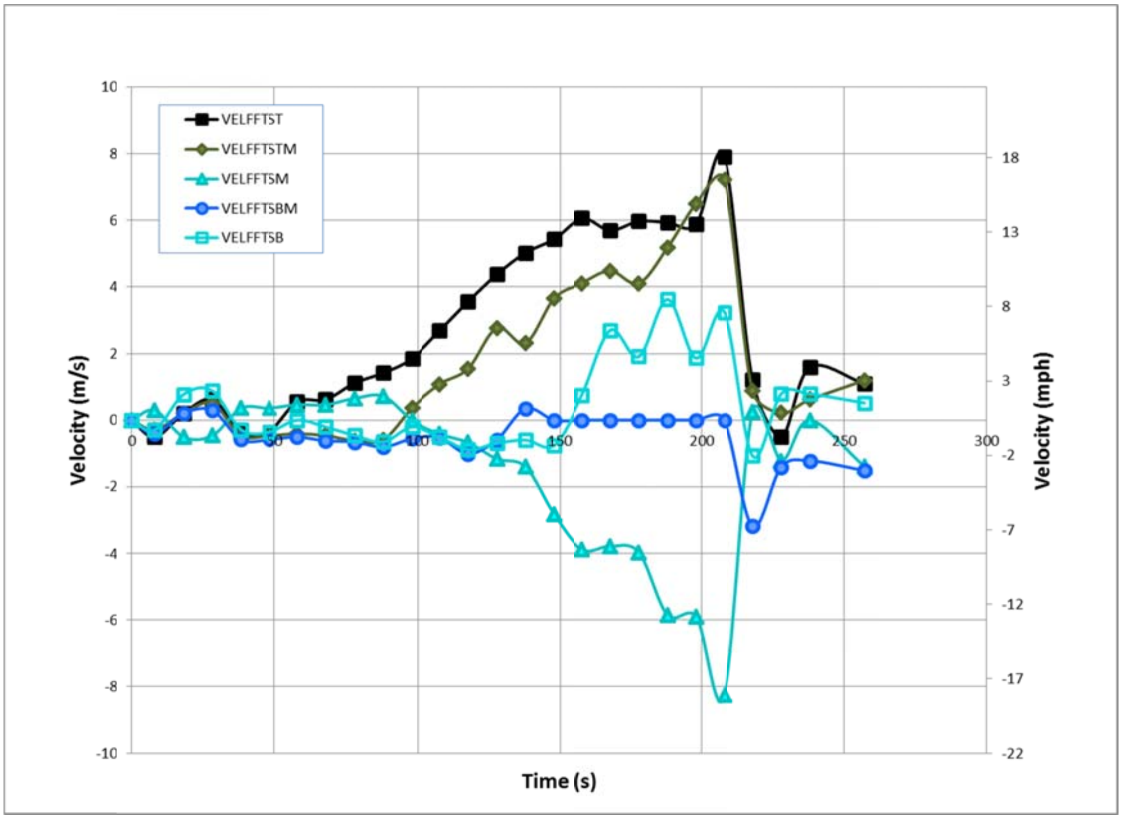

Figure 267. Experiment 10 - First Floor Stair Velocities

7.10.4. Deflection

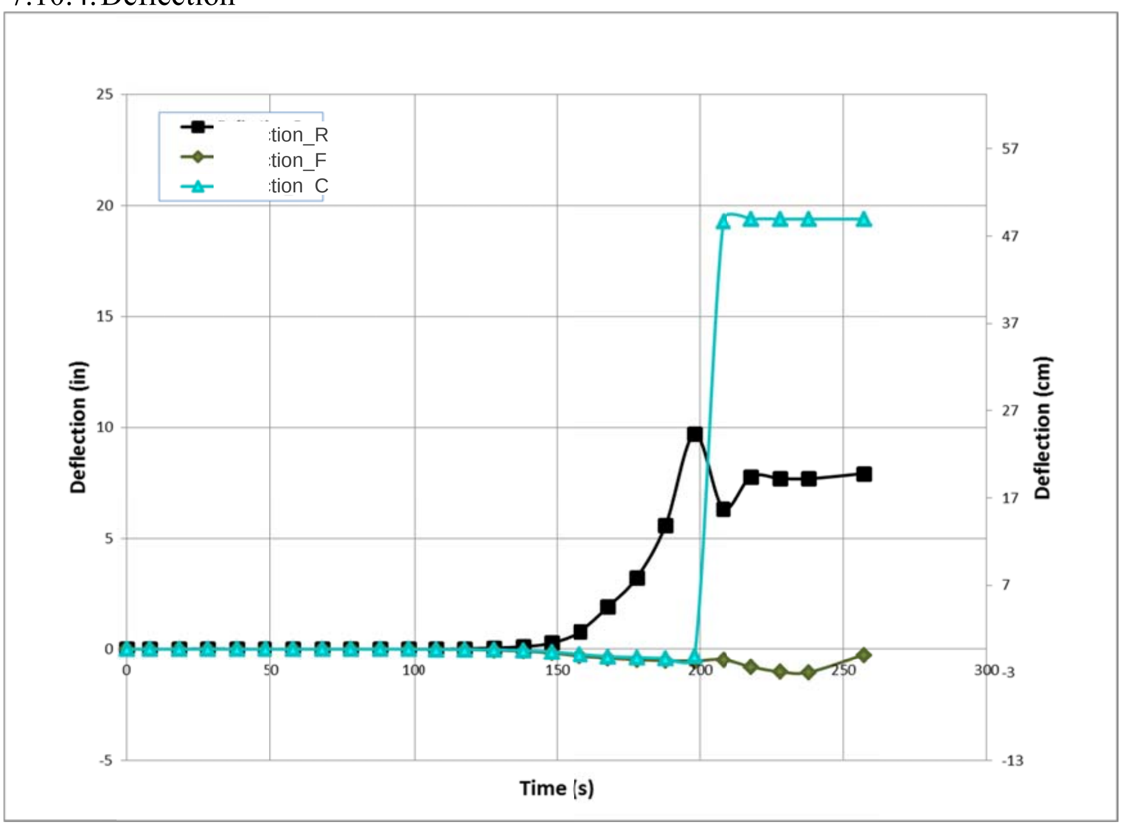

Figure 268. Experiment 10 - Floor System Deflections

7.10.5. Structural Response

The primary structural failure occurred at the rear section of the floor system; local to the initial fire location and extended to the center section as well. The failure mode of the parallel chord metal plate connected trusses was due to steel/wood connection failures. Connection failures were noted at tension splice locations (Figure 271) and at various truss panel points (Figure 272 - Figure 273). The floor system began to progressively deflect from 150 seconds until the end of the test. Experiment 10 induced a collapse of approximately 65 % of the total floor structure (Figure 270). The collapse time for the Experiment 10 was 3:28 after ignition. The collapse time respective of the structural element fire involvement for Experiment 10 was 1:50.

Figure 269 Interior view of percentage of collapsed area from above.

Figure 270 Interior view of percentage of collapsed area from underside of floor.

Figure 271 Connection failure of bottom chord tension splice and truss panel point.

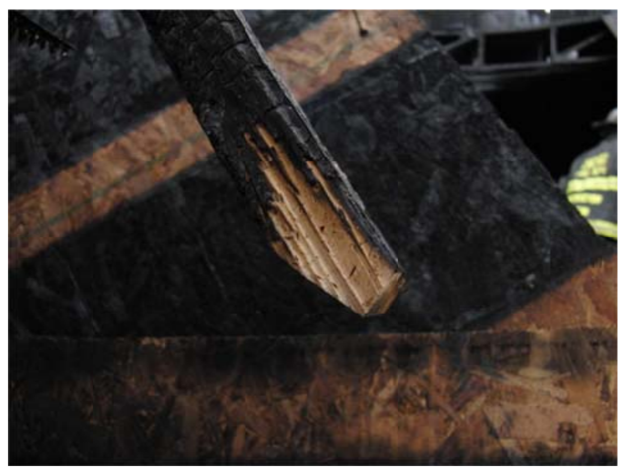

Figure 272 Connection failure at truss panel point.

Figure 273 Connection failure at truss panel point.

Figure 274 Connection failure at truss panel point.

8. Laboratory Experiment Description

UL conducted four real-scale experiments in its large-scale fire test facility (Table 35). The structure used for these experiments was of the same dimensions as the field experiments with the same openings for ventilation. The differences include wood stud walls lined with ½ inch cement board over ½ inch gypsum board 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 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.

Table 35. Experimental Series

Experiment	Floor System	Description
A	Wood I-Joist	Repeat of Field Experiment 3, Max Ventilation
B	Wood I-Joist	Max Ventilation, Torch Ignition
C	Parallel Chord Wood Truss	Gypsum ceiling, Void Ignition
D	Parallel Chord Wood Truss	Gypsum ceiling, 80 ft^2 exposed

8.1. Facility

These experiments were conducted in the large fire facility of Underwriters Laboratories in Northbrook, IL (Figure 275). The experimental structure was built in the 120 ft. by 120 ft. by 55 ft. test cell (Figure 276).

Figure 275. External view of the large fire facility

Figure 276. Internal view of laboratory during an experiment

8.1.1. Structure

The structure was built from wood frame walls. The interior dimensions were 20 ft. wide by 36 ft. long by 8 ft. tall (Figure 277). The floor systems were built on top of the wood frame walls as shown in Figure 278. The walls were sheathed with a base layer of ½ in. gypsum board covered with a layer of ½ in. cement board. There was an interior stairwell that connected the basement to the first floor. The doorway from the stairwell opened to the exterior of the structure unlike the previous field experiments that had an enclosed upper floor. The wall areas outside of the ventilation openings were protected with cement board and angled barriers to make sure there were no exterior ignitions of the floor system and that all fire exposure of the floor system came from the interior of the structure. Figure 279 through Figure 286 show several views of the structure.

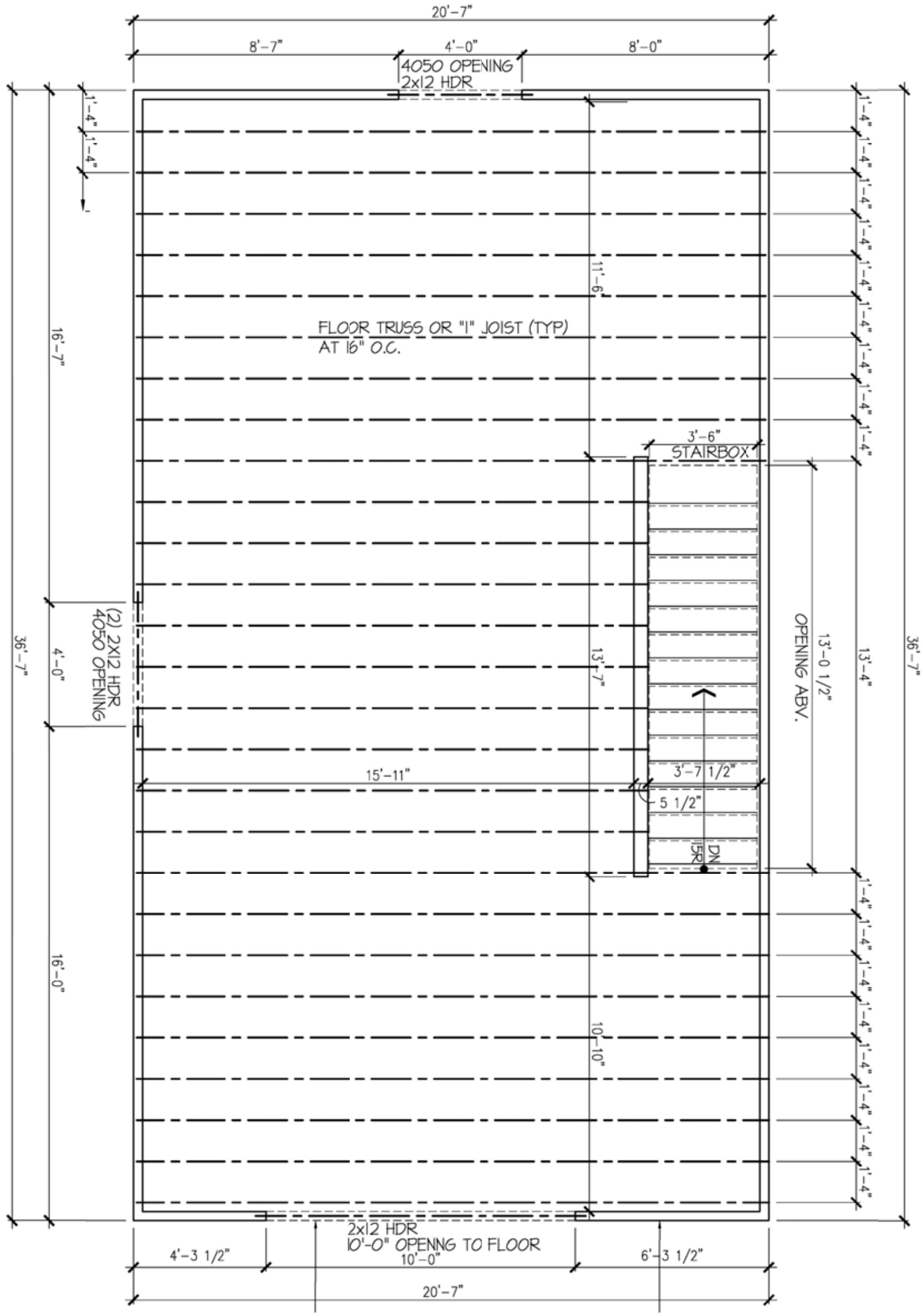

Figure 277. Detailed drawing of experimental structure

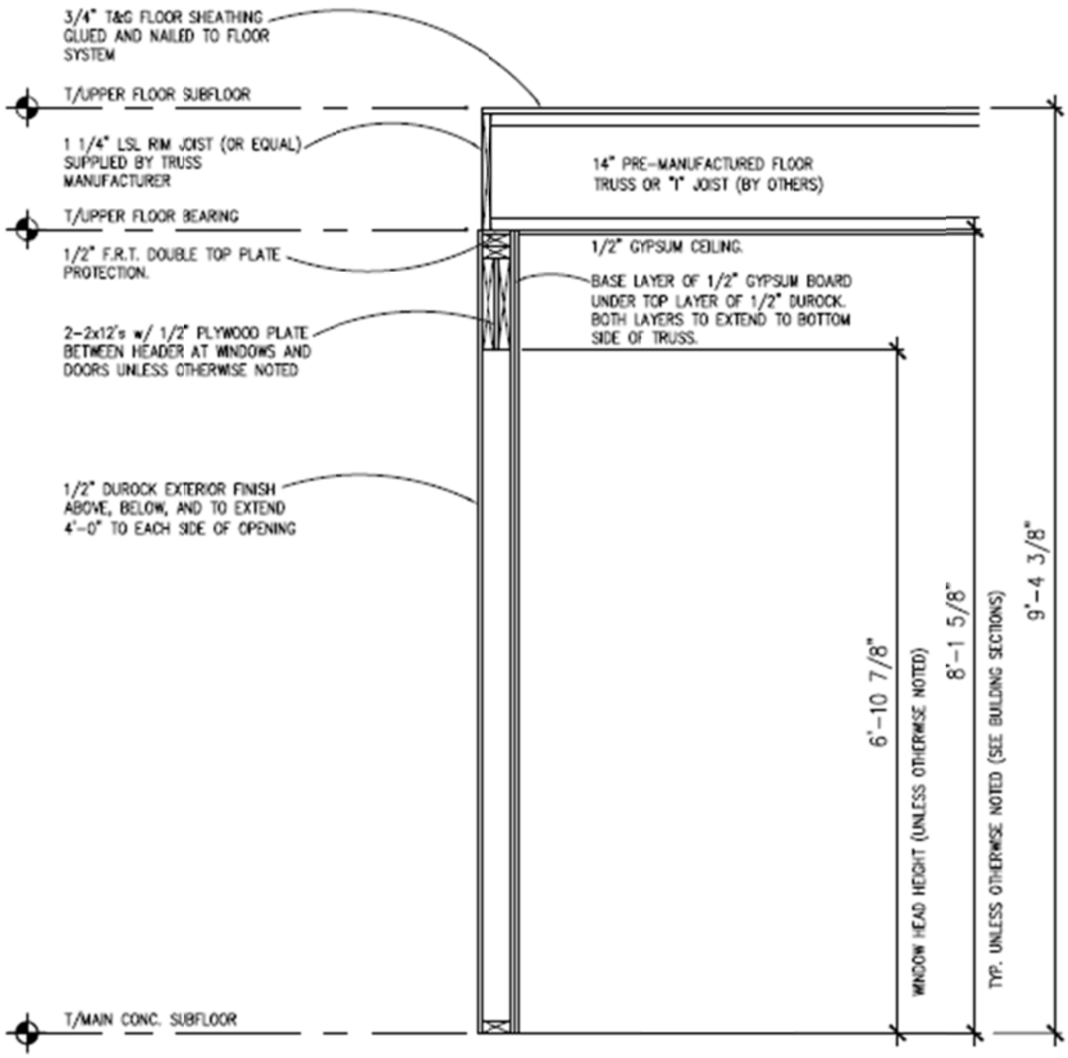

Figure 278. Wall section of experimental structure


Figure 279. Front of structure


Figure 280. Left side of structure


Figure 281. Back of structure


Figure 282. Right side of structure


Figure 283. Interior view looking toward back


Figure 284. Interior view looking toward the front


Figure 285. View up the stairwell


Figure 286. View of stairwell doorway

8.1.2. Floor Systems

Two different floor systems were examined during these experiments. Experiment A and B used the same engineered wood I joist floor system used in field experiments 3 through 6 with a different fuel load and ignition sequence. Experiment C and D used the same floor system as field experiments 9 and 10 with differences in protection areas and ignition sequences. Each floor system utilized 23/32 in. tongue and groove oriented strand board (OSB) decking.

1. Engineered Wood I joist (Depth 11 7/8 in, Flange Thickness 1 ½ in., Flange Width 2 ½ in., Web Depth 8 7/8 in., Web Width 3/8 in.), unprotected [Figure 287]
2. Parallel Chord Wood Truss (14 in. deep), protected with ½ in. gypsum board [Figure 288]

Experiment 3 had a parallel chord wood truss floor system that was protected with a layer of ½ in. gypsum board. The only penetrations were ten recessed lights that were installed in the ceiling (Figure 289). Experiment 4 also had a parallel chord wood truss floor system that was protected with a layer of ½ in. gypsum board and recessed lights. However this floor had a 80 ft^2 exposed section of trusses as allowed by the International Residential Code Section R501.3 (See Below) that will go into effect at the start of 2012 (Figure 290 and Figure 291). The exposed area was fire blocked using gypsum board (Figure 292).

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.*

Figure 287. Engineered wood I joists (Exp. A and B)

Figure 288. MPCWT (Exp. C and D)

Figure 289. Experiment C ceiling with recessed lights

Figure 290. Experiment D ceiling with 80 ft^2 exposed

Figure 291. Close view of exposed trusses

Figure 292. Detailed image showing draft stopping of the exposed trusses

8.1.3. Instrumentation and Uncertainty

The measurements taken during the experiments were very similar to the field experiments included gas temperature, gas velocity, deflection and video recording. Measurement locations can be found in Figure 41. The figure also includes the labels that are used in the data plots and video captures that are in the Experimental Results Section. Gas temperature was measured with bare-bead, Chromel-Alumel (type K) thermocouples, with a 0.5 mm (0.02 in) nominal diameter. Thermocouple arrays were located in 3 locations in the basement of the structure. All of the thermocouple locations had an array of thermocouples with measurement locations of 0.03 m, 0.3 m, 0.6 m, 0.9 m, 1.2 m,1.5 m, 1.8 m and 2.1 m (1 in, 1 ft, 2 ft, 3 ft, 4 ft, 5 ft, 6 ft and 7 ft) below the decking in the basement (Figure 294). The standard uncertainty in temperature of the thermocouple wire itself is ± 2.2 °C at 277 °C and increases to ± 9.5 °C at 871 °C as determined by the wire manufacturer (Omega Engineering Inc., 2011).

Gas velocity was measured utilizing differential pressure transducers connected to bidirectional velocity probes (Figure 295). These probes were located in the basement doorway, doorway at the top of the stairs and each of the three windows. There were five probes on the vertical centerline of each doorway located at 0.3 m (1 ft) from the top of the doorway, the center of the doorway, 0.3 m (1 ft) from the bottom of the doorway and two equally spaced between these probes. There were three probes on the vertical centerline of the windows located 0.15 m (6 in) from the top of the window, the center of the window and 0.15 m (6 in) from the bottom of the window. Thermocouples were co-located with the bidirectional probes to complete the gas velocity measurement. Positive measurements are flows out of the structure while negative velocity measurements are into the structure. The transducers were factory calibrated and documented to have an accuracy of ± 1 % (Setra, 2002).

Deflection of the floor system was measured using linear deflection gauges in five locations. Three locations along the centerline of the long dimension of the structure measuring vertical displacement, and two attached to the top chord of joist above the fire location measuring horizontal displacement (Figure 296). The gauges were set to measure maximums of 5 in. of upward deflection and 20 in. of downward deflection. The gauges have an accuracy of 0.15% of the full-scale measurement with a repeatability of 0.015% of the full-scale measurement (Unimeasure Inc., 2011).

Video cameras were placed inside and outside the structure to monitor both smoke and fire conditions throughout each experiment (Figure 297). Eight video camera views were recorded during each experiment. The views recorded are detailed in Table 22 and shown in Figure 46 and Figure 47.

Table 36. Video camera views

View Description	View Label (Figure 298 and Figure 299)
Inside front basement corner	In Front
Inside rear basement corner	In Back
Inside middle of basement	In Mid
Outside back and side overall	Back/side
Outside close-up of doorway	Doorway
Outside close-up Thermal Imaging	Door IR
Outside front	Front
Outside top	Top

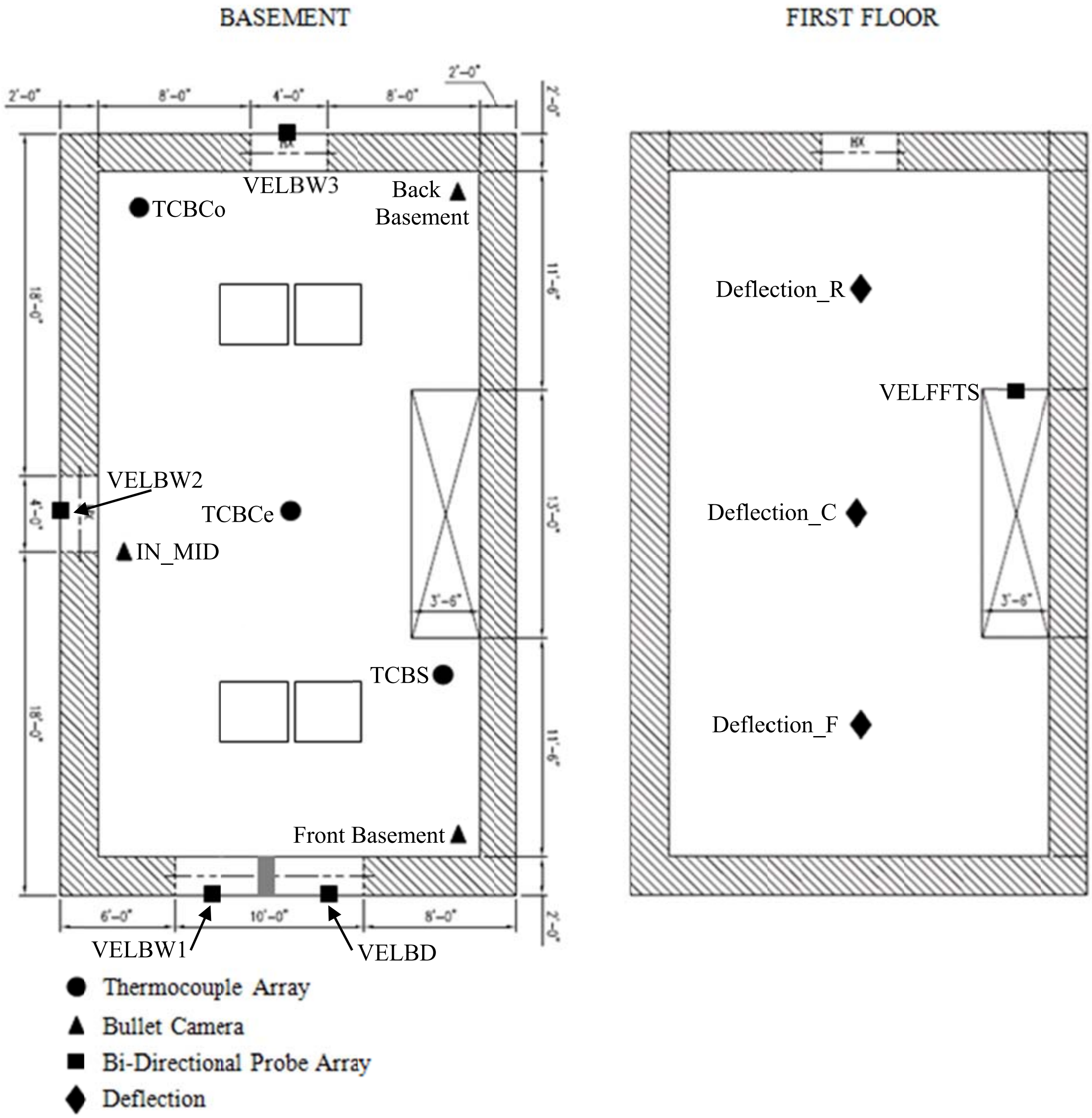

Figure 293. Measurement Locations and Labels

Figure 294. Thermocouple tree locations

Figure 295. Velocity probe locations in window

Figure 296. Deflection Gauge

Figure 297. Bullet camera

Figure 298. Quad Video 1

Figure 299. Quad Video 2

8.2. Fuel Load

There were three different fuel loads for the 4 experiments. Experiments A and D utilized the fuel load described in Chapter 4, the same configuration as most of the field experiments (Figure 300, Figure 303). Experiment B did not have a fuel load; instead a propane plumber's torch was used to ignite the floor system (Figure 301). Experiment C also did not have a fuel load but utilized 2 igniters (described in Chapter 4) placed above the gypsum board ceiling as the ignition source (Figure 302).

Figure 300. Experiment A fuel load

Figure 301. Experiment B ignition sequence

Figure 302. Experiment C ignition location

Figure 303. Experiment D fuel load

8.3. Structural Load

The loading of the floor systems was provided by water filled steel barrels positioned on top of the floor depending on the calculated load for each system (Figure 304). The load was consistent across the floor system technologies and was calculated to be 65% of the design stress of the system. Each barrel was filled to the appropriate level with water and positioned to provide the calculated load. Detailed calculations and details of barrel placement are located in Appendix C.

Figure 304. Barrel loading placement

8.4. Ventilation Parameters

All 4 of these experiments were conducted with “maximum ventilation” meaning all of the ventilation locations were open. The basement door, 3 basement windows and door at the top of the stairs were open at the start and for the duration of the experiments. Figure 305 and Figure 306 show fire coming from the ventilation openings during Experiment 1.

Figure 305. Fire from the ventilation openings

Figure 306. Doorway at the top of the stairs

9. Laboratory Experiment Results

The results of the 4 experiments are detailed in this section. Table 37 details the variables of the experiments. The fuel was varied for Experiments B and C, the floor load was consistent for every experiment and each floor system was tested with a maximum ventilation scenario.

Table 37. Experimental Summary

Experiment	Floor System	Fuel	Load	Ventilation
A	Wood I-Joist	Pallets/boxes	65% of design stress	Maximum
B	Wood I-Joist	Propane Torch/pallets	65% of design stress	Maximum
C	Parallel Chord Wood Truss with gypsum	2 Igniters in void space	65% of design stress	Maximum
D	Parallel Chord Wood Truss with gypsum	Pallets/boxes	65% of design stress	Maximum

9.1. Experiment A – Engineered I Joist

In this experiment all of the ventilation openings were open prior to ignition and the fire was ignited in the front fuel package closest to the base of the stairs. This experiment was a replicate of Field Experiment 3 except that there was no wind condition due to being inside the laboratory. The fire spread until the floor system collapsed and then was suppressed. The timeline of events is detailed in Table 38. The results for the experiment are presented in the following sections: observations, temperature, gas velocity, and deflection.

Table 38. Experiment A Timeline

Time (s, mm:ss)	Event
0 (0:00)	Ignition
140 (2:20)	Flames attach to the floor system
380 (6:20)	Collapse
400 (6:40)	End of experiment

9.1.1. Observations

The observations are presented as a series of images captured from eight camera locations, seven were video cameras and one was a thermal imaging camera. The views were captured at the start of the experiment (0:00, Figure 307), once flames attached to the floor system (2:20, Figure 308), when there was sustained flames coming from the stairwell doorway on the first floor (2:40, Figure 309), 5 minutes after ignition (5:00, Figure 310), and 5 seconds before collapse (6:15, Figure 311).

Figure 307. Experiment A video views at 0:00.

Figure 308. Experiment A video views at 2:20.

Figure 309. Experiment A video views at 2:40.

Figure 310. Experiment A video views at 5:00.

Figure 311. Experiment A video views at 6:15.

9.1.2. Temperatures

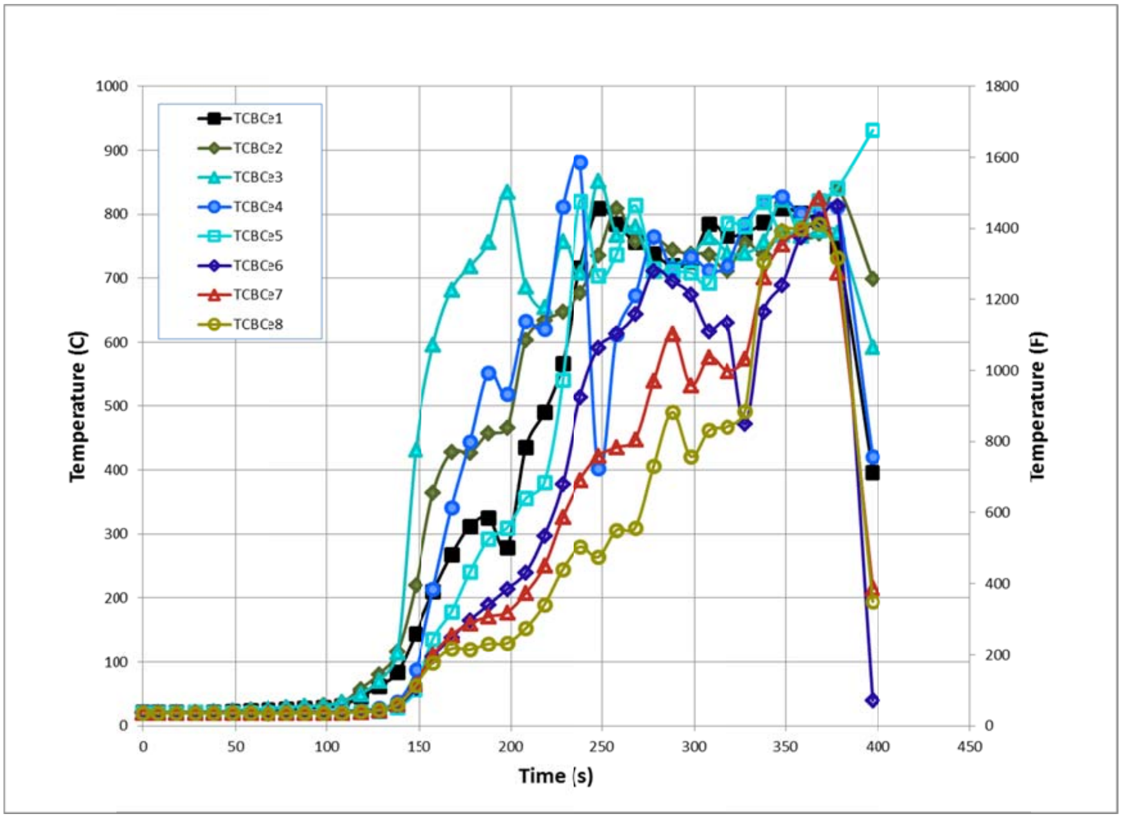

Figure 312. Experiment A - Basement Center Temperatures

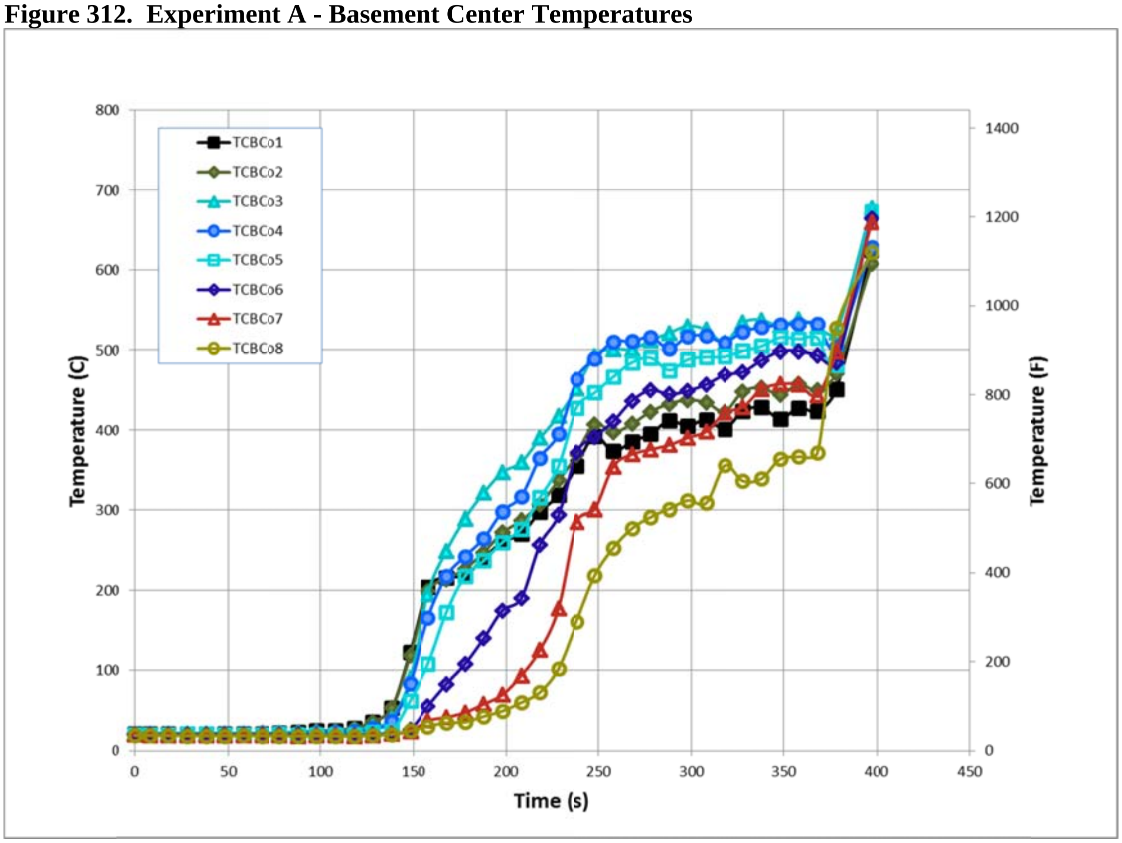

Figure 313. Experiment A - Basement Corner Temperatures

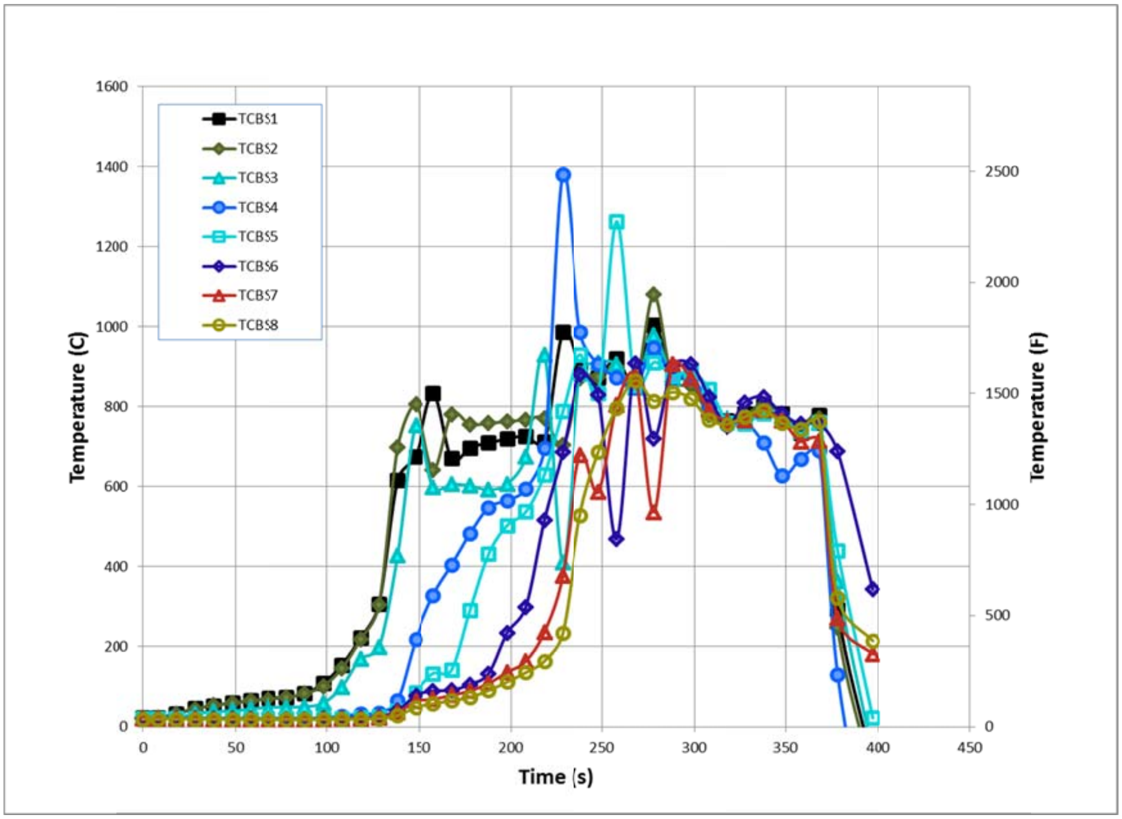

Figure 314. Experiment A - Basement Base of Stair Temperatures

9.1.3. Gas Velocities

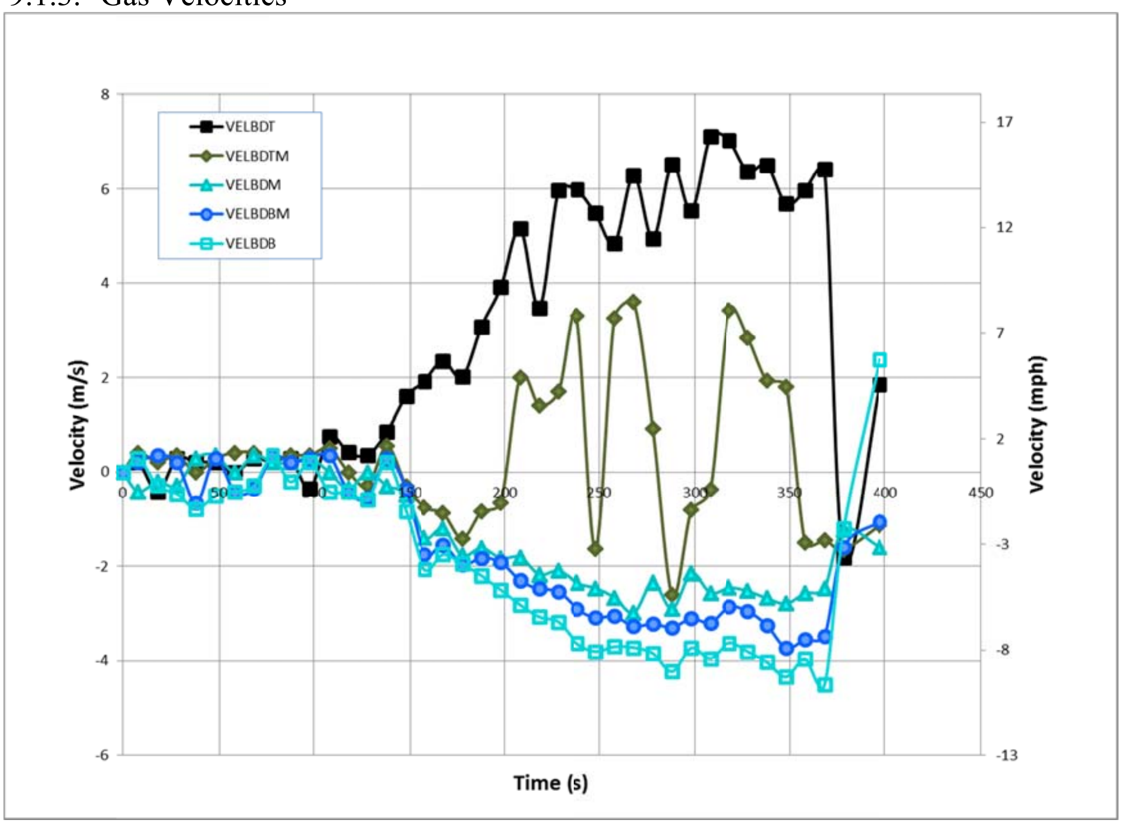

Figure 315. Experiment A - Basement Door Velocities

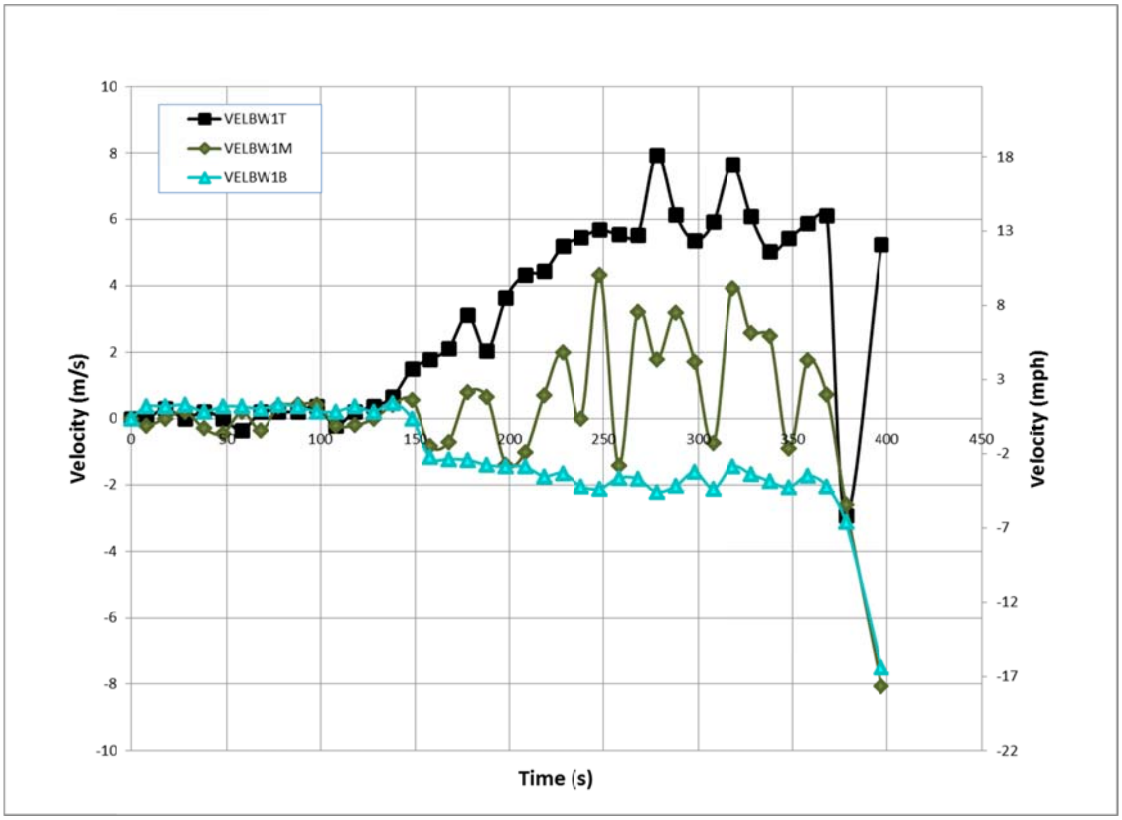

Figure 316. Experiment A - Basement Window 1 Velocities

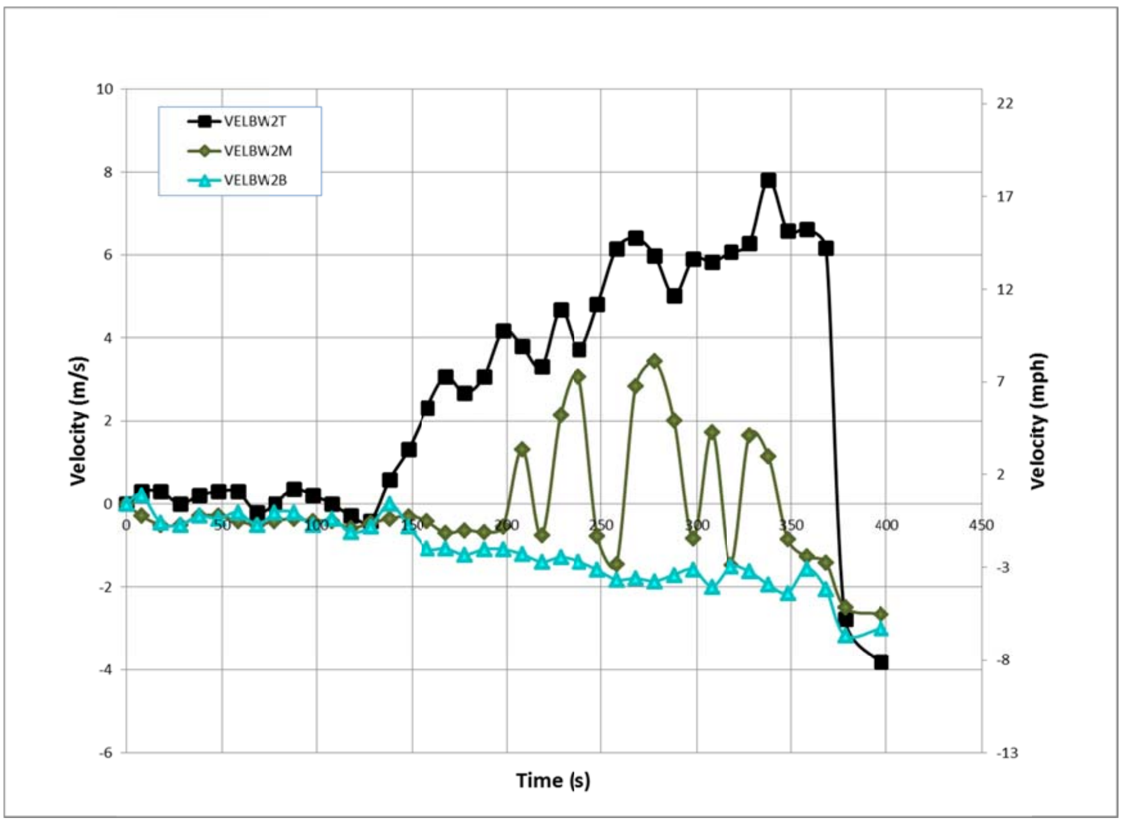

Figure 317. Experiment A - Basement Window 2 Velocities

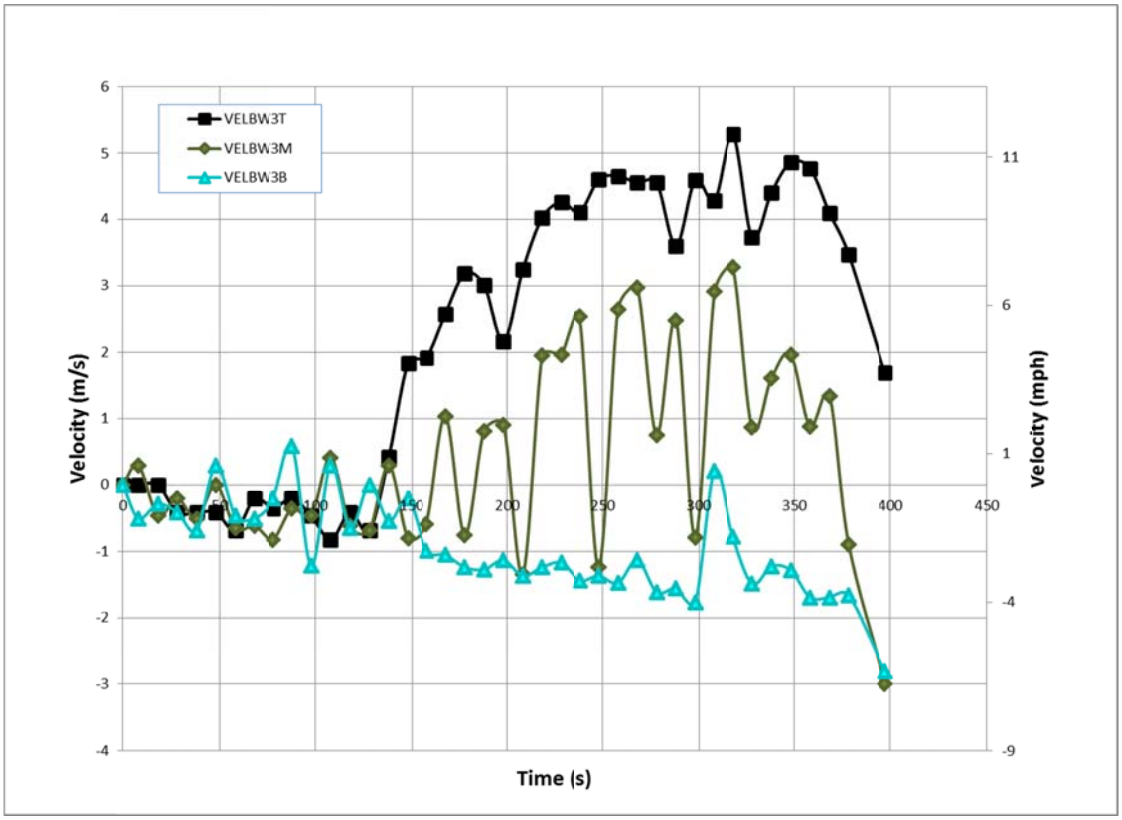

Figure 318. Experiment A - Basement Window 3 Velocities

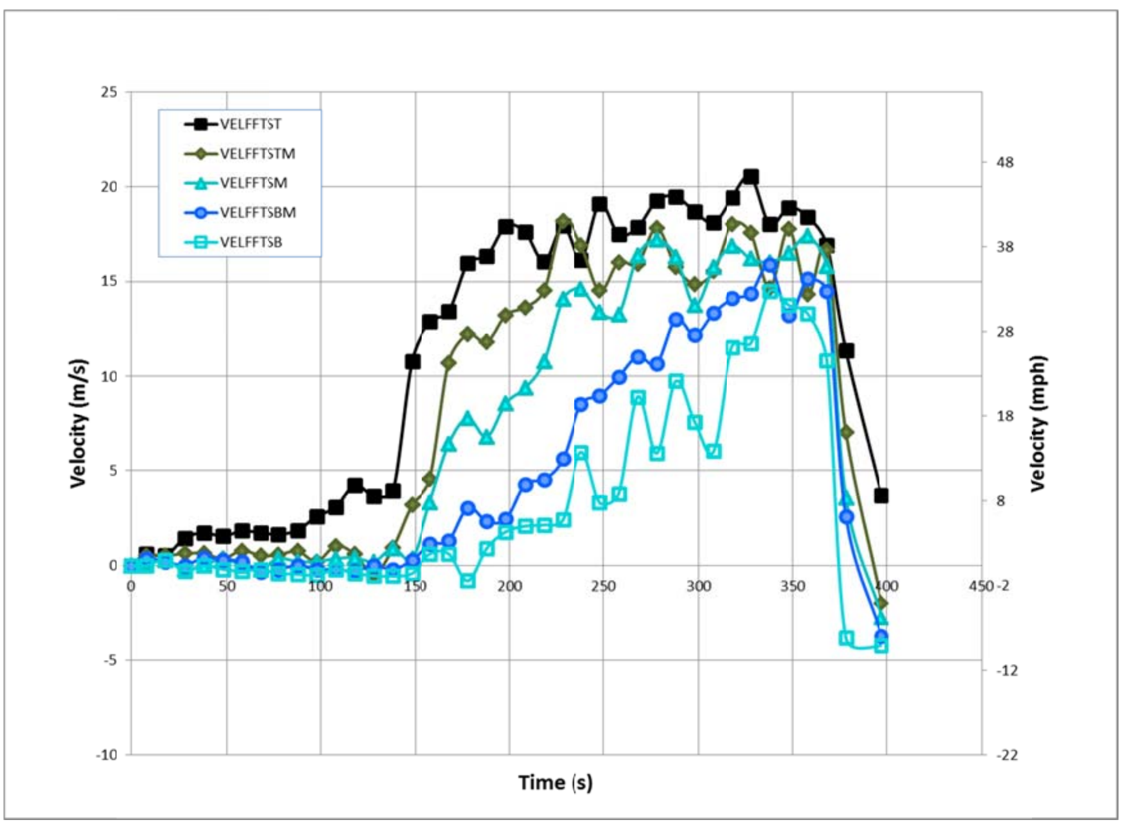

Figure 319. Experiment A - First Floor Stair Velocities

9.1.4. Deflection

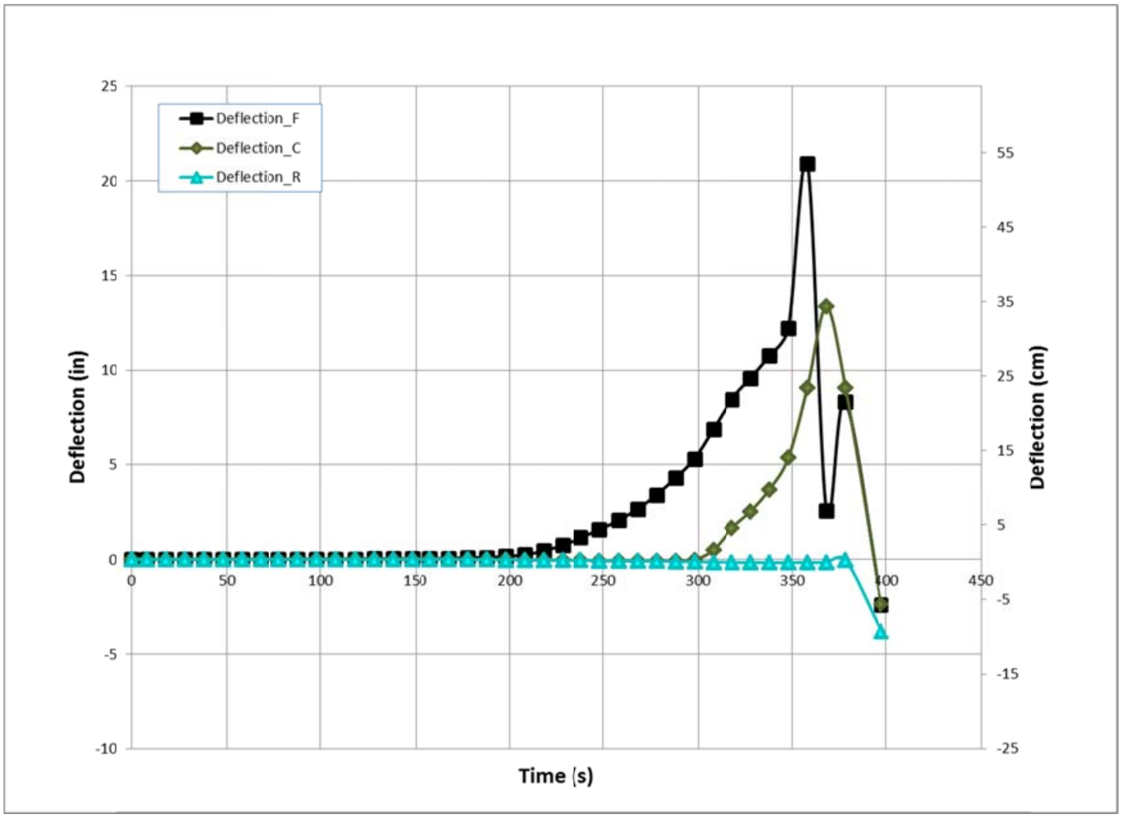

Figure 320. Experiment A - Floor System Deflections

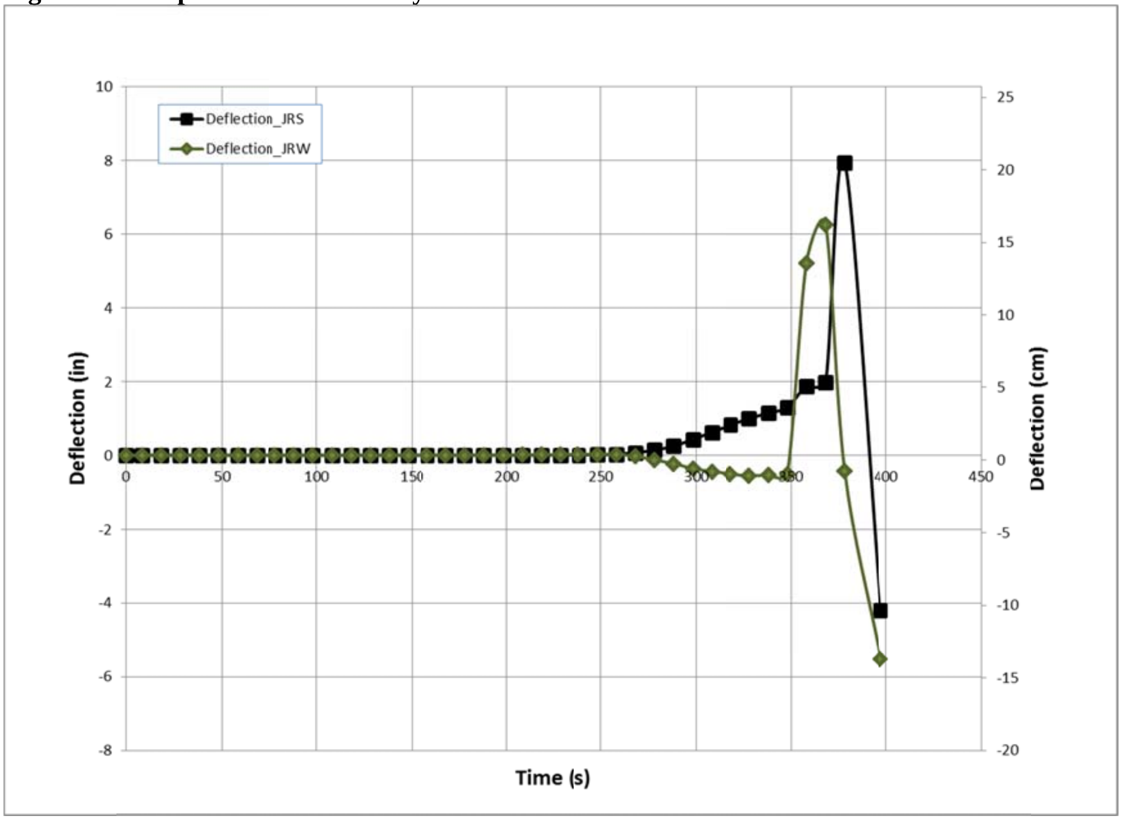

Figure 321. Experiment A - Joist Rotation

9.1.5. Structural Response

The primary structural failure occurred at the front section of the floor system, local to the initial fire location. A secondary collapse of the center and front sections occurred moments later. The failure mode for the engineered I-joists was due to burn-out of the web members in the front and center sections of the floor system (Figure 322 and Figure 323) and joist rupture at the rear section of the floor system. The web burn-out induced separation of the top and bottom flange members, in some cases causing complete rupture of the flanges (Figure 324). Mechanical separations of the web to flange connection, failure of web butt joint connections, and flange member rupture were also noted in joists at the front section of the floor structure (Figure 324 and Figure 325). The floor system began to progressively deflect from approximately 150 seconds until the end of the test. Experiment A induced a collapse of approximately 100% of the total floor structure. The collapse time for the Experiment A was 6:20 after ignition. The collapse time respective of the structural element fire involvement for Experiment A was 4:00.

Figure 322 Web burn-out of the engineered I-joist local to collapsed area at center section of the floor system.

Figure 323 Web burn-out of the engineered I-joist local to collapsed area at center section of the floor system.

Figure 324 Mechanical separations of the web to flange connections and flange member rupture.

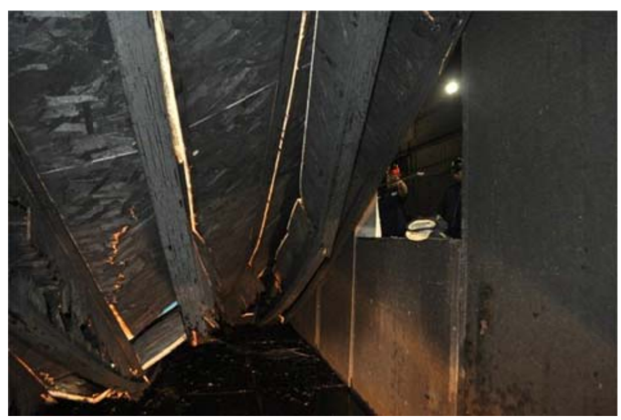

Figure 325 Mechanical separations of the web to flange connections, and flange member rupture.

9.2. Experiment B – Engineered I Joist

In this experiment all of the ventilation openings were open prior to ignition and the fire was ignited using a propane plumbers torch placed on an I- joist located at the center, where the fuel load would be placed as in the previous experiment. The torch initially burnt through the web of the joist and did not ignite it. The torch was repositioned but burned through the joist again and did not create a fire that would spread beyond the area of ignition. Pallets were brought into the structure as a back-up ignition source. As the pallets were being ignited the small self-sustaining flame from the plumbers torch spread across the floor system and combustion was maintained. The fire spread until the floor system collapsed and then was suppressed. The timeline of events is detailed in Table 39. The results for the experiment are presented in the following sections: observations, temperature, gas velocity, and deflection.

Table 39. Experiment B Timeline

Time (s, mm:ss)	Event
0 (0:00)	Ignition
1320 (22:00)	Torch removed
1508 (25:08)	Stack of 6 pallets ignited
1555 (25:55)	Flames attach
1885 (31:25)	Collapse
2020 (33:40)	End of experiment

9.2.1. Observations

The observations are presented as a series of images captured from eight camera locations, seven were video cameras and one was a thermal imaging camera. The views were captured at the start of the experiment (0:00, Figure 326), just after the torch was removed (22:02, Figure 327), once flames attached to the floor system (25:55, Figure 328), when there was sustained flames coming from the stairwell doorway on the first floor (27:28, Figure 329), and 5 seconds before collapse (31:20, Figure 330).

Figure 326. Experiment B video views at 0:00.

Figure 327. Experiment B video views at 22:02.

Figure 328. Experiment B video views at 25:55.

Figure 329. Experiment B video views at 27:28.

Figure 330. Experiment B video views at 31:20.

9.2.2. Temperatures

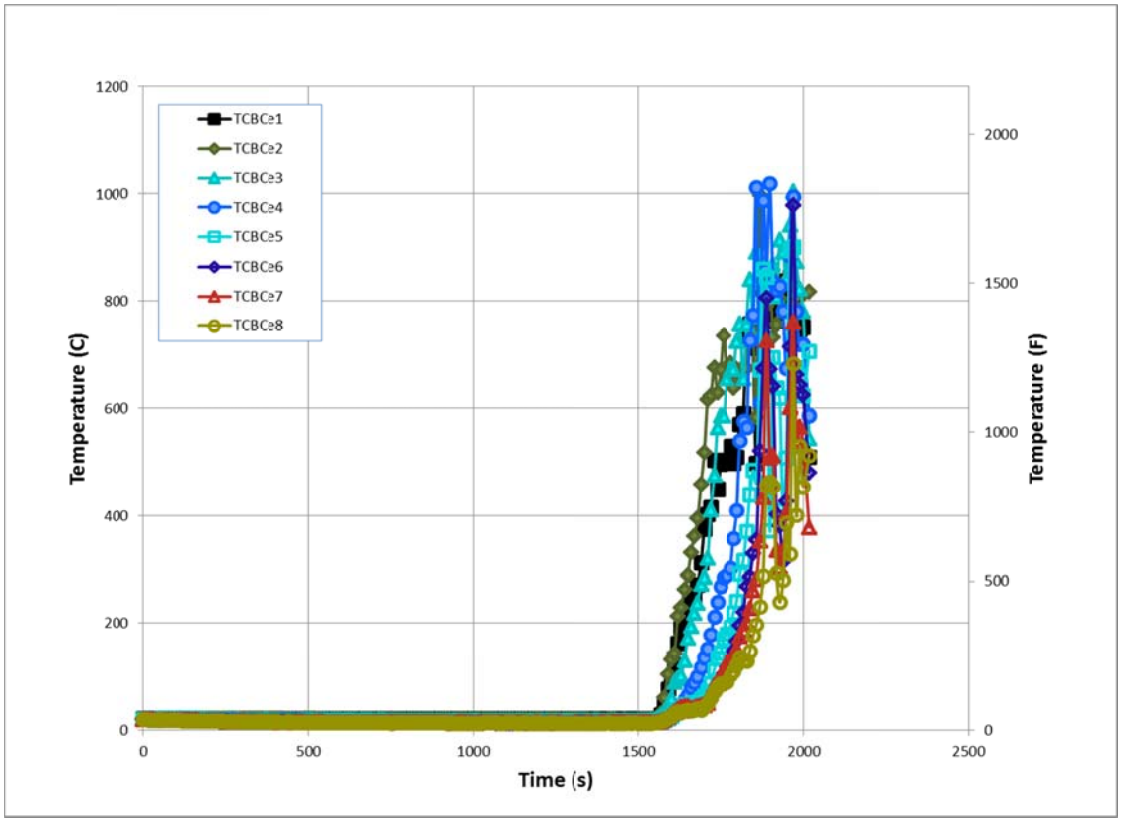

Figure 331. Experiment B - Basement Center Temperatures

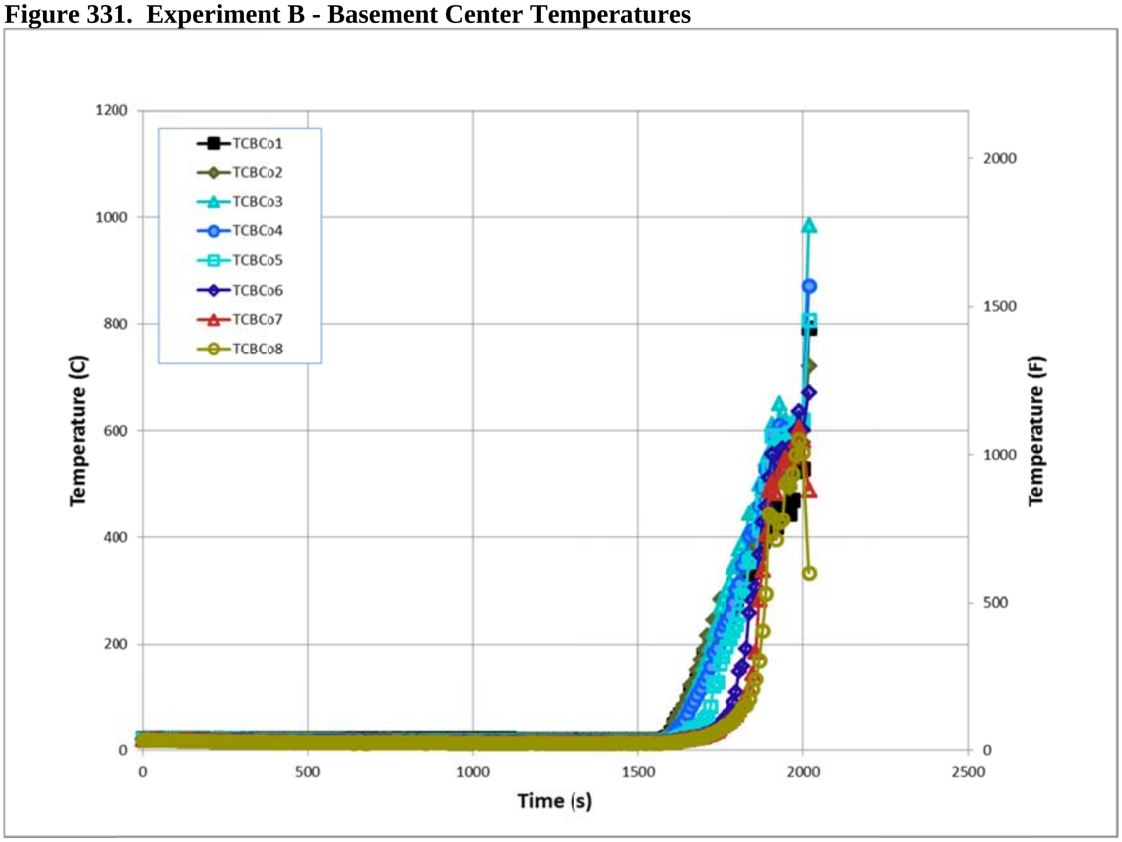

Figure 332. Experiment B - Basement Corner Temperatures

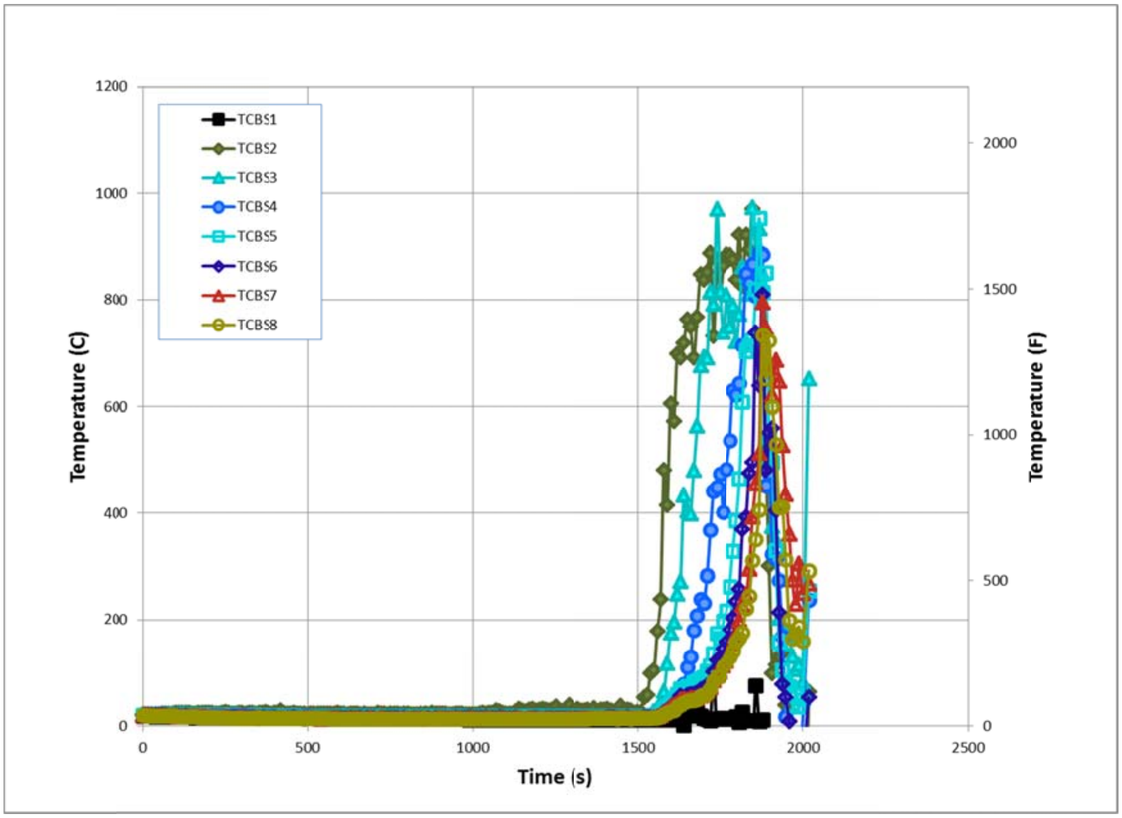

Figure 333. Experiment B - Basement Base of Stair Temperatures

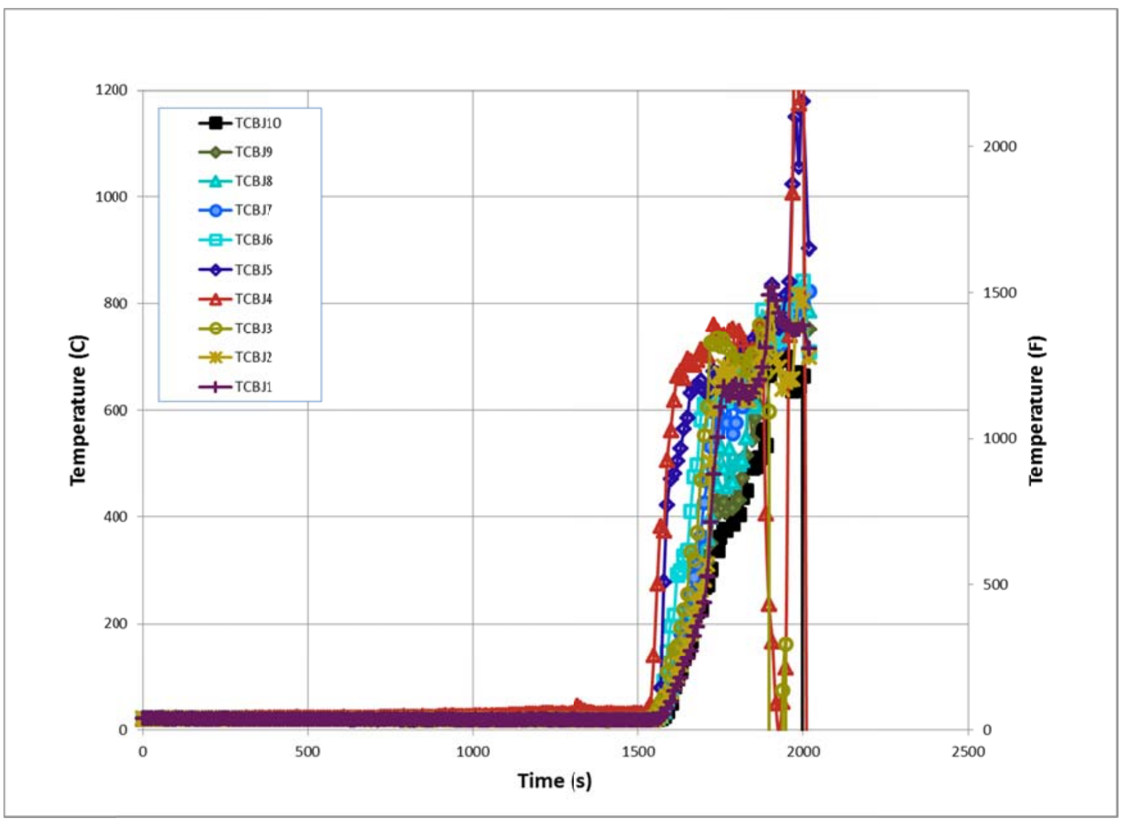

Figure 334. Experiment B - Basement Joist Temperatures

9.2.3. Gas Velocities

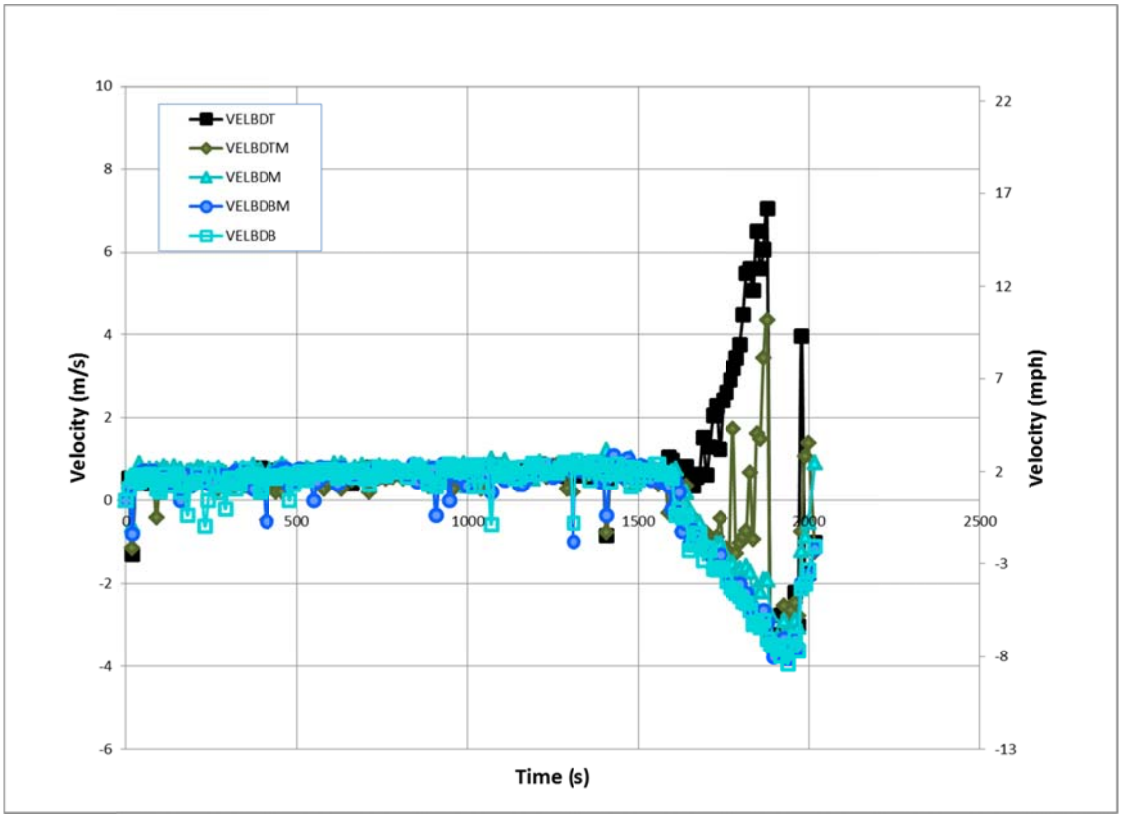

Figure 335. Experiment B - Basement Door Velocities

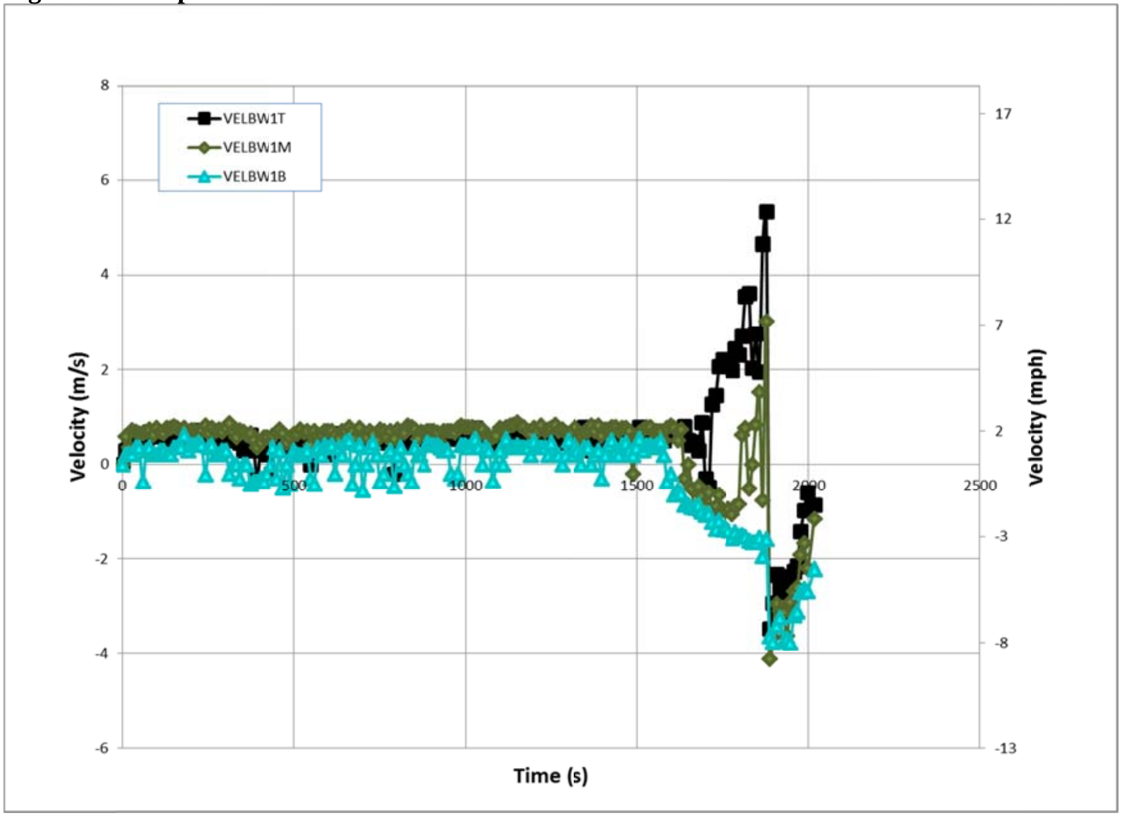

Figure 336. Experiment B - Basement Window 1 Velocities

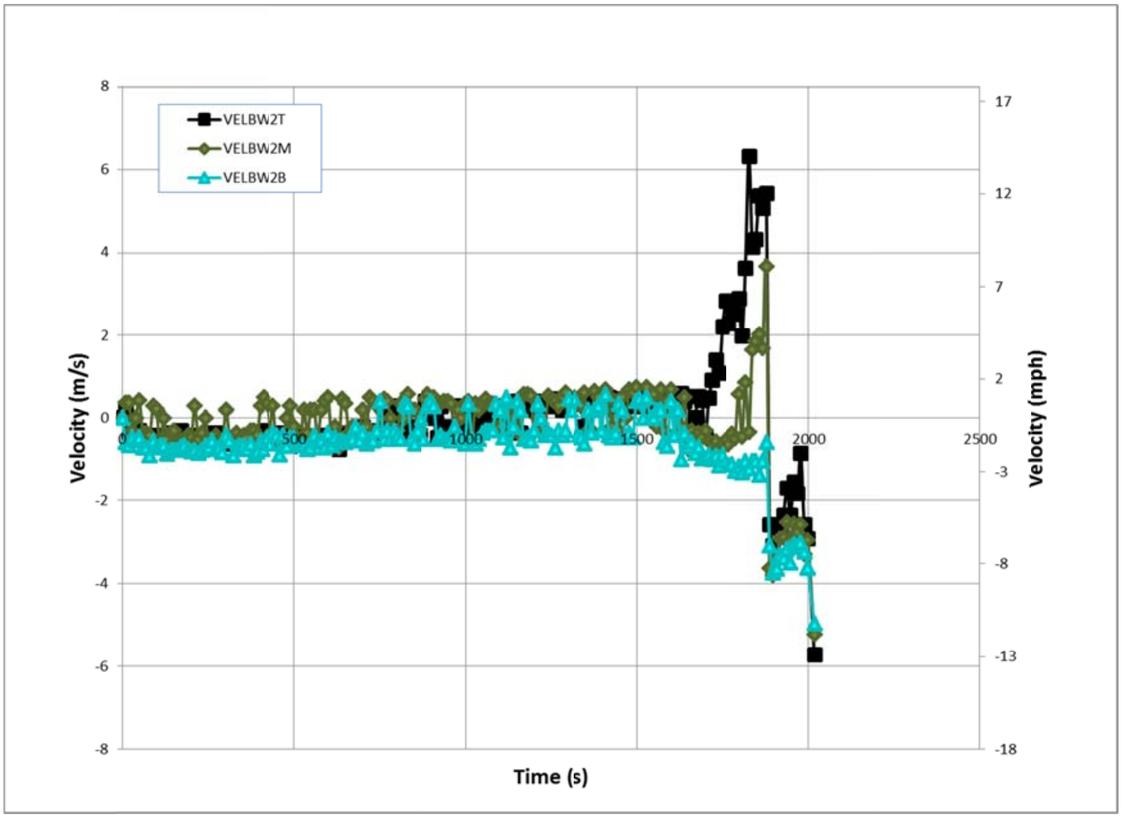

Figure 337. Experiment B - Basement Window 2 Velocities

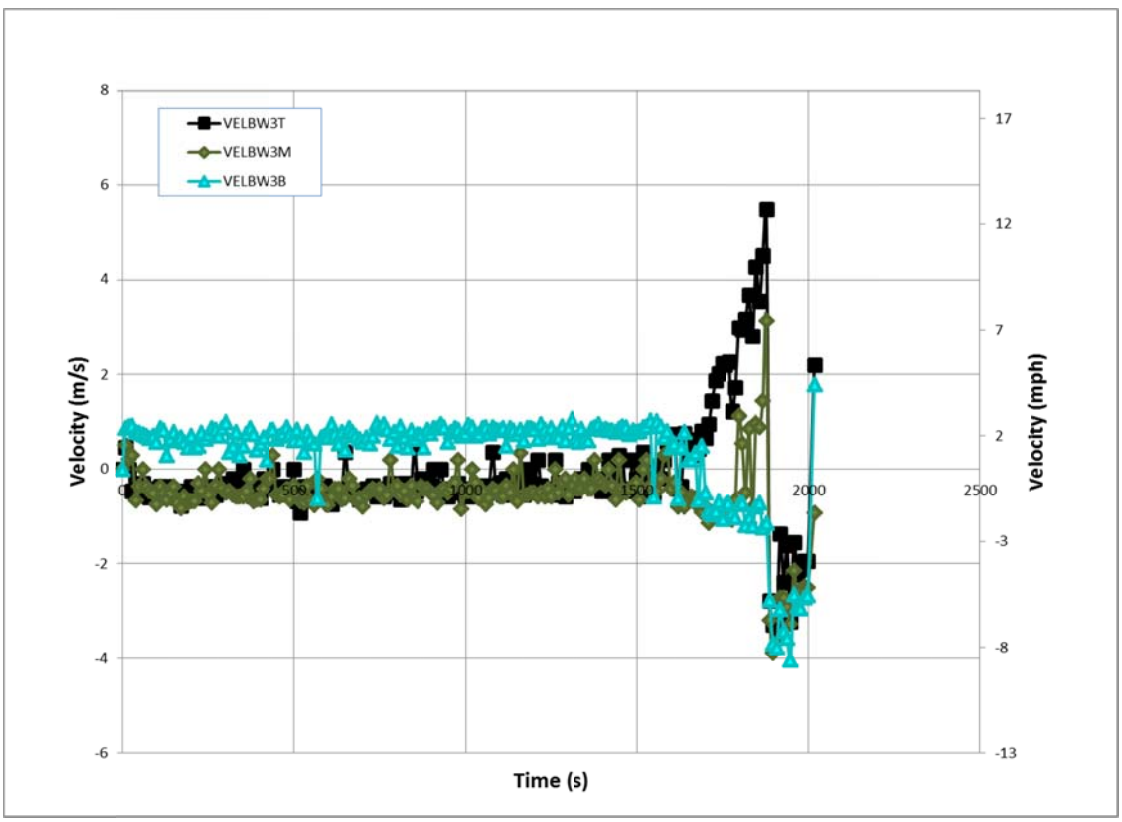

Figure 338. Experiment B - Basement Window 3 Velocities

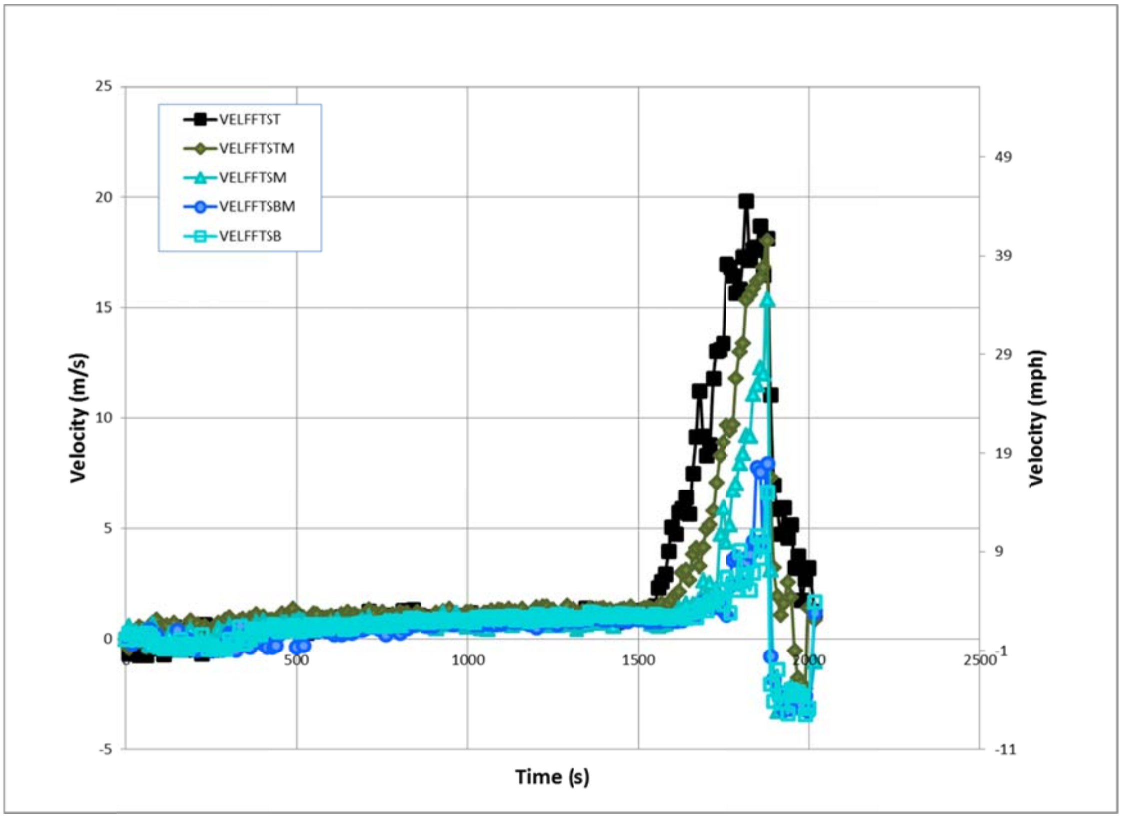

Figure 339. Experiment B - First Floor Stair Velocities

9.2.4. Deflection

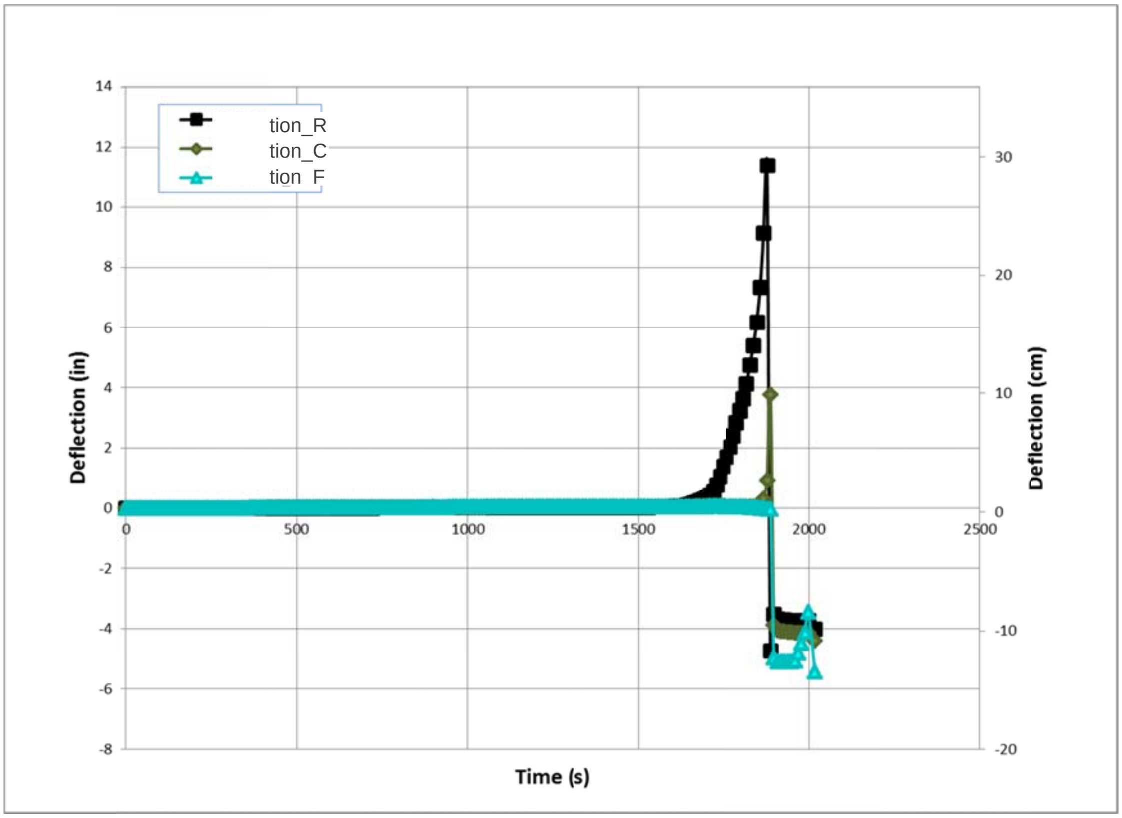

Figure 340. Experiment B - Floor System Deflections

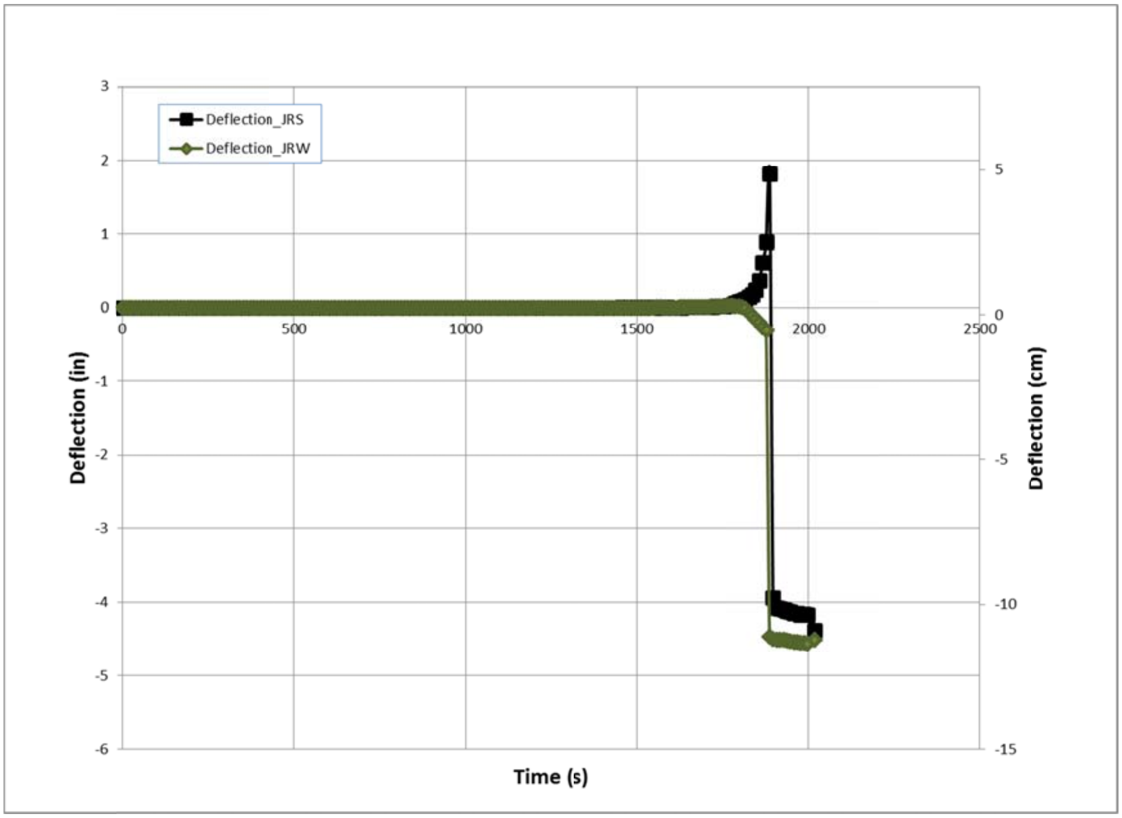

Figure 341. Experiment B – Joist Rotation

9.2.5. Structural Response

Experiment B utilized a modified ignition source, a propane plumbers torch placed on an engineered I joist located at the center of the joist within the front section of the floor system, where the fuel load would be placed as in the previous experiments. The primary structural failure occurred at the front and center sections of the floor system, local and adjacent to the initial fire location. A secondary collapse of the front section occurred moments later. The failure mode for the engineered I-joists was due to burn-out of the web members (Figure 342 and Figure 343). The floor system began to progressively deflect from approximately 1700 seconds until the end of the test. Experiment B induced a collapse of approximately 100 % of the total floor structure (Figure 344). The collapse time for the Experiment B was 31:25 after the initial placement of the plumbers torch. The collapse time respective of the structural element fire involvement for Experiment B was 5:30.

Figure 342 Web burn-out of the engineered I-joist local to collapsed area at front section of the floor system.

Figure 343 Web burn-out of the engineered I-joist local to collapsed area at front section of the floor system.

Figure 344 Interior view of percentage of collapsed area.

9.3. Experiment C – Parallel Chord Truss

In this experiment all of the ventilation openings were open prior to ignition and the fire was ignited remotely above the gypsum board ceiling with 2 igniters placed on a truss located at the center of the span, directly above where the front fuel load would be placed as in the previous experiment. The fire burned and filled the void space with smoke but ran out of oxygen and began to decay. At 15:00 after ignition firefighters used tools to open a hole in the gypsum board ceiling approximately 2 ft. by 3 ft. just inside the basement door. The hole was completed by 17:45 after the initial ignition. This allowed for some smoke to clear and oxygen to enter the void space however the fire had self-extinguished. At 23:30 two additional igniters were placed on the bottom chord of a truss in the hole that was created. At 24:00 the igniters were ignited with a propone torch. The fire spread in the space above the gypsum board ceiling, until the floor system collapsed and then it was suppressed. The timeline of events is detailed in Table 40. The results for the experiment are presented in the following sections: observations, temperature, gas velocity, and deflection.

Table 40. Experiment C Timeline

Time (s, mm:ss)	Event
0 (0:00)	Ignition in the void above the gypsum board
900-1065 (15:00-17:45)	2 ft. by 3 ft. (approximate) hole opened in ceiling by fire fighters
1440 (24:00)	Second ignition of 2 igniters in hole
2686 (44:46)	Collapse
2700 (45:00)	End of experiment

9.3.1. Observations

The observations are presented as a series of images captured from eight camera locations, seven were video cameras and one was a thermal imaging camera. The views were captured at the start of the experiment (0:00, Figure 345), when smoke had spread throughout the void space above the gypsum board ceiling and reduced visibility (4:00, Figure 346), just after firefighters finished creating an opening in the gypsum board to provide oxygen to the void space (17:45, Figure 347), conditions as the second ignition took place (24:00, Figure 348), when flames first became visible through the decking of the floor system (40:20, Figure 349), and 5 seconds before collapse (44:41, Figure 350).

Figure 345. Experiment C video views at 0:00.

Figure 346. Experiment C video views at 4:00.

Figure 347. Experiment C video views at 17:45.

Figure 348. Experiment C video views at 24:00.

Figure 349. Experiment C video views at 40:20.

Figure 350. Experiment C video views at 44:41.

9.3.2. Temperatures

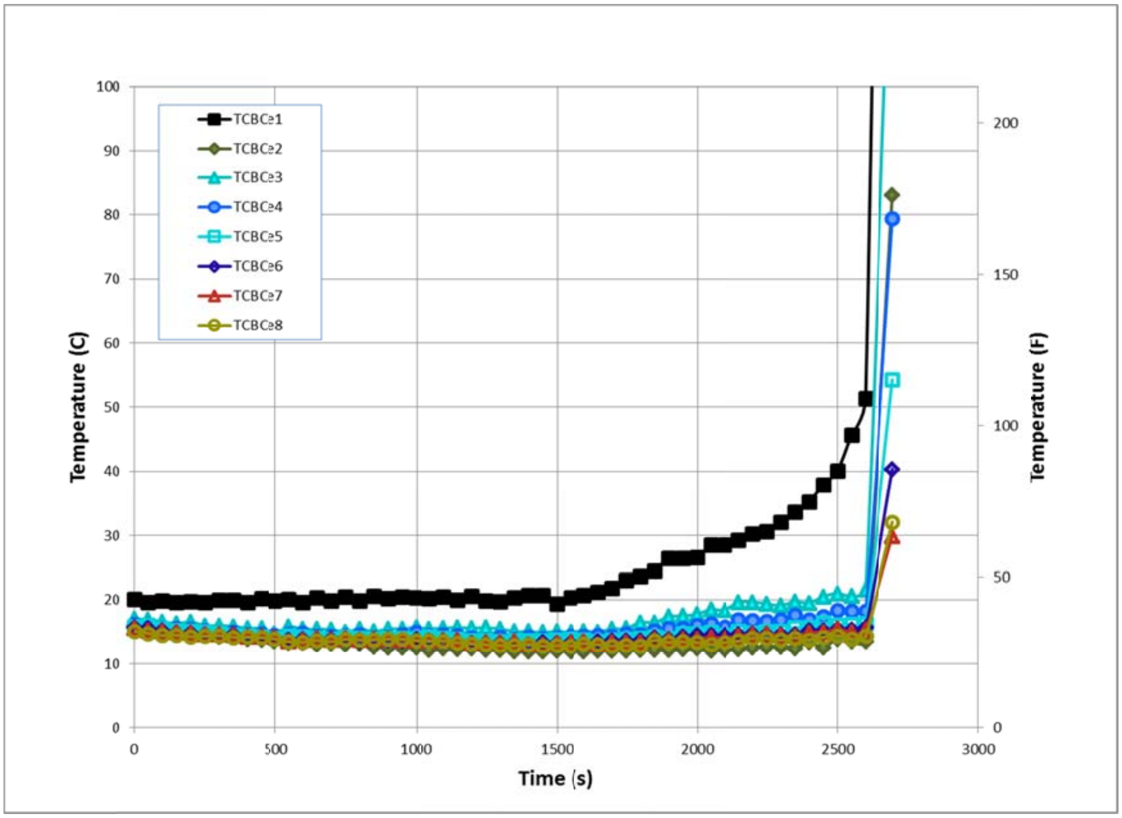

Figure 351. Experiment C - Basement Center Temperatures

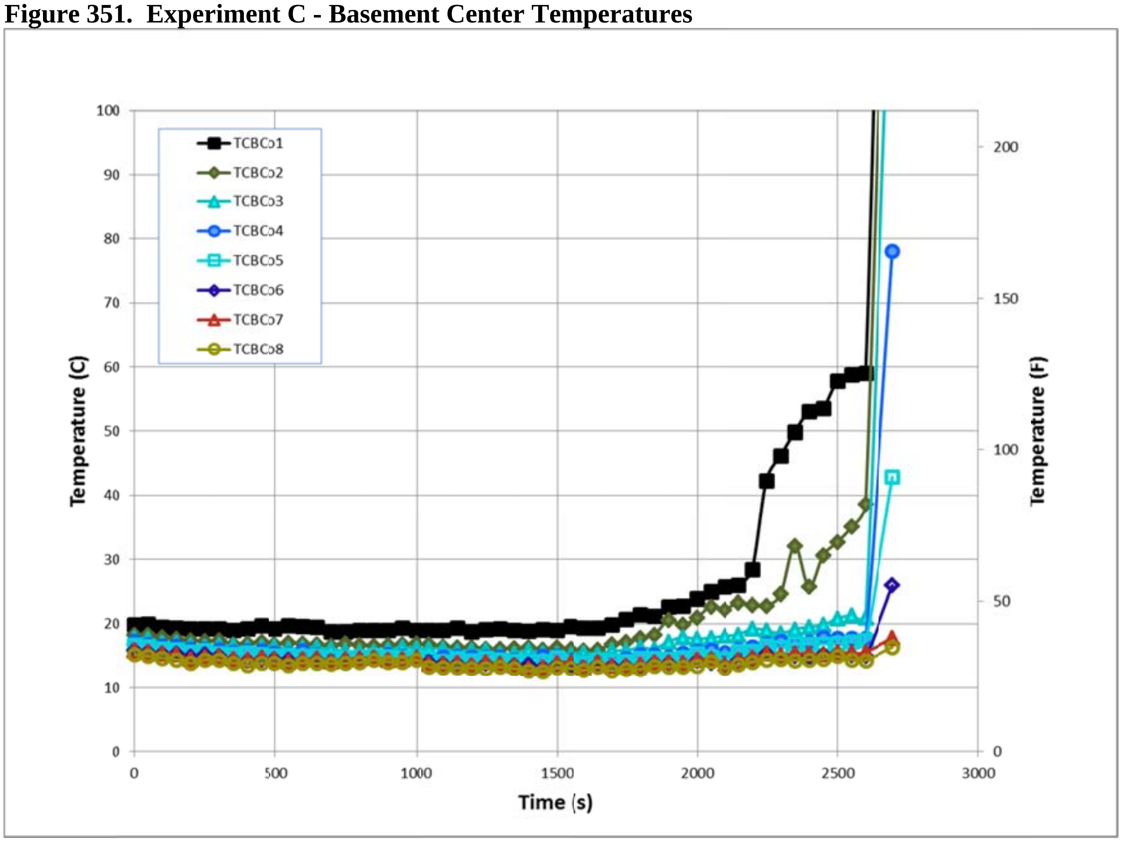

Figure 352. Experiment C - Basement Corner Temperatures

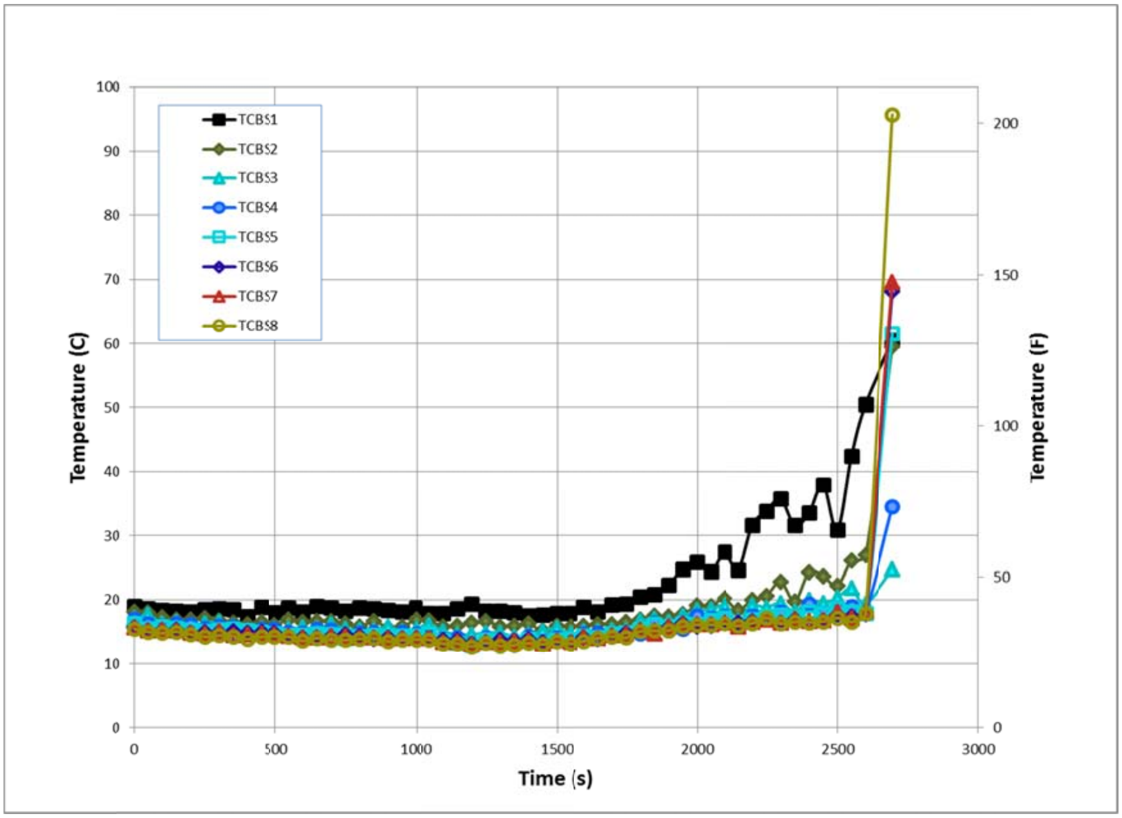

Figure 353. Experiment C- Basement Base of Stair Temperatures

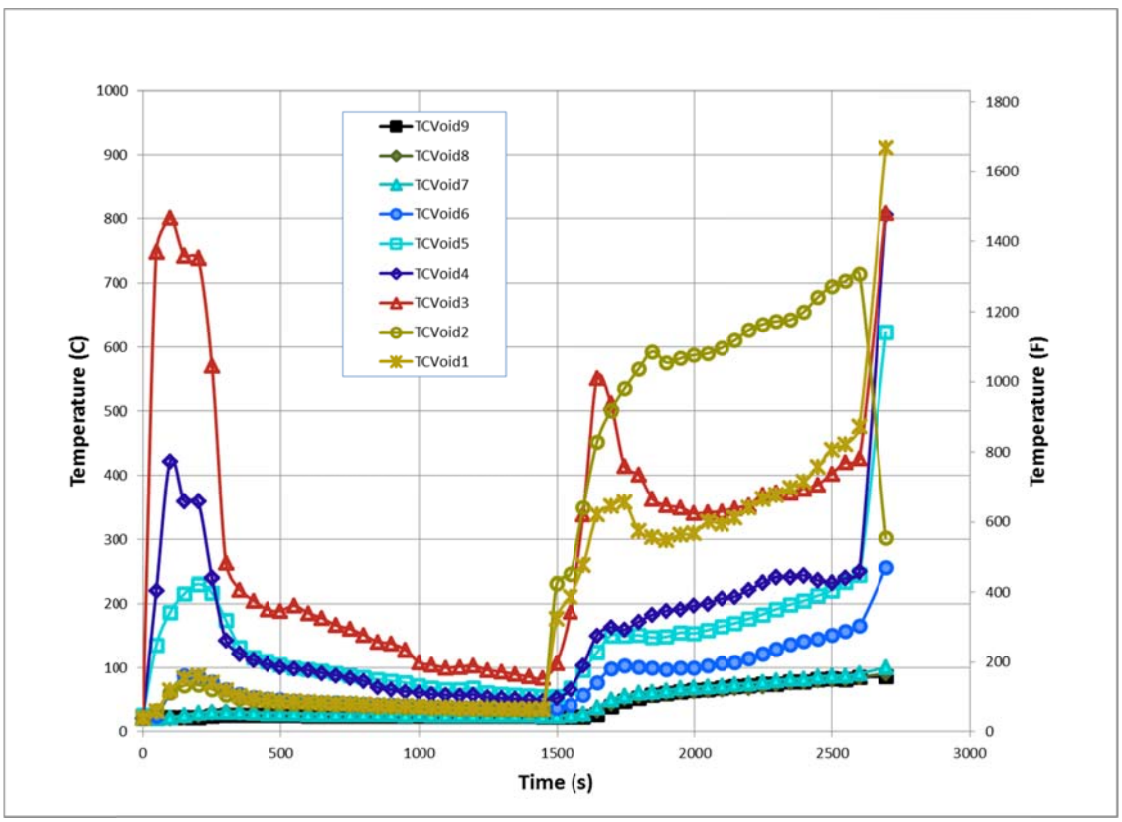

Figure 354. Experiment C - Basement Void Space Temperatures

9.3.3. Gas Velocities

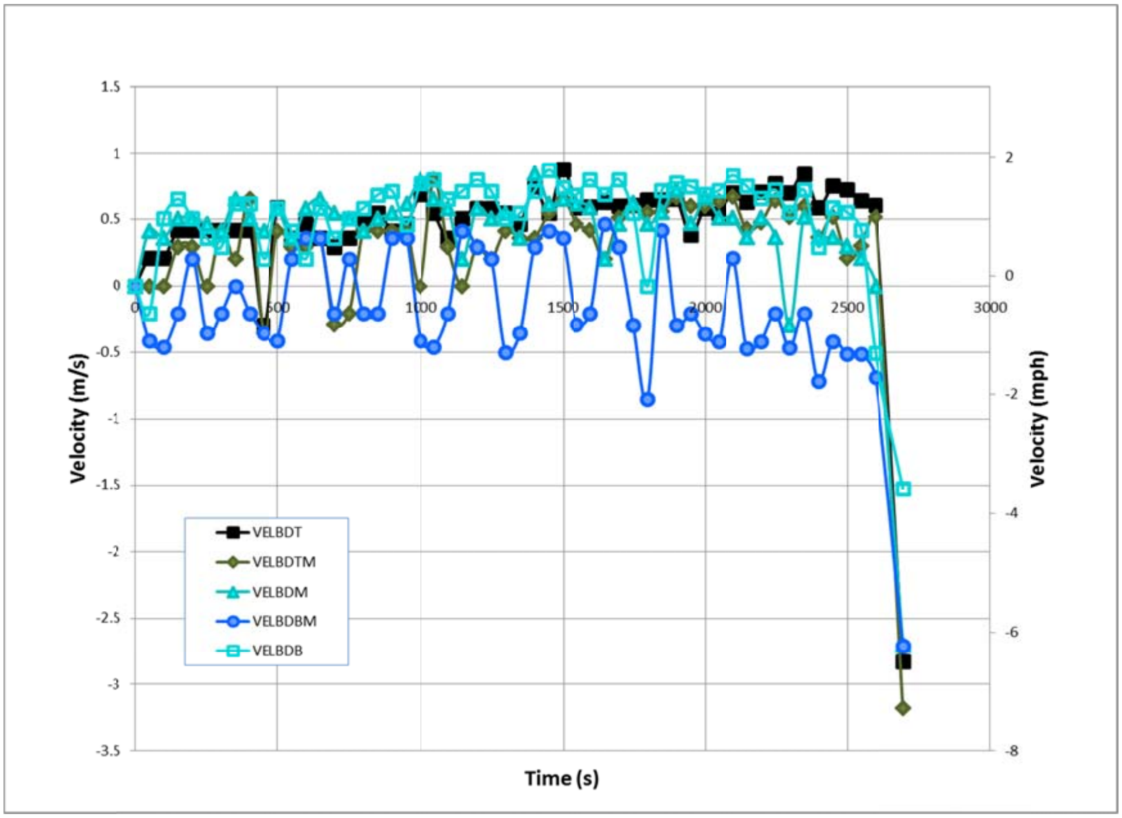

Figure 355. Experiment C - Basement Door Velocities

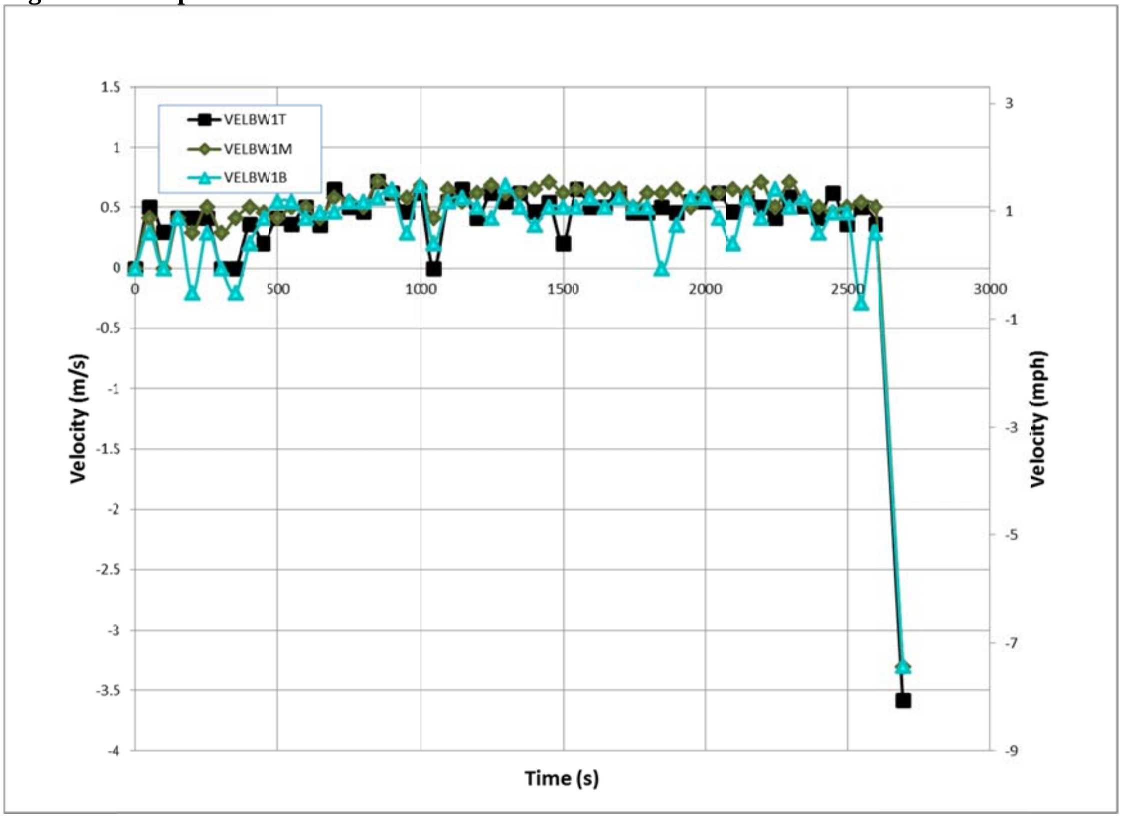

Figure 356. Experiment C - Basement Window 1 Velocities

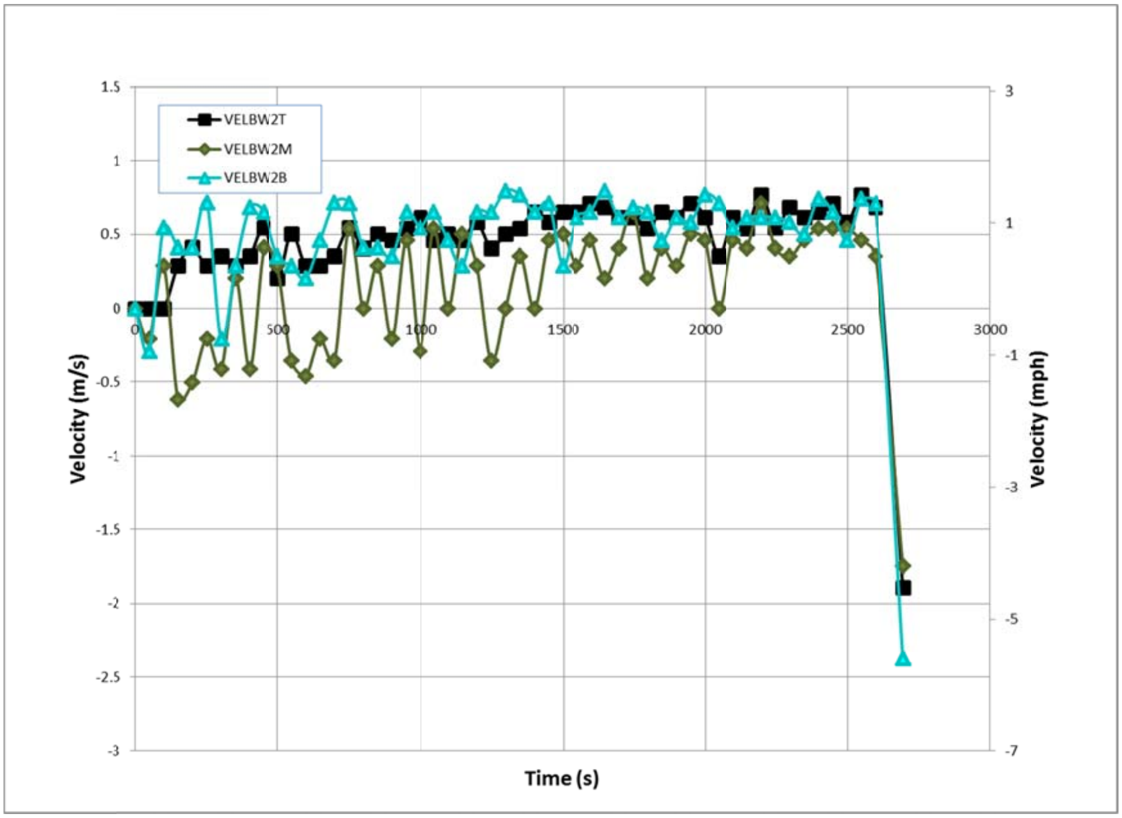

Figure 357. Experiment C - Basement Window 2 Velocities

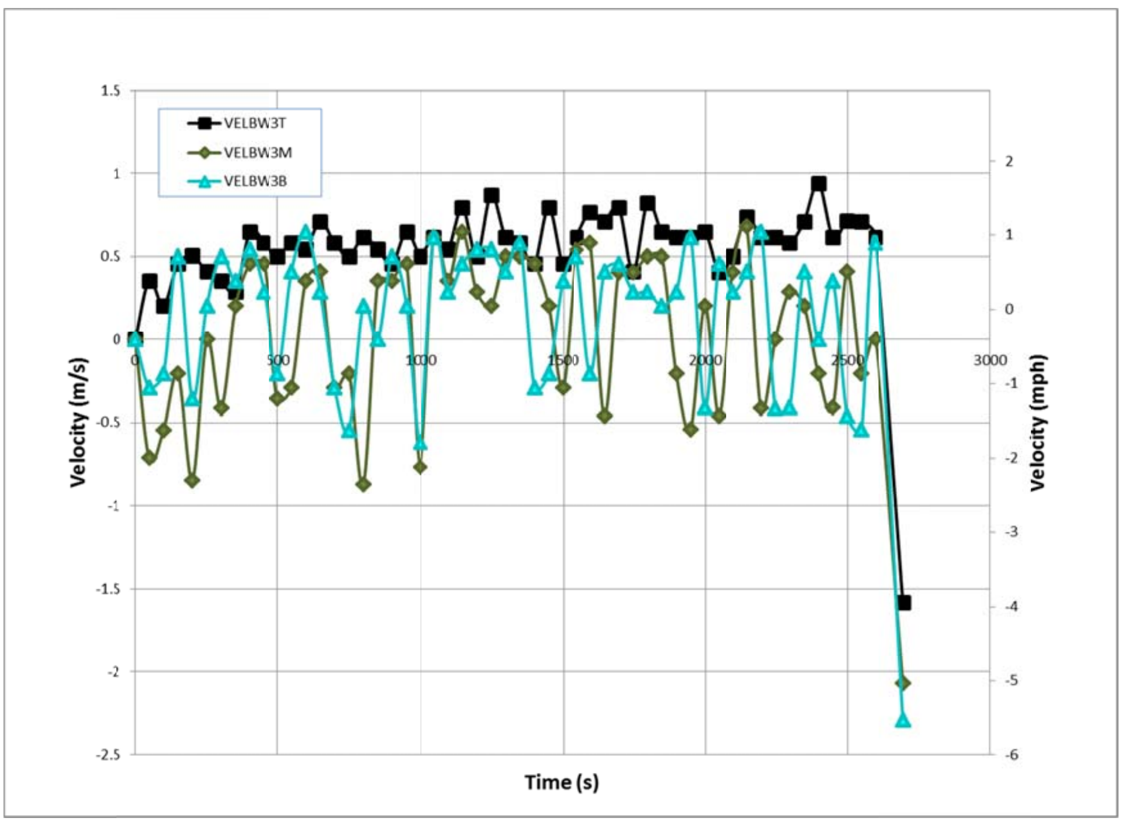

Figure 358. Experiment C - Basement Window 3 Velocities

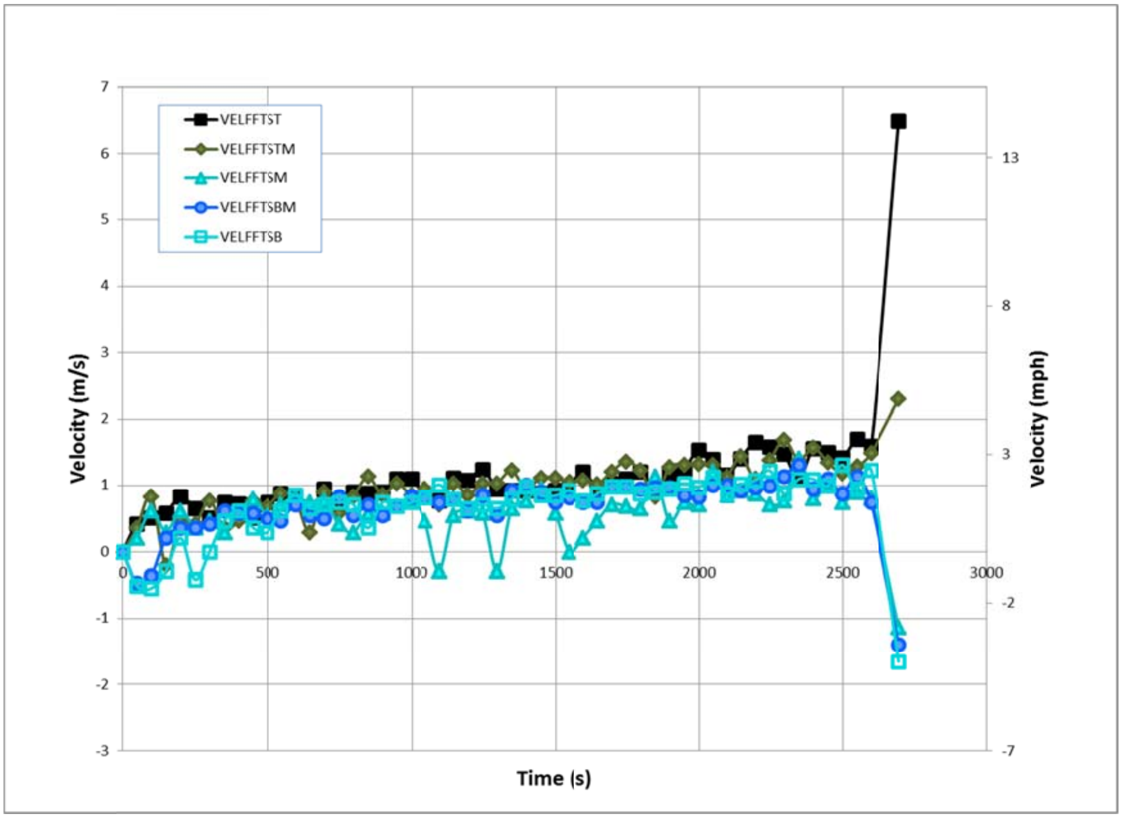

Figure 359. Experiment C - First Floor Stair Velocities

9.3.4. Deflection

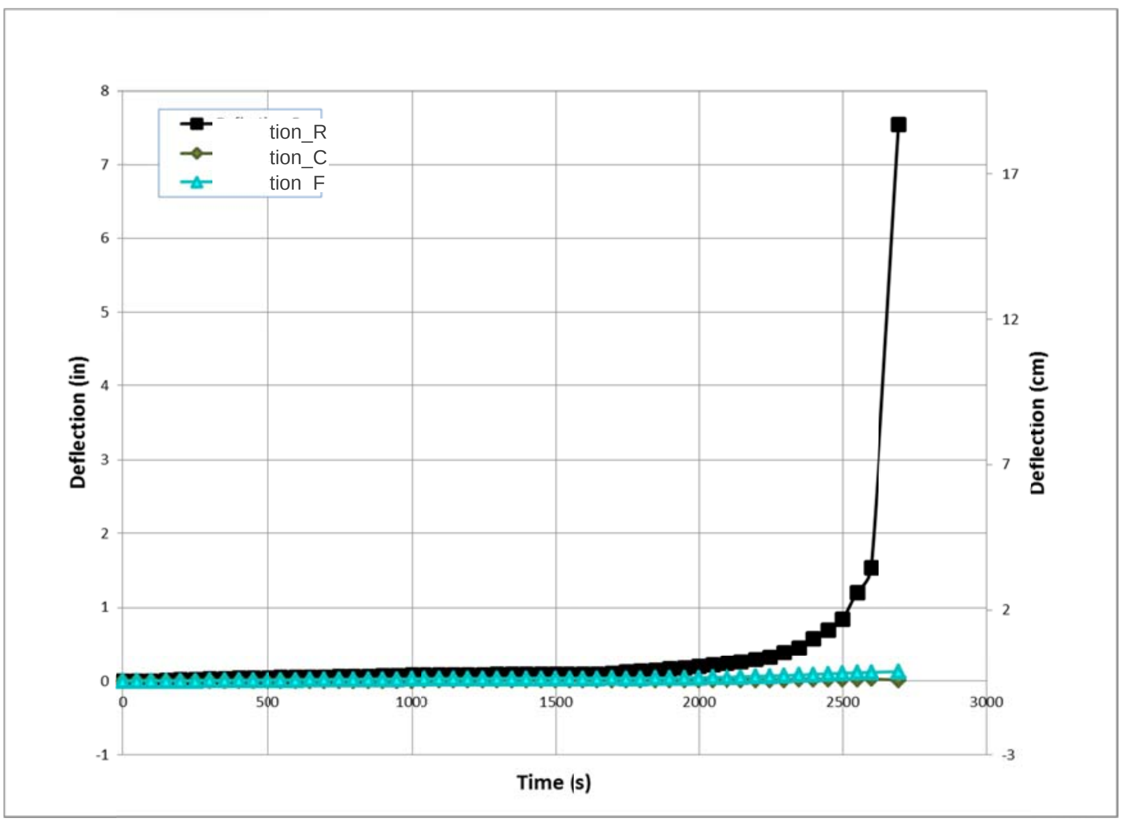

Figure 360. Experiment C - Floor System Deflections

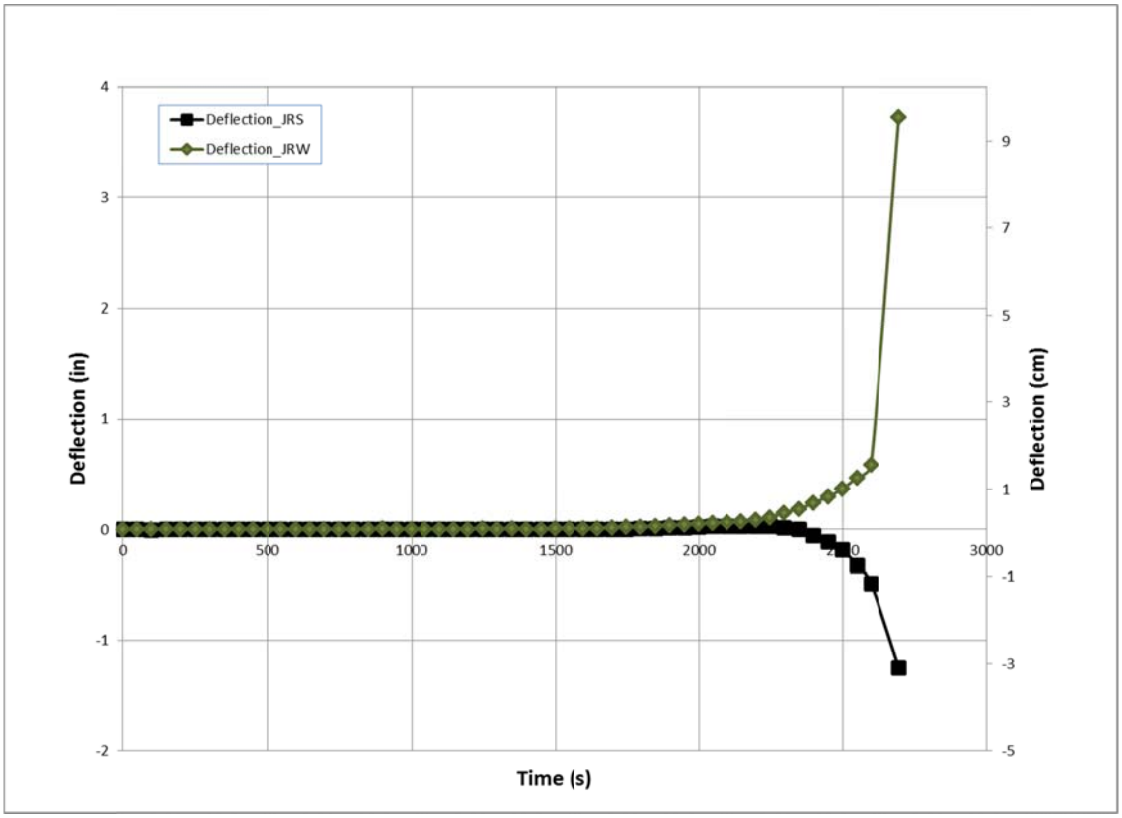

Figure 361. Experiment C – Joist Rotation

9.3.5. Structural Response

Experiment C utilized a modified ignition source, in this experiment all of the ventilation openings were open prior to ignition and the fire was ignited remotely above the gypsum board ceiling with 2 igniters placed on a truss located at the center of the span, directly above where the front fuel load would be placed as in the previous experiment. The primary structural failure occurred at the front section of the floor system; local to the initial fire location. The failure mode of the parallel chord metal plate connected trusses was due to steel/wood connection failures. Connection damage was noted at various truss panel points (Figure 363) and failures were recorded at various truss panel point and bottom chord tension splice locations (Figure 364). The collapse also produced a collapse local to the wood truss bearing condition (Figure 365). The floor system began to progressively deflect from 1750 seconds until the end of the test. Experiment C induced a collapse of approximately 40 % of the total floor structure (Figure 366 and Figure 367). The collapse time for the Experiment C was 44:46 after ignition. The collapse time respective of the structural element fire involvement for Experiment C was 20:46.

Figure 362 Interior view of percentage of collapsed area.

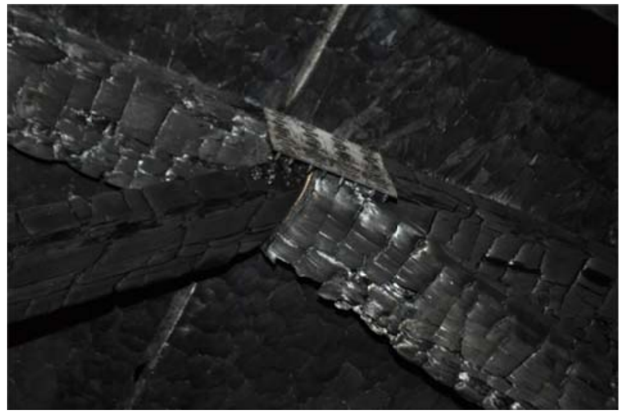

Figure 363 Connection damage at truss panel point.

Figure 364 Connection failure of bottom chord tension splice.

Figure 365 Collapse local to the wood truss bearing condition.

Figure 366 Interior view of percentage of floor assembly from underside of floor with remaining drywall intact.

Figure 367 Interior view of condition of floor assembly from underside of floor after remaining drywall removed.

9.4. Experiment D – Parallel Chord Truss

In this experiment the parallel chord truss floor system was covered with a ½ in. layer of gypsum board with the exception of 80 ft^2 that was exposed at the back of the structure as detailed in Section 8.1.2. All of the ventilation openings were open prior to ignition and the fire was ignited in the front fuel package closest to the base of the stairs. The fuel package ignited and the exposed wood floor system were on opposite sides of the basement. The fire spread until the floor system collapsed and then was suppressed. The initial collapse occurred above the fuel package and not in the unprotected floor system area. The timeline of events is detailed in Table 41. The results for the experiment are presented in the following sections: observations, temperature, gas velocity, and deflection.

Table 41. Experiment D Timeline

Time (s, mm:ss)	Event
0 (0:00)	Ignition
105 (1:45)	Flames impinge on ceiling
790 (13:10)	Collapse
935 (15:35)	Front section of floor collapses
945 (15:45)	End of experiment

9.4.1. Observations

The observations are presented as a series of images captured from eight camera locations, seven were video cameras and one was a thermal imaging camera. The views were captured at the start of the experiment (0:00, Figure 368), once flames impinged on the floor system (1:45, Figure 369), when there was sustained flames coming from the stairwell doorway on the first floor (3:42, Figure 370), 5 minutes after ignition (5:00, Figure 371), 10 minutes after ignition (10:00, Figure 372), when flames were visible in the exposed 80 ft^2 (12:10, Figure 373), and 5 seconds before collapse (13:05, Figure 374). This experiment was allowed to burn until the rear section of the floor collapsed. Figure 375 shows four video captures of the thermal imaging camera as the rear section collapsed. The bottom chord of the trusses disconnects at the chord splice on a couple trusses and then the whole section collapsed.

Figure 368. Experiment D video views at 00:00.

Figure 369. Experiment D video views at 1:45.

Figure 370. Experiment D video views at 3:42.

Figure 371. Experiment D video views at 5:00.

Figure 372. Experiment D video views at 10:00.

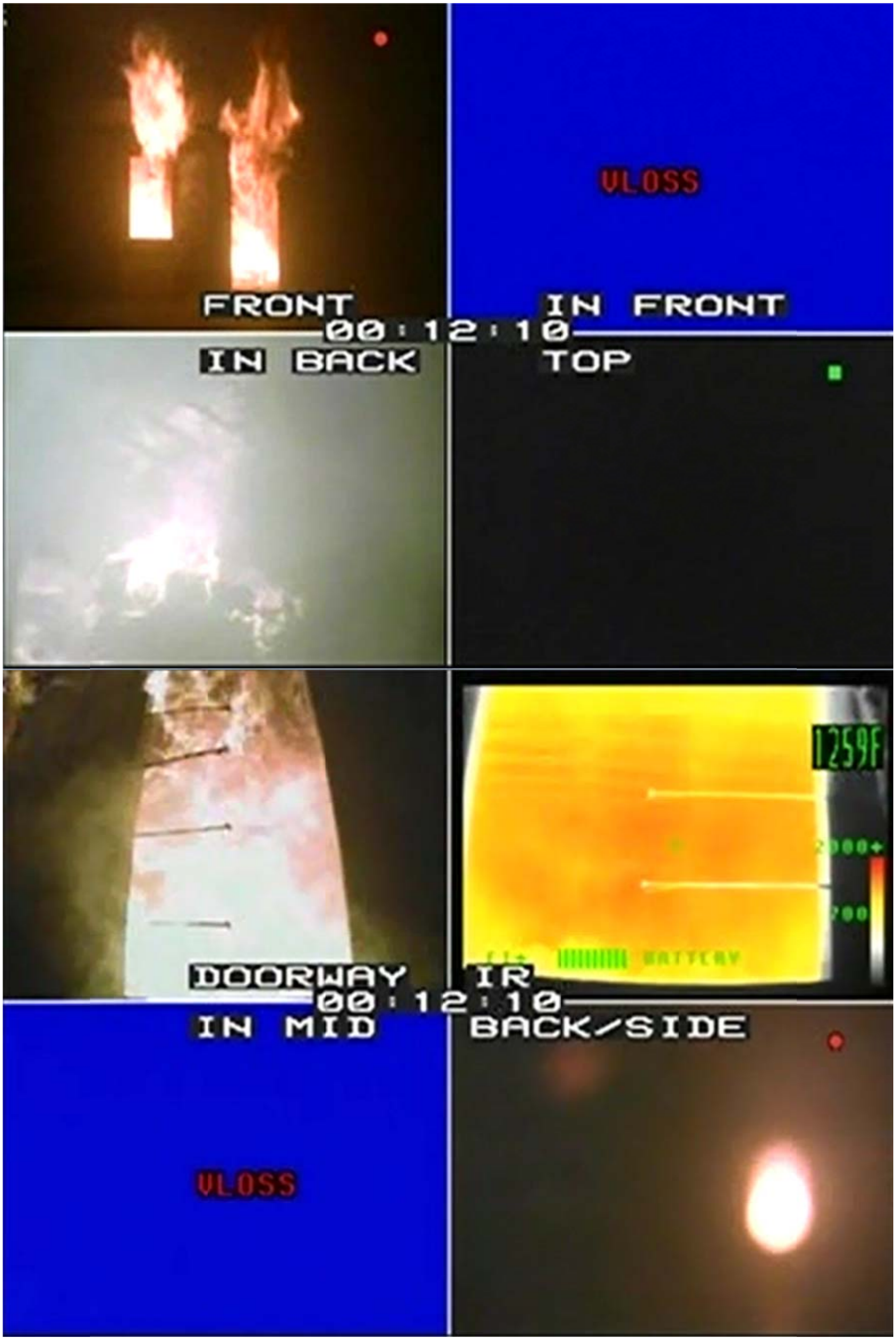

Figure 373. Experiment D video views at 12:10.

Figure 374. Experiment D video views at 13:05.

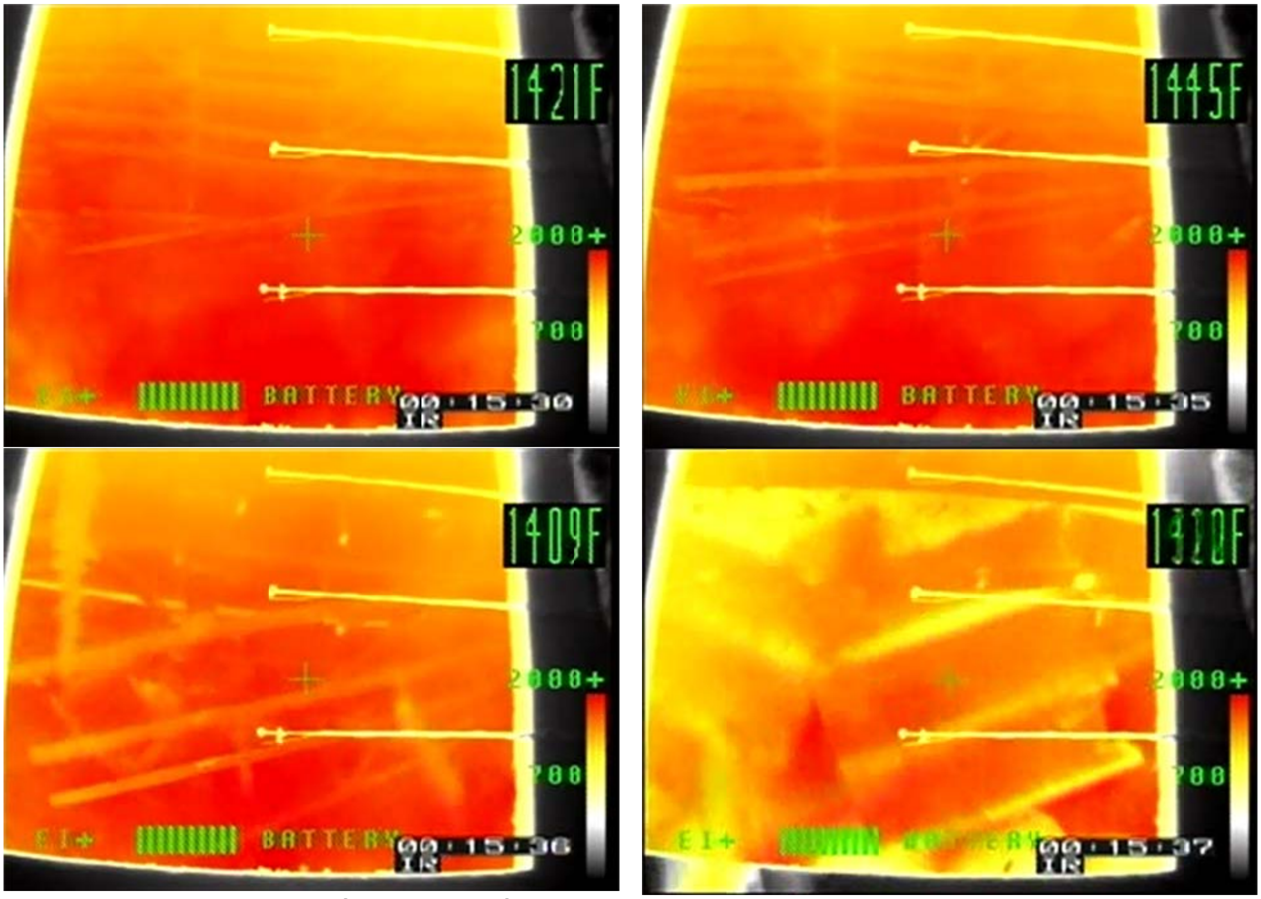

Figure 375. Experiment D Infrared views of rear floor failure.

9.4.2. Temperatures

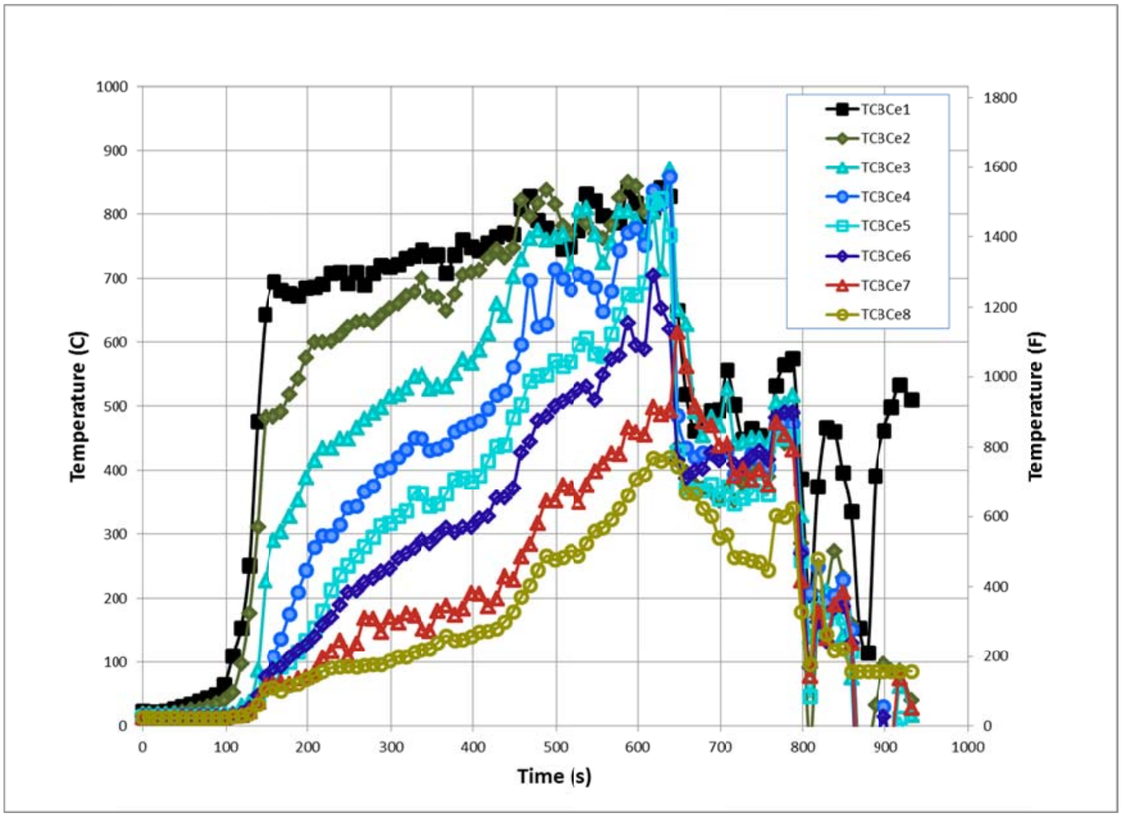

Figure 376. Experiment D - Basement Center Temperatures

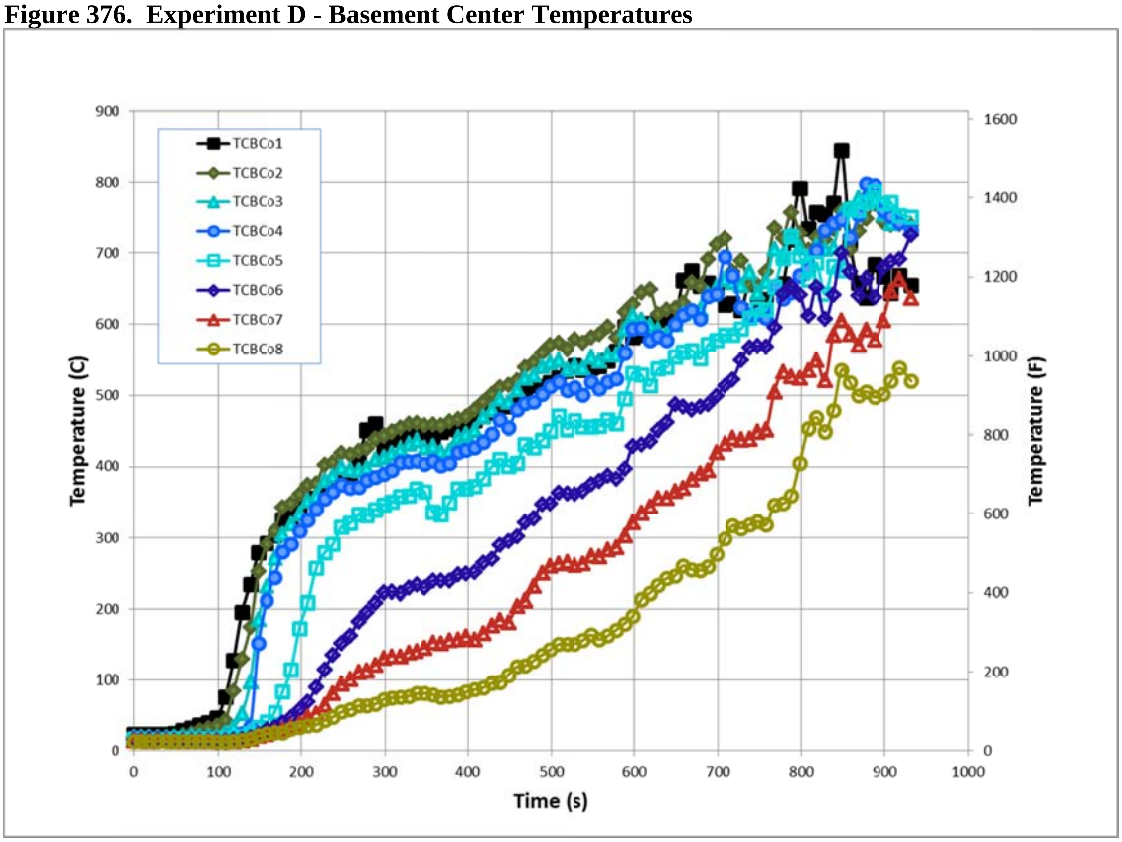

Figure 377. Experiment D - Basement Corner Temperatures

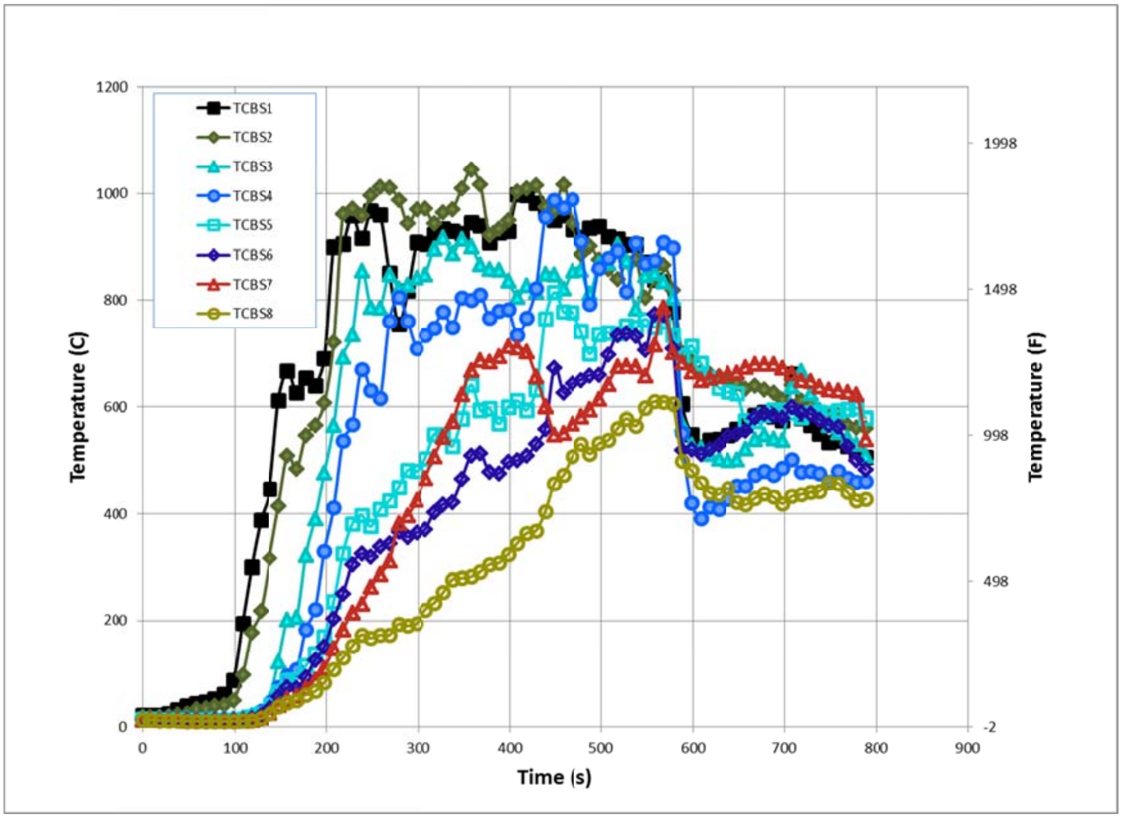

Figure 378. Experiment D - Basement Base of Stair Temperatures

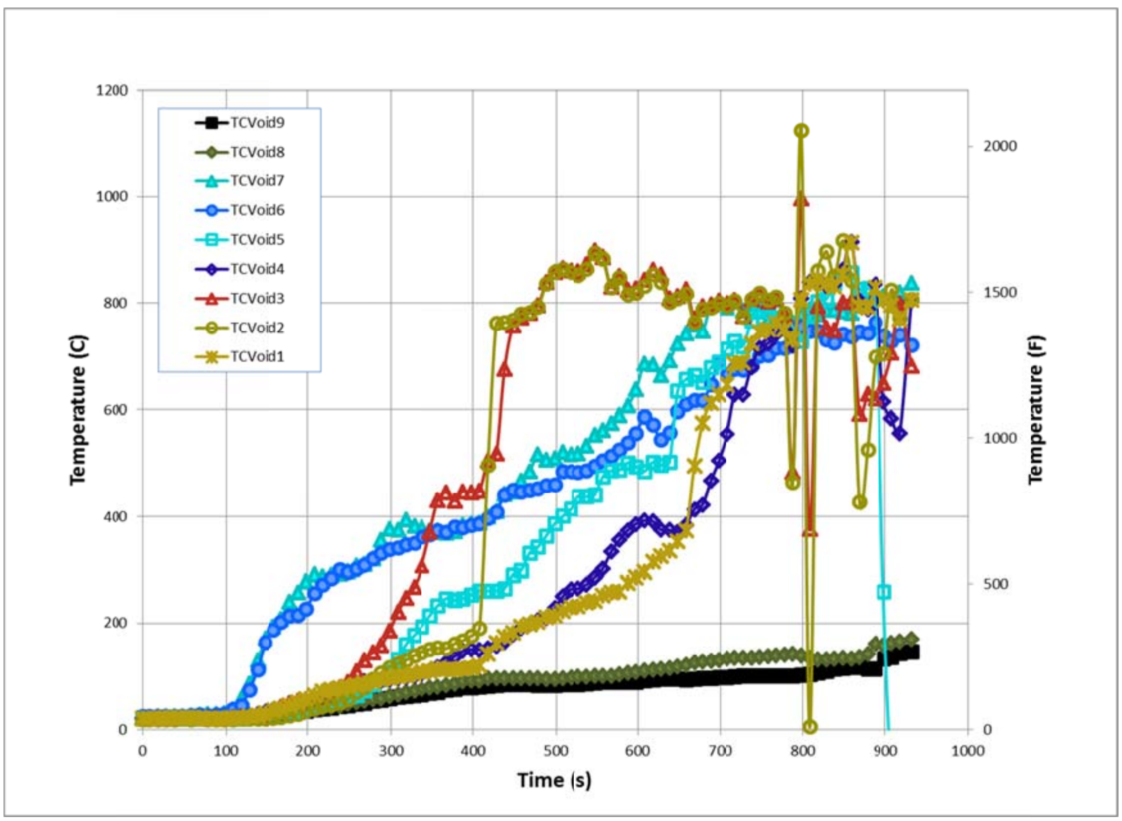

Figure 379. Experiment D - Basement Void Space Temperatures

9.4.3. Gas Velocities

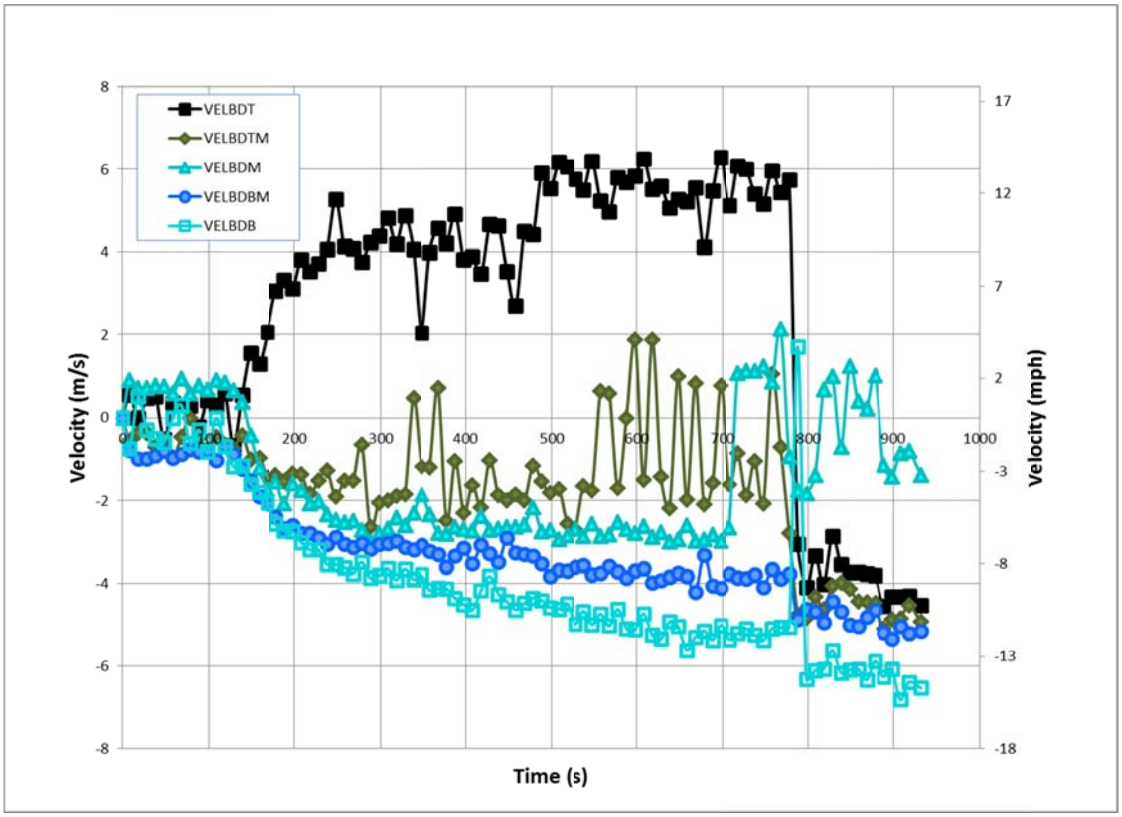

Figure 380. Experiment D - Basement Door Velocities

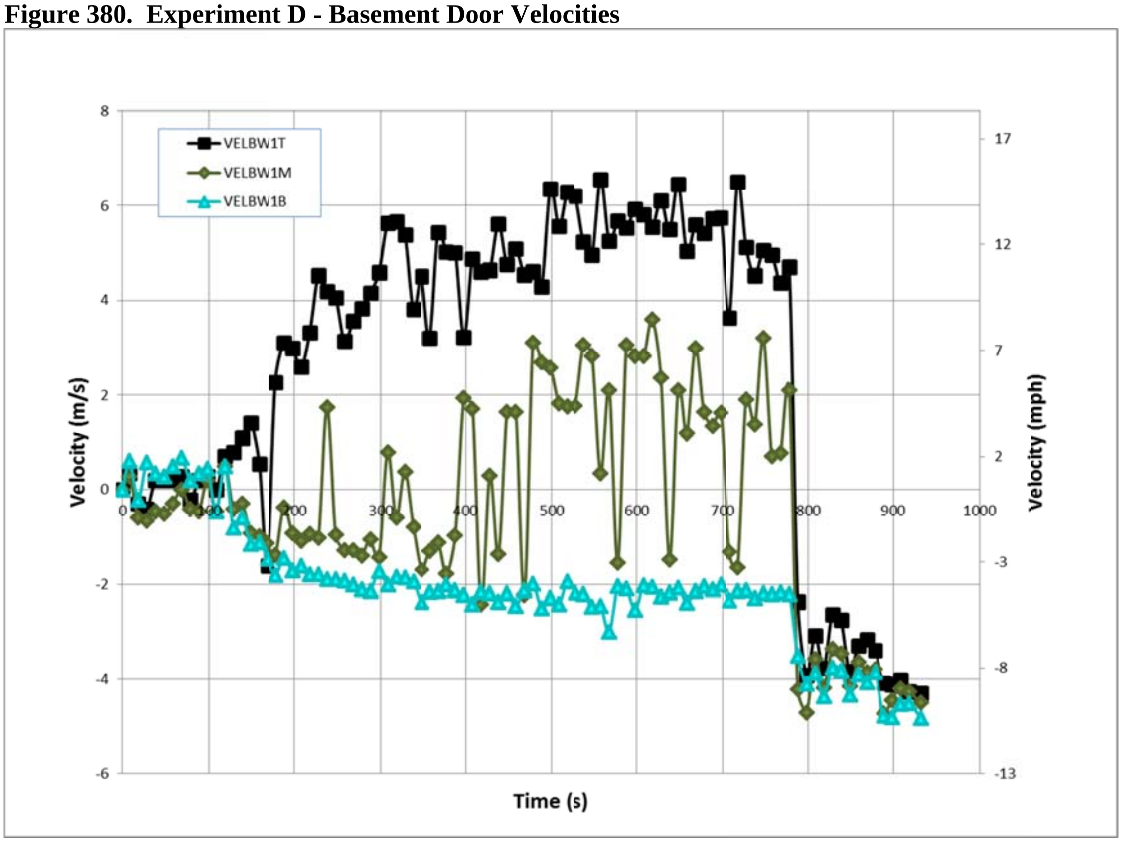

Figure 381. Experiment D - Basement Window 1 Velocities

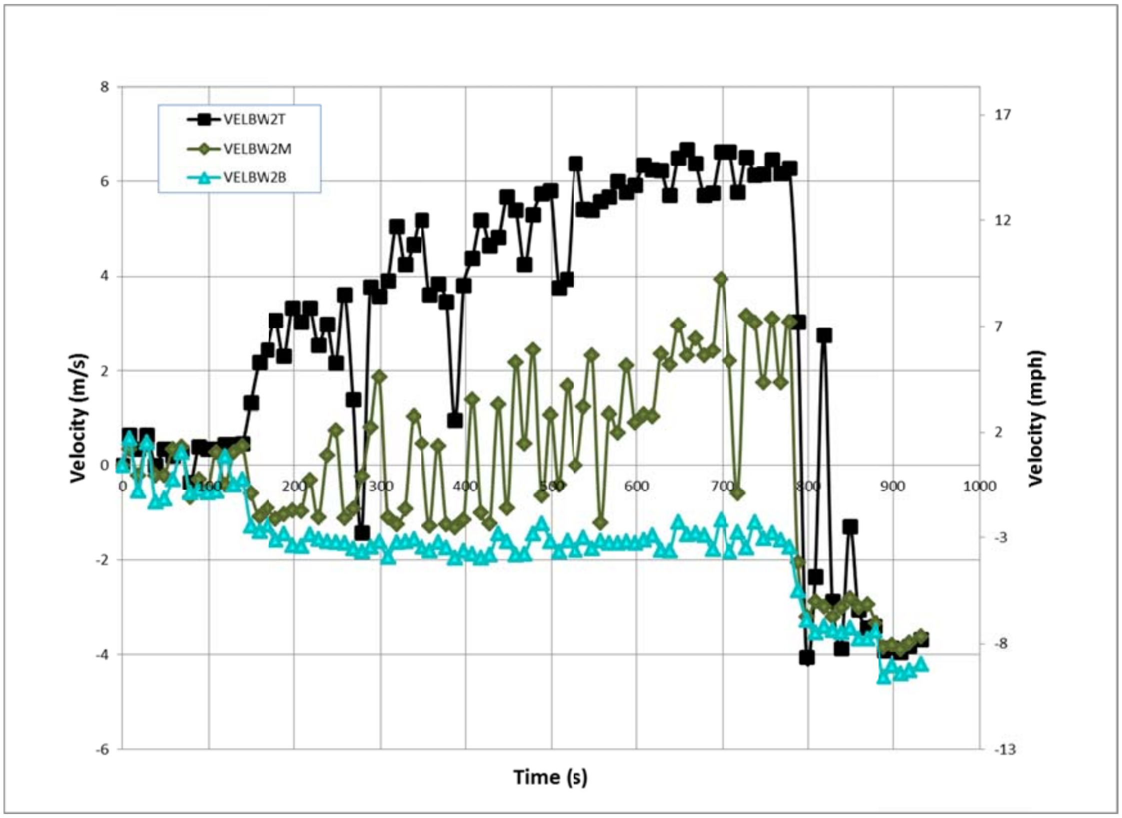

Figure 382. Experiment D - Basement Window 2 Velocities

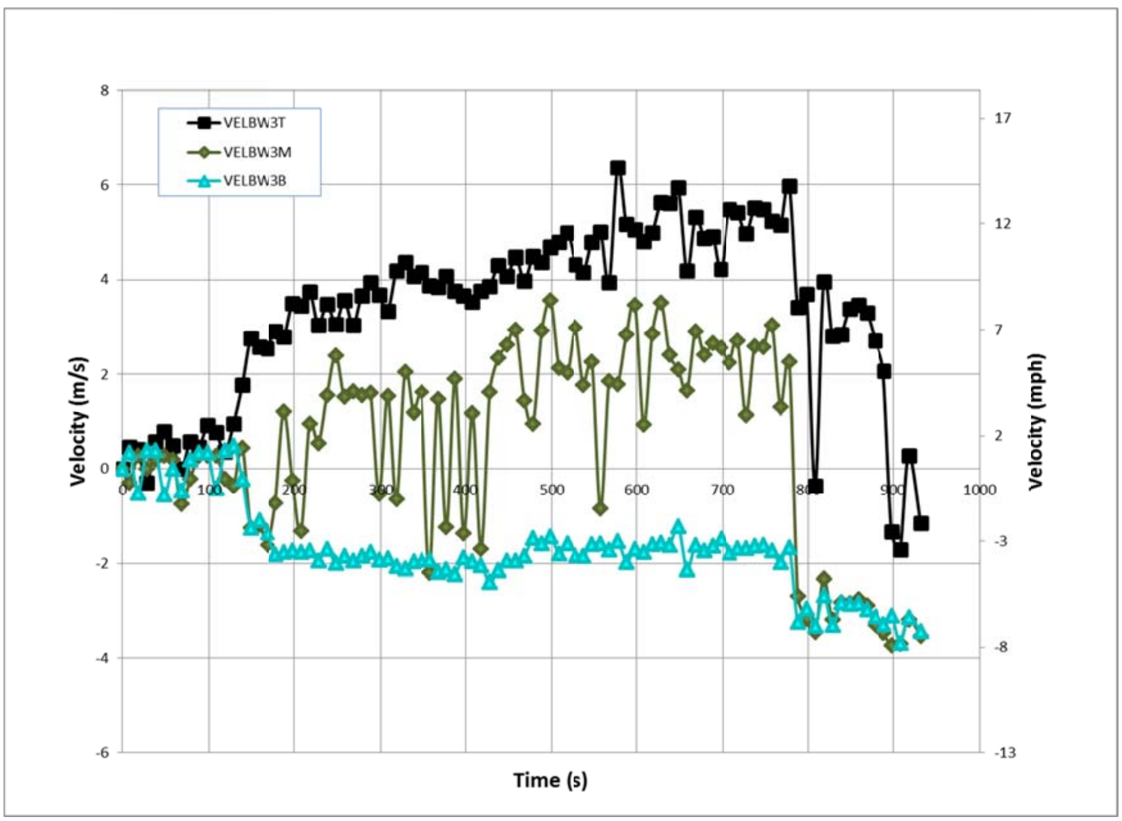

Figure 383. Experiment D - Basement Window 3 Velocities

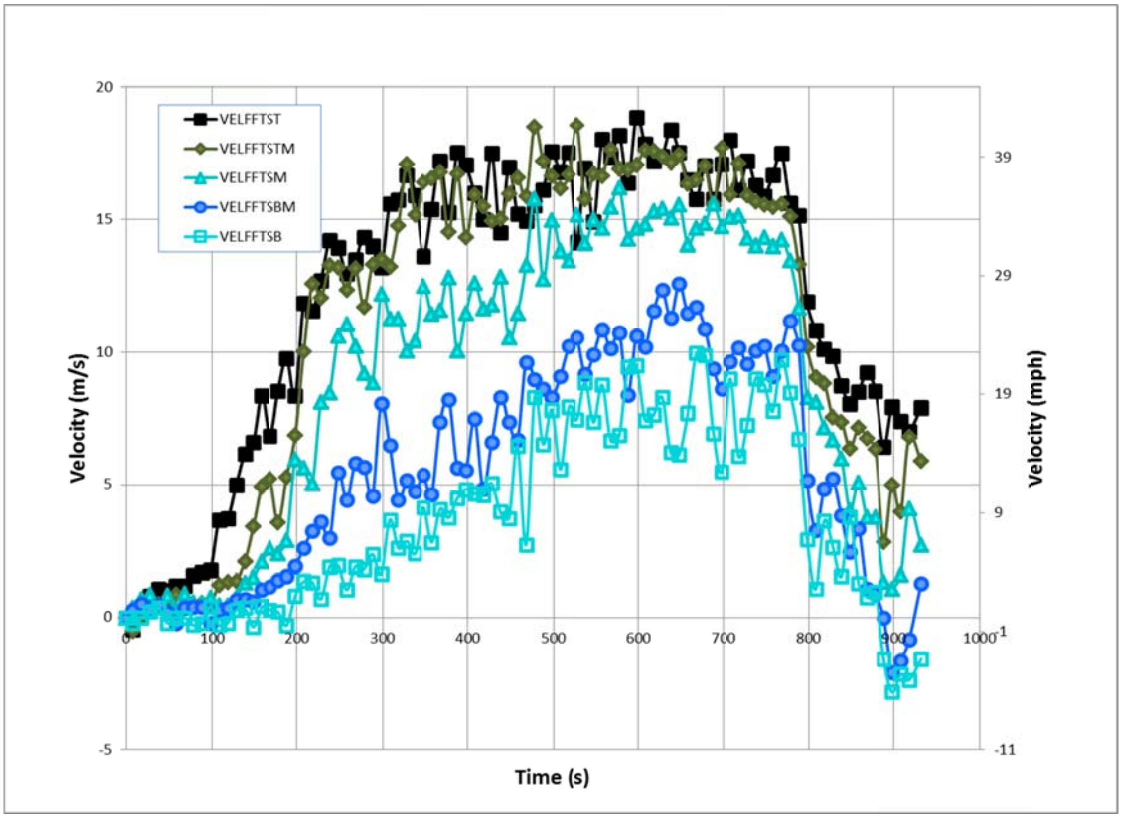

Figure 384. Experiment D - First Floor Stair Velocities

9.4.4. Deflection

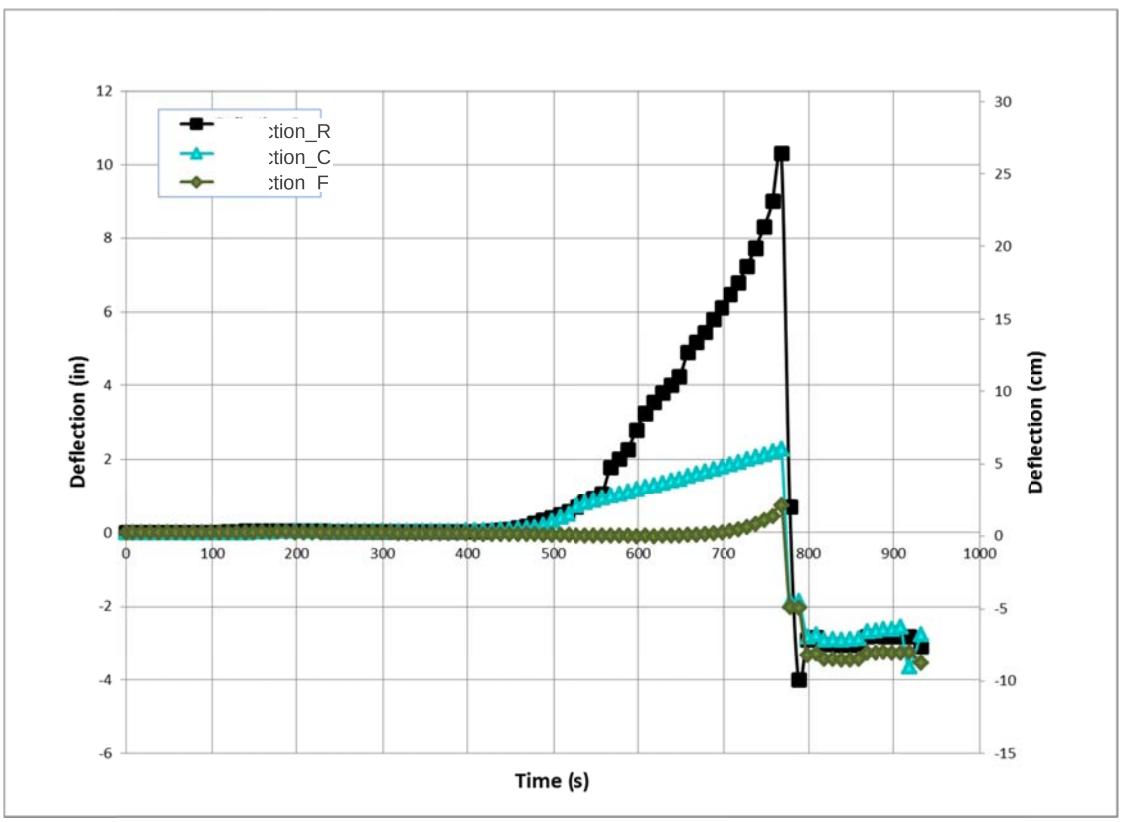

Figure 385. Experiment D - Floor System Deflections

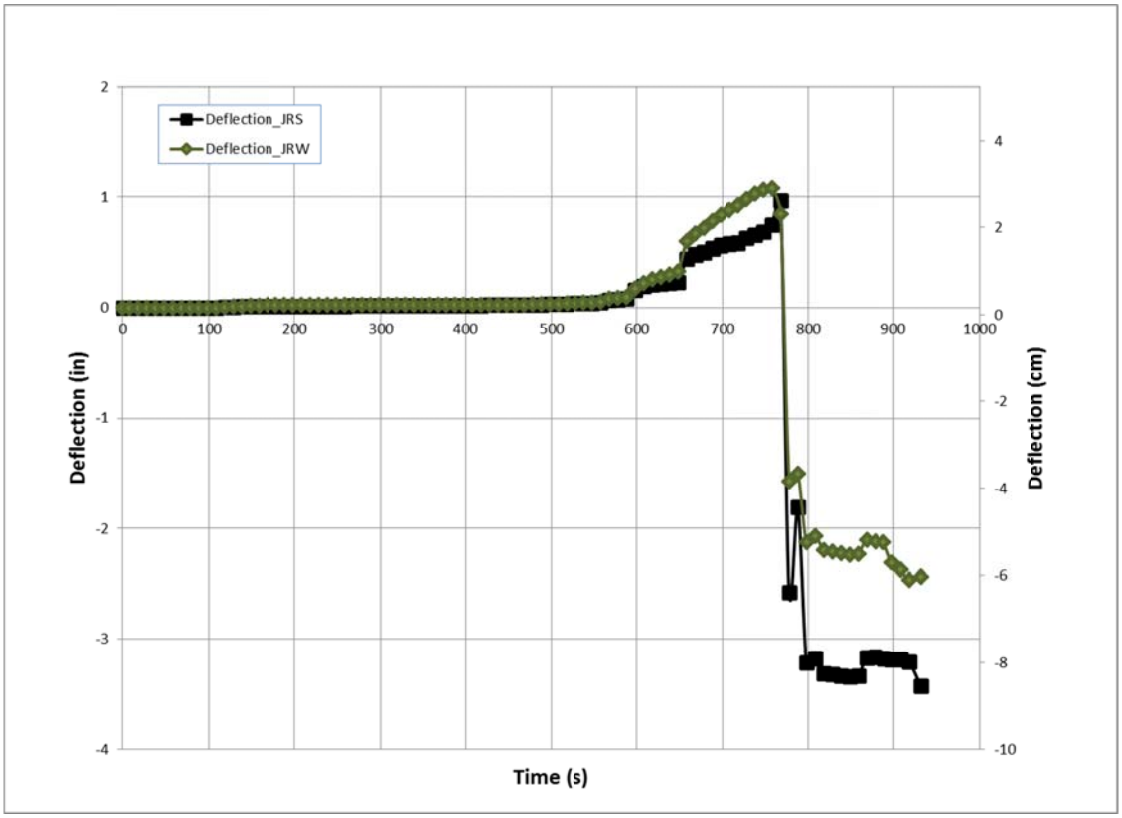

Figure 386. Experiment D - Floor System Deflections

9.4.5. Structural Response

Experiment D utilized a parallel chord truss floor system covered with a ½ in. layer of gypsum board with the exception of 80 ft^2 that was exposed at the back of the structure. Flames began to impinge on the ceiling above the ignited fuel package at 105 seconds. Temperatures taken from the interstitial space in this area suggest that the drywall provided protection from the fire event for approximately 400 seconds above the initial fire location. Ceiling failure occurred in this area at approximately 400 seconds.

The primary structural failure occurred at the front section of the floor system; local to the initial fire location. A secondary collapse of the remaining sections occurred moments later.
The failure mode of the parallel chord metal plate connected trusses was due to steel/wood connection failures. Connection damage was noted at various truss panel points (Figure 388) and failures were recorded at various truss panel point and bottom chord tension splice locations (Figure 391). The fire also produced a collapse local to the wood truss bearing condition (Figure 389). The floor system began to progressively deflect from 450 seconds until the end of the test. Experiment D induced a collapse of approximately 80 % of the total floor structure (Figure 387 and Figure 388). The collapse time for the Experiment D was 15:35 after ignition. The collapse time respective of the structural element fire involvement for Experiment D was 8:00.

Figure 387 Interior view of percentage of collapsed area.

Figure 388 Interior view of percentage of collapsed area.

Figure 389 Collapse local to the wood truss bearing condition.

Figure 390 Remaining section of the floor system near the rear of the structure with gypsum board removed

Figure 391 Connection failure of bottom chord tension splice.

10. Discussion

The field and laboratory 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.

10.1. Structural Analysis

In order to understand how the different floor systems behave when subjected to fire conditions it is important to analyze when the floor structure becomes weakened, collapse times, and failure mechanisms. Weakening of the floor structure can be described as the moment when the structure demonstrates behaviors that would not be expected during the normal service life of the structure, i.e. progressive deflections beyond acceptable design limits. This weakening indicates that the floor structure has been damaged by the fire event and that the structural integrity has been compromised. When the vertical deflections exceed acceptable design limits, a high degree of variability and unpredictability is introduced. The floor structure's ability to carry the applied loads during this weakened fire damaged state is not accounted for during the design process and therefore cannot be described as "reliable or safe" for fireground operations. The fire service should realize that they are being subjected to rapidly changing dangerous conditions during these periods of progressive deflections and that the published collapse times **DO NOT** represent the only time period where they can become trapped due to a collapse of a damaged floor system.

Table 42 details two different times during the experiment and introduces a third time for use during the analysis. The first is the time in which the fire attaches to the floor system and begins to spread horizontally. This time was determined based on observations from the video of the experiments. This time ranges from 1:38 to 3:58. Reasons for the differences include air temperature, humidity, wind conditions, ventilation parameters, floor system moisture content and fuel package moisture content and geometry. The second time recorded in the table is the time to floor collapse. This was the time that at least one of the 55 gallon drums that was providing loading fell through the floor or the time that the ISO 834 criteria was exceeded. In every experiment at least one full section of floor collapsed, usually the full section between the basement door and the start of the stairwell. The final time recorded in the table is the difference between the collapse time and when the fire spread to the floor system. This difference in time will be referred to as Δt. In an attempt to separate the fuel load and environmental issues from the time to collapse this value allows for a comparison across the experiments which partially filter out the events leading up to floor ignition. In other words the floor could be ignited by pallets or furniture or an electrical short but once it attaches to the floor system, the floor system becomes the dominant fuel to increase the size of the fire. It also serves as the starting point for the loss of structural integrity for the wood floor system.

It is important that the fire service reinforce their understanding of the content driven fires as compared to fires driven by contents and involved areas of combustible elements of the building structure, commonly referred to as content and structure fires by the fire service. The following analysis illustrates how quickly a fire spreads to unprotected combustible elements of the building structure. This timeline, when compared to the response timeline of responding departments, demonstrates the likelihood that the arriving firefighters will be faced with mitigating a content and structure fire for fires originating or spreading to unfinished areas of the building.

The subsequent sections of the structural analysis examine alternative methods to determine structural failure as well as go into detail on what mechanisms may have caused the floor systems to collapse.

Table 42. Collapse Time Table

Experiment Number	Floor Support	Ventilation Description	Fire Spread to Floor	Collapse	Δt (min:sec)
1	Dimensional Lumber (2 x12)	Max Vent	3:58	11:09	7:11
2	Dimensional Lumber (2 x12)	Sequenced Vent	2:00	12:45	10:45
3	Engineered Wood I-Joist (12 in.)	Max Vent	3:15	6:00	2:45
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
6	Engineered Wood I-Joist (12 in.)	Max Vent/Furnace DHS load	3:00	6:49	3:49
7	Steel C-Joist (12 in.)	Max Vent	3:00	8:15 (6:11 exceeds ISO 834:1*)	3:11
8	Steel C-Joist (12 in.)	Sequenced Vent	3:32	14:04** (10:08 exceeds ISO 834:1*)	6:36
9	Parallel Chord MPCWT***	No Vent	2:26	6:08	3:42
10	Parallel Chord MPCWT	Max Vent	1:38	3:28	1:50

* Collapse is defined by the sooner of these times in the analysis
** Water from barrels at 11:10, also deflection max at 10:08
*** MPCWT = Metal Plate Connected Wood Truss

Experiment Number	Floor Support	Ventilation Description	Fire Spread to Floor	Collapse	Δt (min:sec)
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
C	Parallel Chord MPCWT	Max Vent / Void Ignition	24:00	44:46	20:46
D	Parallel Chord MPCWT	No Vent / 80 ft^2 exposed	Unknown	13:10	NA

10.1.1. ISO Analysis

There are standard test methods used to test the structural stability of floor systems such as UL 263 – Fire Tests of Building Construction and Materials. This is the standard that is followed that results in an hourly rating of an assembly. Commonly these hourly ratings are required by code in commercial buildings; public buildings, multi-family structures, etc. (Not single family homes). One of the requirements that pertain to floor system stability is that it is intended to evaluate the length of time that these types of assemblies will contain a fire or retain their structural integrity, or both, dependent upon the type of assembly involved, during a predetermined test exposure. The test evaluates the assembly's resistance to heat, and in some instances to a hose stream, while carrying an applied load, if the assembly is load bearing.

Several fire test standards similar to UL 263 such as "ISO 834:1 Fire-resistance tests – Elements of building construction – Part 1: General requirements" define load bearing capacity as the elapsed time that a test sample is able to maintain its ability to support the applied load during the fire test. The ability to support the applied load is determined when both:

(1) Deflection exceeds: $\frac{L^2}{400d}$; and

(2) When the deflection exceeds: $\frac{L}{30}$, the Rate of Deflection exceeds: $\frac{L^2}{9000d}$ per min

where L is the clear span measured in millimeters and d is the distance from the extreme fiber of the design compression zone to the extreme fiber of the design tensile zone of the structural element as measured in millimeters. The values of these calculations for these experiments are in Table 43.

Table 43. ISO 834:1 Calculated Values

Floor System	L mm (ft.)	d mm (in.)	$\frac{L^2}{400d}$ mm (in.)	$\frac{L}{30}$ mm (in.)	$\frac{L^2}{9000d}$ mm (in.)
Dimensional Lumber	4877 (16)	286 (11.25)	208 (8.2)	163 (6.4)	9 (0.4)
Engineered I-Joist	6096 (20)	302 (11.875)	308 (12.1)	203 (8.0)	14 (0.6)
Steel C-Joist	6096 (20)	302 (11.875)	308 (12.1)	203 (8.0)	14 (0.6)
Parallel Chord MPCWT	6096 (20)	356 (14)	261 (10.3)	203 (8.0)	12 (0.5)

The time to exceed the two criteria that ISO 834:1 uses to define structural stability is shown in Table 44. This shows that all of the wood floor systems maintained structural stability until failure while the metal C-joist floor system lost structural stability for a long time period, 124 s and 236 s respectively prior to their ultimate collapse. Experiment 8 actually deflected so much prior to collapse that some of the 55 gallon drums providing the loading tipped over.

Table 44. Time to exceed ISO values for each experiment

Test	Exceeds criteria 1 ($L^2/400d$) (s)	Exceeds criteria 2 (L/30 and rate of $L^2/9000d$) (s)	ISO Value for loss of integrity (s)	Time to Collapse (s)	Difference (s)
1	669	669	669	669	0
2	760	760	760	765	5
3	356	355	356	360	4
4	406	403	406	409	3
5	503	493	503	507	4
6	401	388	401	409	8
7	346	371	371	495	124
8	543	608	608	844	236
9	347	362	362	368	6
10	203	197	203	208	5
A	348	356	356	380	24
B	1880	1881	1881	1885	4
C	2686	2686	2686	2686	0
D	768	769	769	790	21

10.1.2. Mechanisms of Structural Collapse

The structural stability of a floor system during fire conditions is dependent on a number of simultaneous variables that are constantly being changed by the fire's ability to weaken, damage, or consume the structural element. The existing literature, and the results of this test series, have concluded consistent failure mechanisms for the respective tested elements.

The following describes the key structural collapse failure mechanism for the structural framing members tested:

1. The failure mode of dimensional lumber is due to cross section reduction which results in joist rupture.
2. The failure mode of engineered lumber I-Joist is due to burn-out of the web members.

3. The failure mode of steel C-Joists is due to a significant loss in strength when exposed to high temperatures. This loss of strength then induces progressive deformations which exceed various deflection limits prior to complete collapse.
4. The failure mode of the parallel chord metal plate connected trusses was due to steel/wood connection failures

The structural collapse time of the floor system should not be interpreted by the fire service as representative of a period of safe operating time when considering or conducting fire ground operations. The stability of the floor structure assembly depends on a number of conditions to ensure the applied load can be carried safely. In general a collapse may be induced by a stability failure of the floor system or a strength failure of the floor system. It is difficult to ascertain by experimental data and post fire forensics exactly how the collapse occurred. It is also difficult to ascertain when the fire event has significantly compromised the structures ability to carry its applied loads. One potential indicator of significant structural damage would be to evaluate when the structural elements deflection exceeds limits accounted for in the structural design of the floor assembly. Generally most floor systems are designed to perform with allowable deflection induced by the total applied load are less than L/240, where L is the span of the element in inches.

Applying this rational the following table delineates when the structural elements has been weakened beyond the normal parameters considered for the service life of the structure.

Table 45. Time to exceed the allowable design deflection limits.

Experiment Number	Floor Support	Ventilation Description	Fire Spread to Floor	Deflection greater than L/240	Structural Collapse
1	Dimensional Lumber (2 x12)	Max Vent	3:58	10:47	11:09
2	Dimensional Lumber (2 x12)	Sequenced Vent	2:00	12:22	12:45
3	Engineered Wood I-Joist (12 in.)	Max Vent	3:15	4:52	6:00
4	Engineered Wood I-Joist (12 in.)	No Vent	2:43	4:38	6:49
5	Engineered Wood I-Joist (12 in.)	No Vent/No boxes	3:45	5:25	8:27
6	Engineered Wood I-Joist (12 in.)	Max Vent/Furnace DHS load	3:00	5:19	6:49
7	Steel C-Joist (12 in.)	Max Vent	3:00	3:10	8:15 (6:11 exceeds ISO 834:1)
8	Steel C-Joist (12 in.)	Sequenced Vent	3:32	3:43	14:04* (10:08 exceeds ISO 834:1)
9	Parallel Chord MPCWT**	No Vent	2:26	3:35	6:08
10	Parallel Chord MPCWT	Max Vent	1:38	2:32	3:28

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

Experiment Number	Floor Support	Ventilation Description	Fire Spread to Floor	Structural Collapse
A	Engineered Wood I-Joist (12 in.)	Max Vent / Same as Exp. 3	2:20	6:20
B	Engineered Wood I-Joist (12 in.)	Max Vent / Torch ignition	25:55	31:25
C	Parallel Chord MPCWT	Max Vent / Void Ignition	24:00	44:46
D	Parallel Chord MPCWT	No Vent / 80 ft^2 exposed	Unknown	13:10

10.2. Fuel Load

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 this 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. The impact of the reduced fuel load in Experiment 5 was a 62 second delay in fire spread to the floor system. Experiment 5 had just the wood pallets and no boxes. Figure 392 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 46 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.

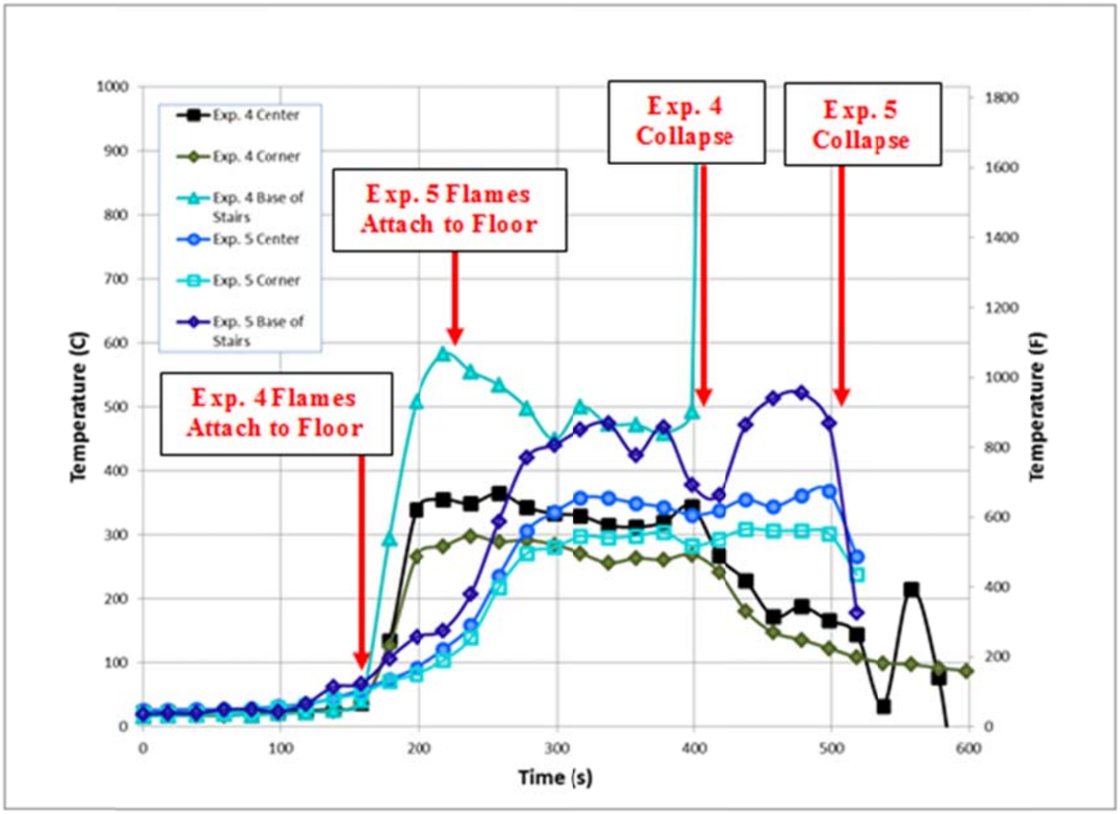

Figure 392. Basement temperatures at 6 ft above the floor for Experiments 4 and 5

Table 46. 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 393 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 47 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 eachother.

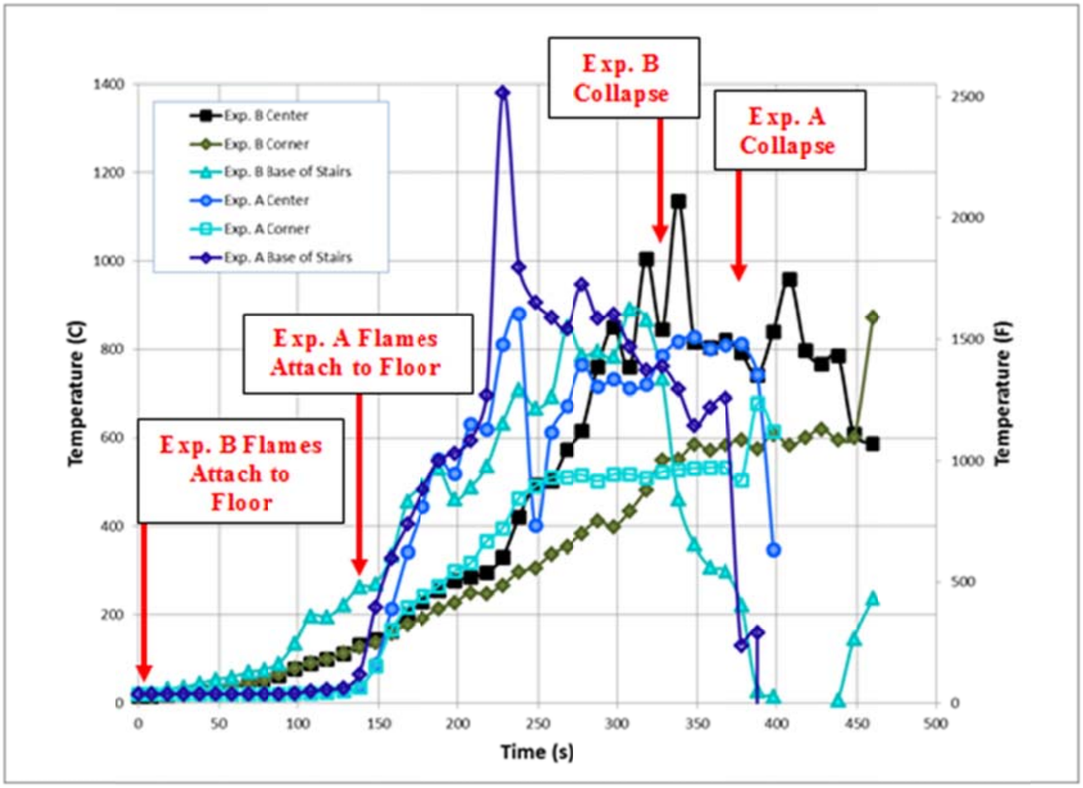

Figure 393. Basement temperatures at 6 ft above the floor for Experiments A and B

Table 47. Comparison of Basement Temperatures at 5 ft. above the floor

	Peak Temperature [Temperature 10 seconds Prior to Collapse] (^{o}C)		
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 48).

Table 48. 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

10.3. Ventilation

Ventilation or the amount of air available to the fire can play 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). In some cases the floor system collapsed within 8 minutes after ignition of the fuel package, therefore doing a sequenced scenario was not possible with the engineered I-joist or parallel chord truss floor systems.

Each floor system type had 2 ventilation scenarios to compare. For the dimensional lumber floor system, Experiment 1 was conducted with maximum ventilation or all of the openings in the open position and Experiment 2 was opened sequentially simulating fire department operations. Experiment 1 collapsed 96 seconds faster due to the increased amount of ventilation. Figure 394 through Figure 397 show a comparison of temperatures between experiments at two different elevations, 7 ft. and 3 ft. above the floor on both levels of the structure, basement and first floor.

The basement temperatures in the open structure (Experiment 1) remained lower as the fire grew and cool air was able to flow into the structure from the outside. The temperatures in the closed structure (Experiment 2) increased much faster at the start of the experiment as the heat was contained within the structure. At approximately 140 seconds after ignition in Experiment 2, which corresponds to floor system ignition, the fire became ventilation limited as the fuel production began to exceed the oxygen available for combustion. Temperatures decreased by approximately 25% and then remain steady until the sequential ventilation began. Once the floor system in Experiment 1became involved in the fire (238 s) the temperatures increased quickly. Temperatures throughout the basement at 7 ft. increased from below 100 °C to above 800 °C in less than 2 minutes as oxygen was available from the open doors and windows. At 480 seconds in Experiment 2 the first floor front door was opened and the temperatures remained steady. Once the basement door and windows began to be opened the fire increased in intensity and the temperatures increased to above their original peaks, due to the additional availability of oxygen.

Examining the temperatures on the first floor of the structure in Figure 395 and Figure 397 shows the extreme temperatures at the top of the stairway. Once the basement fire increased in intensity in Experiment 1 the hot gases, in excess of 700 °C, flowed up the stairway and out through the open first floor door. The temperatures flowing up the stair increased from 100 °C to 600 °C in less than 30 seconds. The rest of the first floor temperatures increased to between 300 °C and 450 °C. While still high these temperatures were much less than the temperatures in the flow path from the basement to the first floor doorway. This same phenomena occurred in Experiment 2 once the flow path was established. As the first floor door was opened smoke was able to escape allowing air to be pulled in through the cracks in the basement, but once the basement door was opened the flow path was created and temperatures at the top of the stairs 7 ft. above the floor increased 400 °C in 40 seconds. The temperatures 3 ft. above the floor increased 300 °C in 40 seconds.

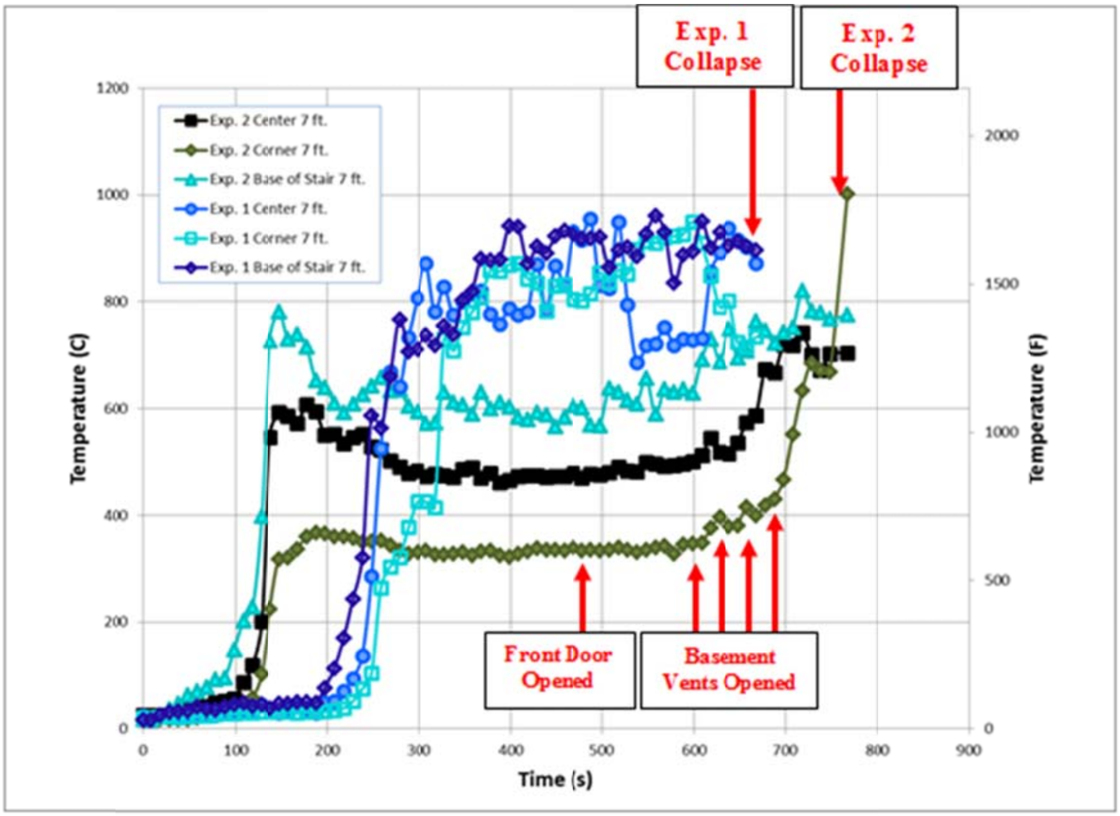

Figure 394. Experiment 1 and 2 Comparison of Basement Temperatures at 7 ft. above the floor

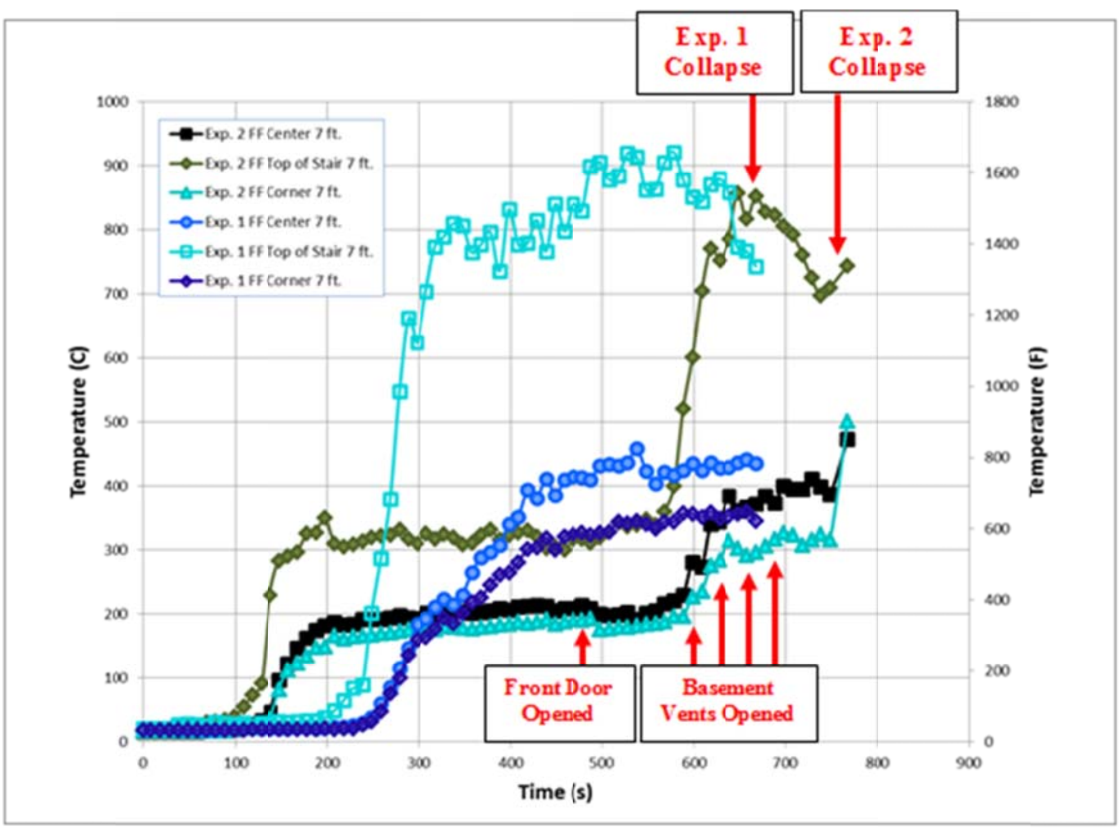

Figure 395. Experiment 1 and 2 Comparison of First Floor Temperatures at 7 ft. above the floor

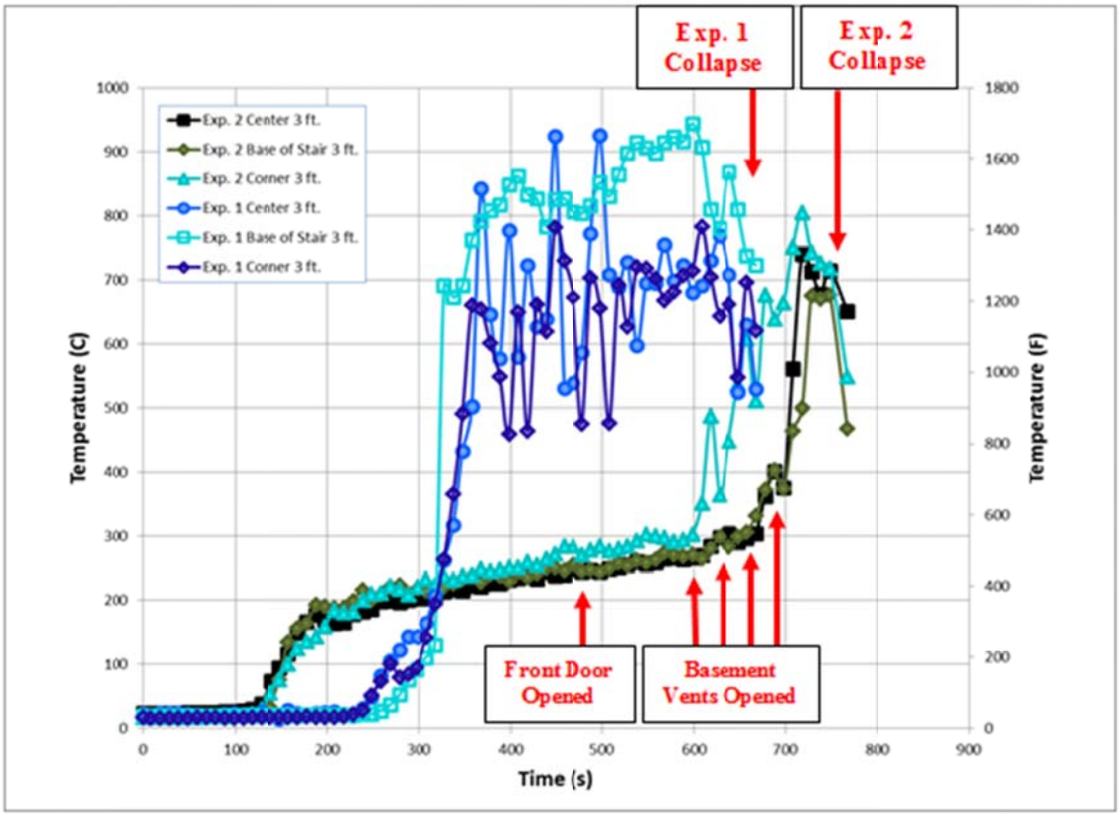

Figure 396. Experiment 1 and 2 Comparison of Basement Temperatures at 3 ft. above the floor

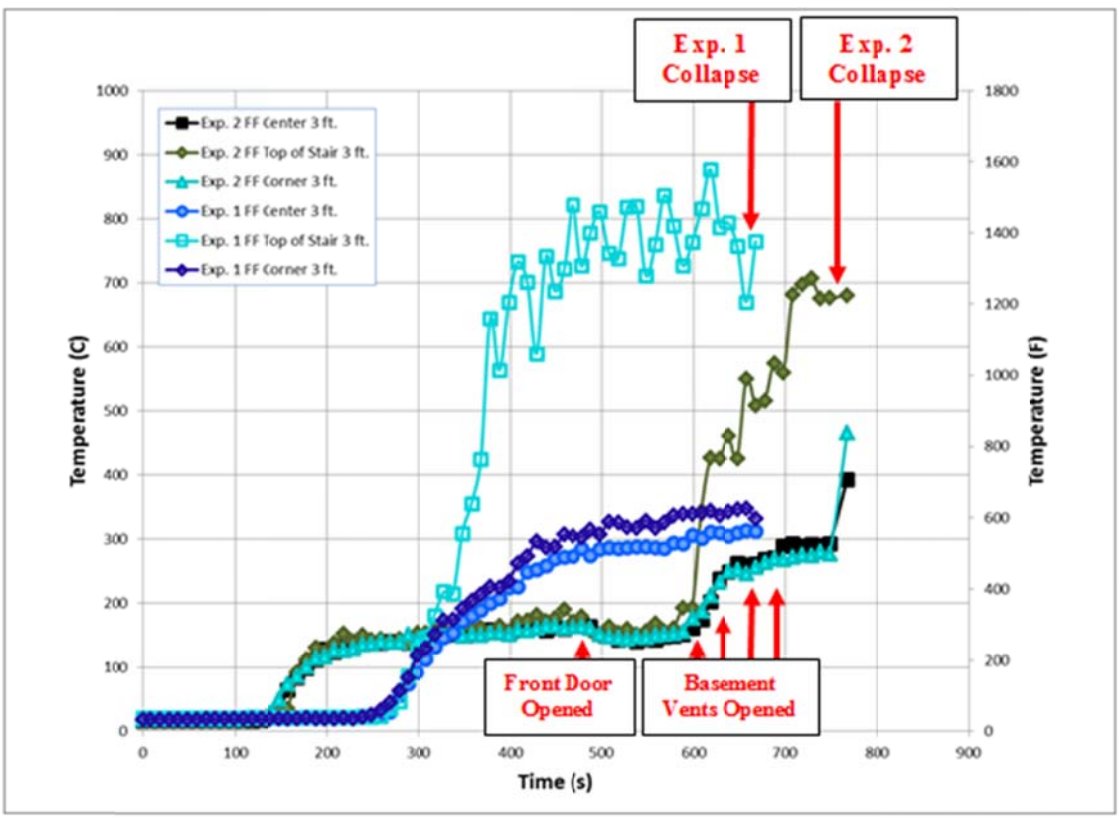

Figure 397. Experiment 1 and 2 Comparison of First Floor Temperatures at 3 ft. above the floor

The second comparison was the engineered I-joist floor system. Experiment 3 was conducted with maximum ventilation or all of the openings in the open position and Experiment 4 was completed with all the ventilation opening closed. Figure 398 through Figure 401 show a comparison of temperatures between experiments at two different elevations, 7 ft. and 3 ft. above the floor on both levels of the structure, basement and first floor.

Experiment 4 was closed, therefore the temperatures increased faster than Experiment 3. Shortly after the floor system ignited in Experiment 4 the fire became ventilation limited and began to decrease in temperature. There was a fairly steady decrease in temperature all the way through collapse at 6 minutes and 49 seconds after ignition. Experiment 3 had lower temperatures to start due to the ventilation openings, however once the floor system became involved in the fire the available oxygen allowed for the entire basement to achieve post-flashover conditions. Temperatures in the basement at 3 ft. and 7 ft. above the floor exceeded 600 C at 280 seconds after ignition. The additional ventilation of Experiment 3 allowed for a 49 second faster collapse of the floor system.

Much like the first comparison the difference between being in the flow path of the fire and not is significant. The difference between the temperatures at the top and bottom of the stairs, 3 ft. above the floor at 5 minutes after ignition, with the doors to the basement and first floor opened or not is 600 °C. During Experiment 4, one minute prior to collapse, at 3 ft. above the first floor, the temperature in the flow path was 700 °C while the temperature less than 10 ft. away at the same elevation in the center of the first floor was 225 °C. This demonstrates the importance for firefighters to stay out of the flow path of the fire, especially when operating above a basement fire.

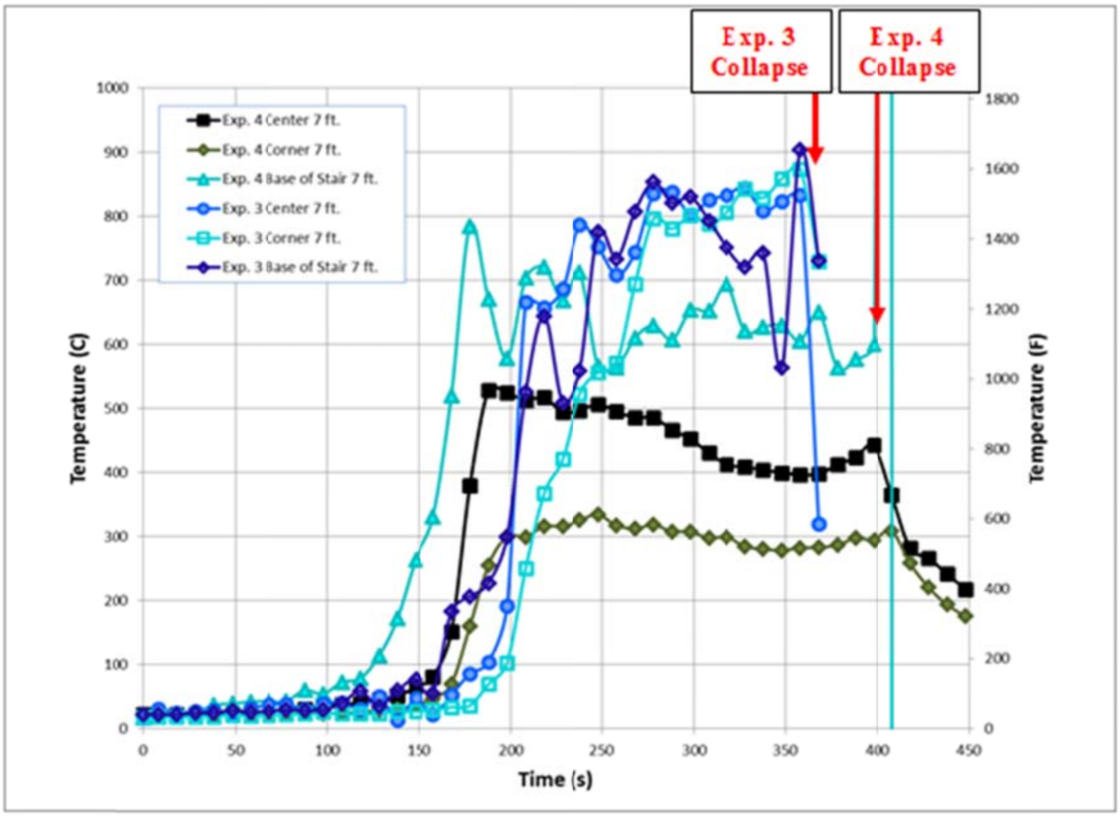

Figure 398. Experiment 3 and 4 Comparison of Basement Temperatures at 7 ft. above the floor

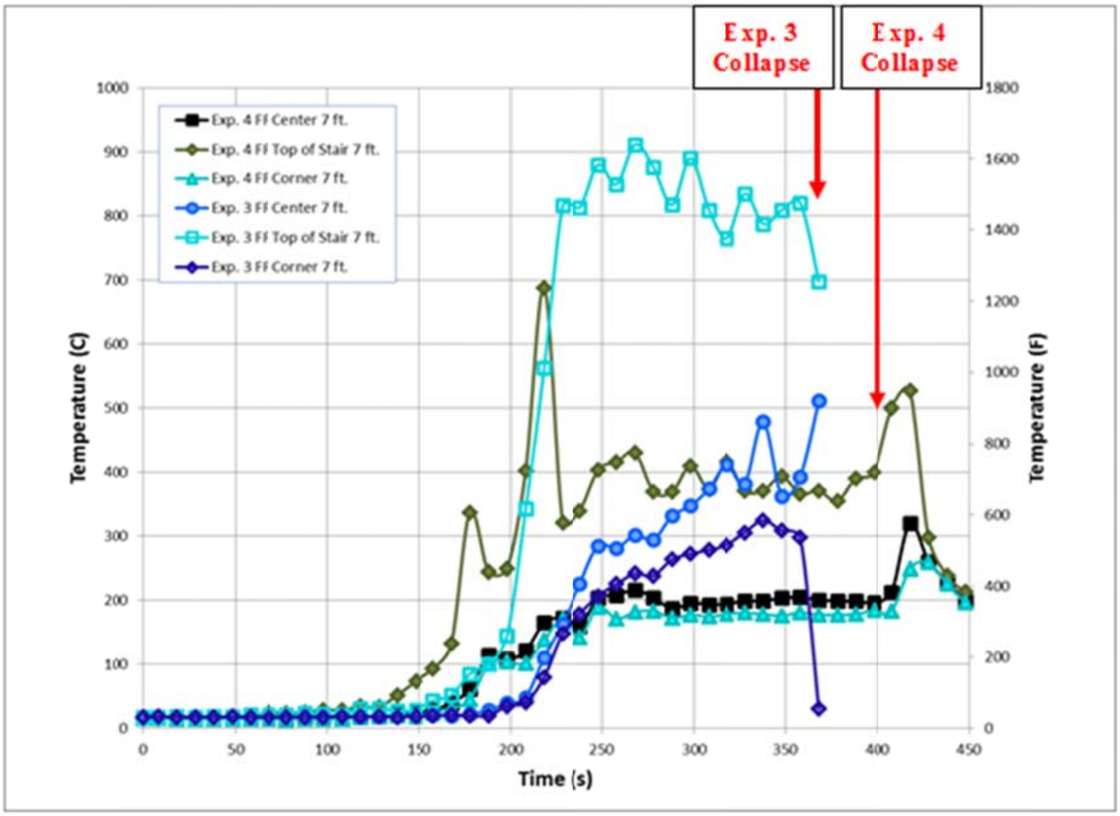

Figure 399. Experiment 3 and 4 Comparison of First Floor Temperatures at 7 ft. above the floor

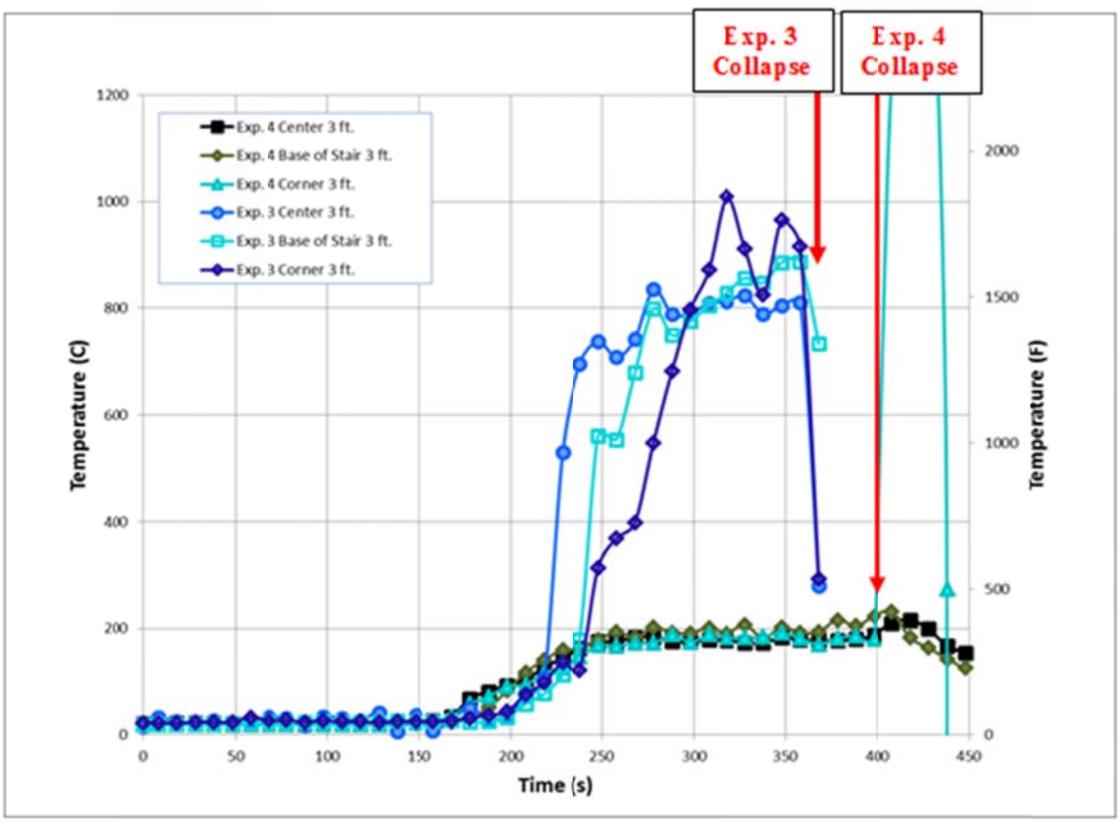

Figure 400. Experiment 3 and 4 Comparison of Basement Temperatures at 3 ft. above the floor

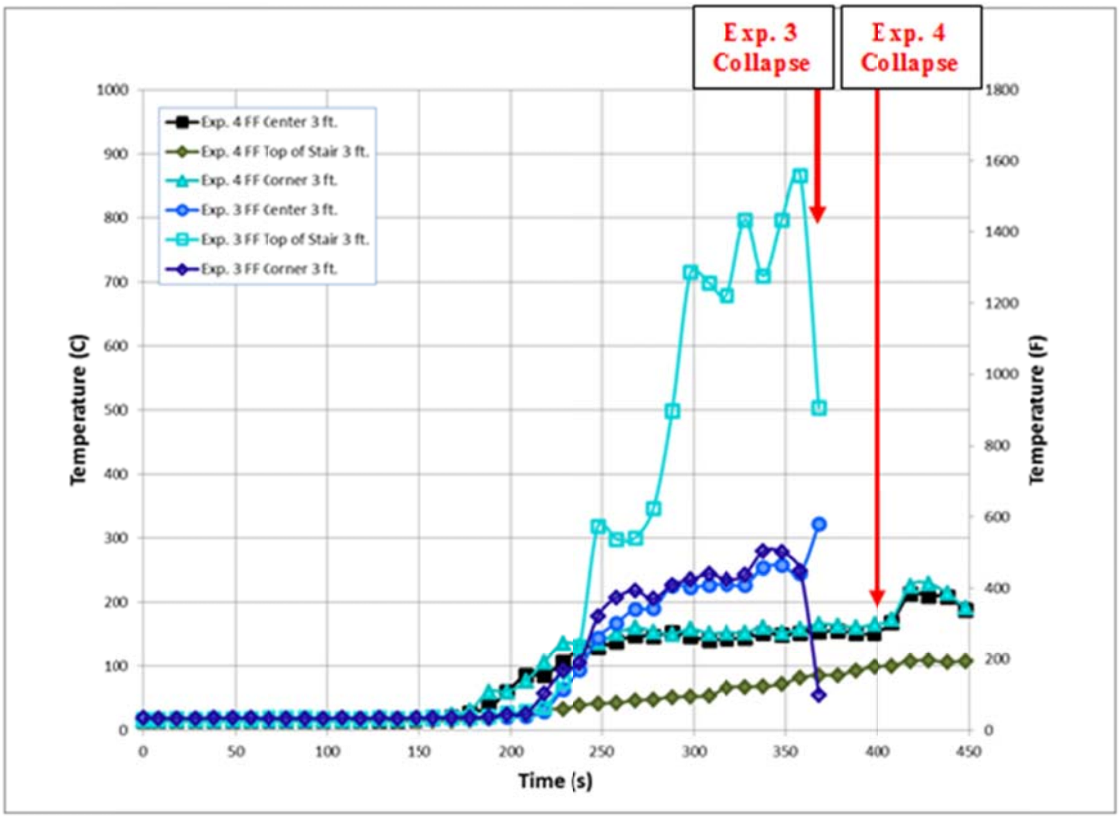

Figure 401. Experiment 3 and 4 Comparison of First Floor Temperatures at 3 ft. above the floor

The third comparison was the steel C-joist floor system. Experiment 7 was conducted with maximum ventilation or all of the openings in the open position and Experiment 8 was opened sequentially simulating fire department operations. Figure 402 through Figure 405 show a comparison of temperatures between experiments at two different elevations, 7 ft. and 3 ft. above the floor on both levels of the structure, basement and first floor.

Both experiments increased in temperature similarly for the first 5 minutes of the experiment. At approximately this time Experiment 8 became ventilation limited and the temperatures decreased slightly and remained constant. The temperatures in Experiment 7 remained high through the time to collapse because of the additional air available. As sequential ventilation began at 8 minutes after ignition in Experiment 8 the temperatures began to increase. The was a significant temperature increase, from 380 °C to 680 °C at the top of the stairs when the door to the basement was opened completing the flow path from the basement to the first floor and out through the open doorway on the first floor. The temperatures at 3 ft. became much less tenable throughout the structure once the basement door and windows were opened and the ventilation limited fire was provided oxygen. The additional ventilation during Experiment 7 allowed for collapse to occur 3 minutes and 57 seconds faster than Experiment 8.

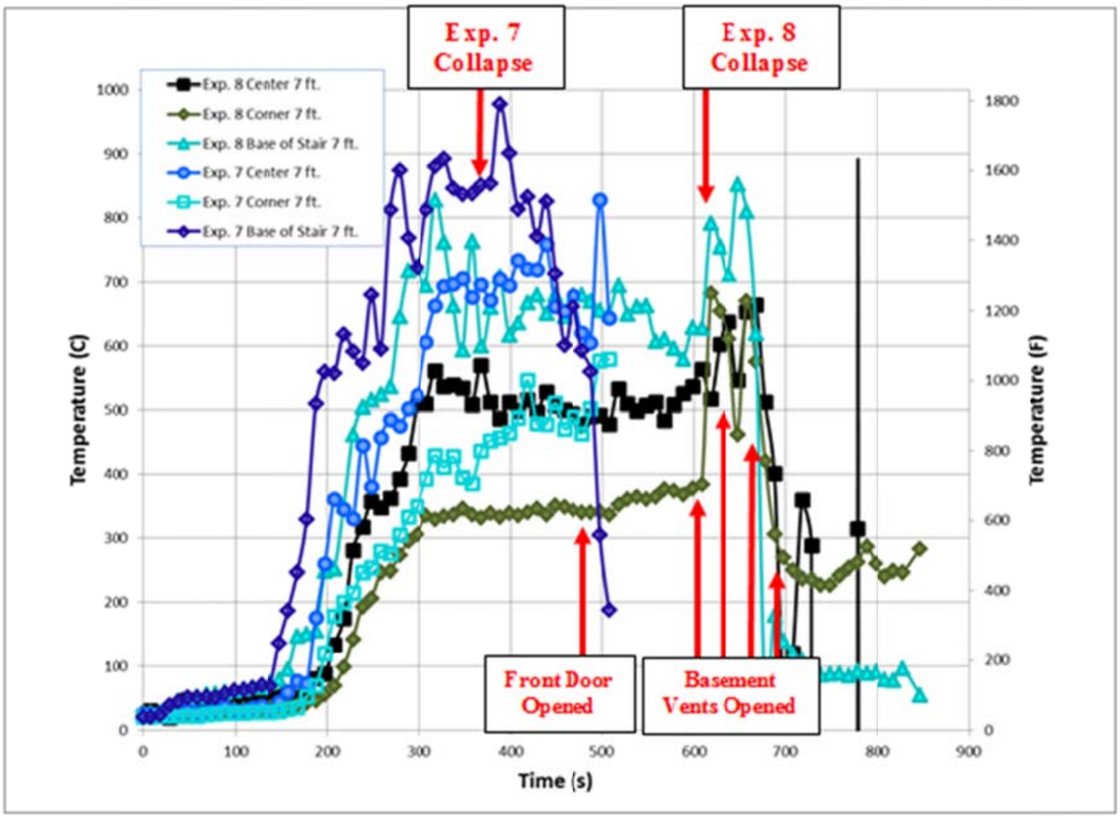

Figure 402. Experiment 7 and 8 Comparison of Basement Temperatures at 7 ft. above the floor

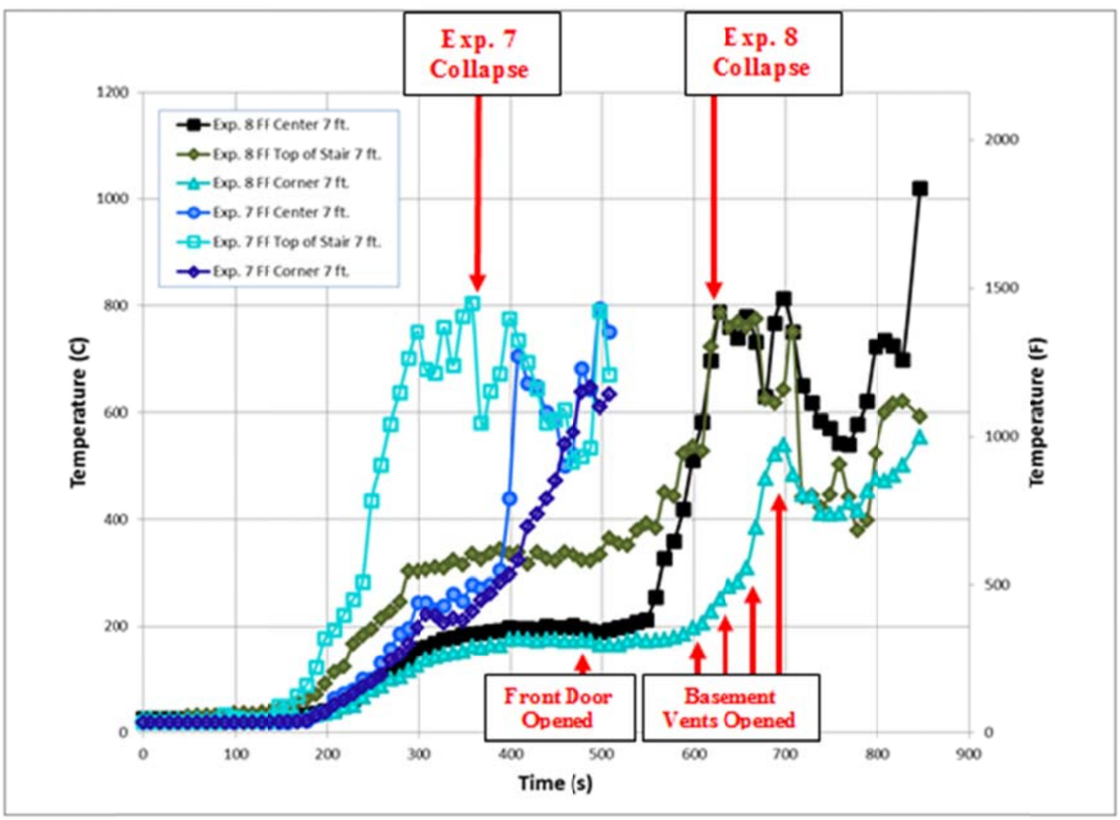

Figure 403. Experiment 7 and 8 Comparison of First Floor Temperatures at 7 ft. above the floor

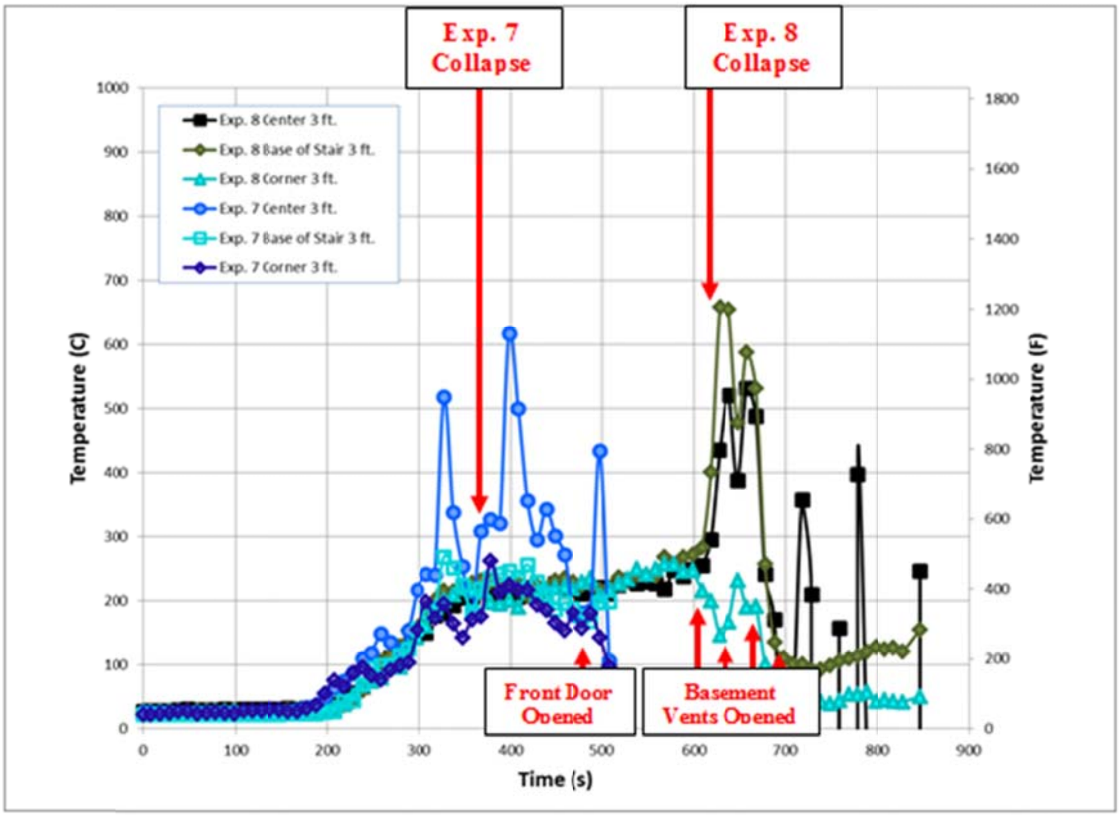

Figure 404. Experiment 7 and 8 Comparison of Basement Temperatures at 3 ft. above the floor

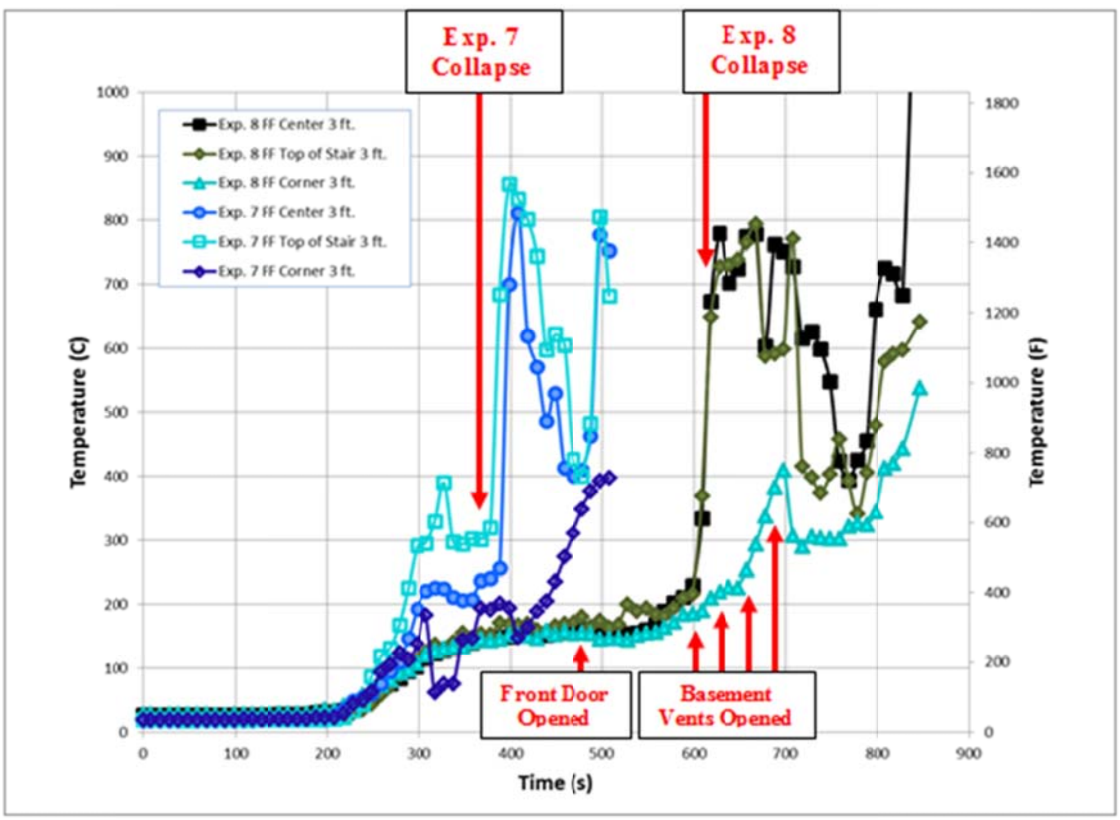

Figure 405. Experiment 7 and 8 Comparison of First Floor Temperatures at 3 ft. above the floor

The final comparison was the parallel chord metal plate connected wood truss floor system. Experiment 9 was completed with all the ventilation openings closed and Experiment 10 was conducted with maximum ventilation or all of the openings in the open position. Figure 406 through Figure 409 show a comparison of temperatures between experiments at two different elevations, 7 ft. and 3 ft. above the floor on both levels of the structure, basement and first floor.

This comparison was similar to the previous 3 in that the closed structure, Experiment 9, became ventilation limited and the temperatures declined or remained the same at every measurement point. The maximum ventilation structure, Experiment 10, did not have this decline and was able to reach maximum temperatures and remain there until collapse. In this comparison the lack of ventilation caused a 2 minute and 40 second delay in collapse. The temperature at the top of the stairs, 3 ft above the floor, was 500 °C less in the closed structure than the opened structure due to lack of oxygen and flow path.

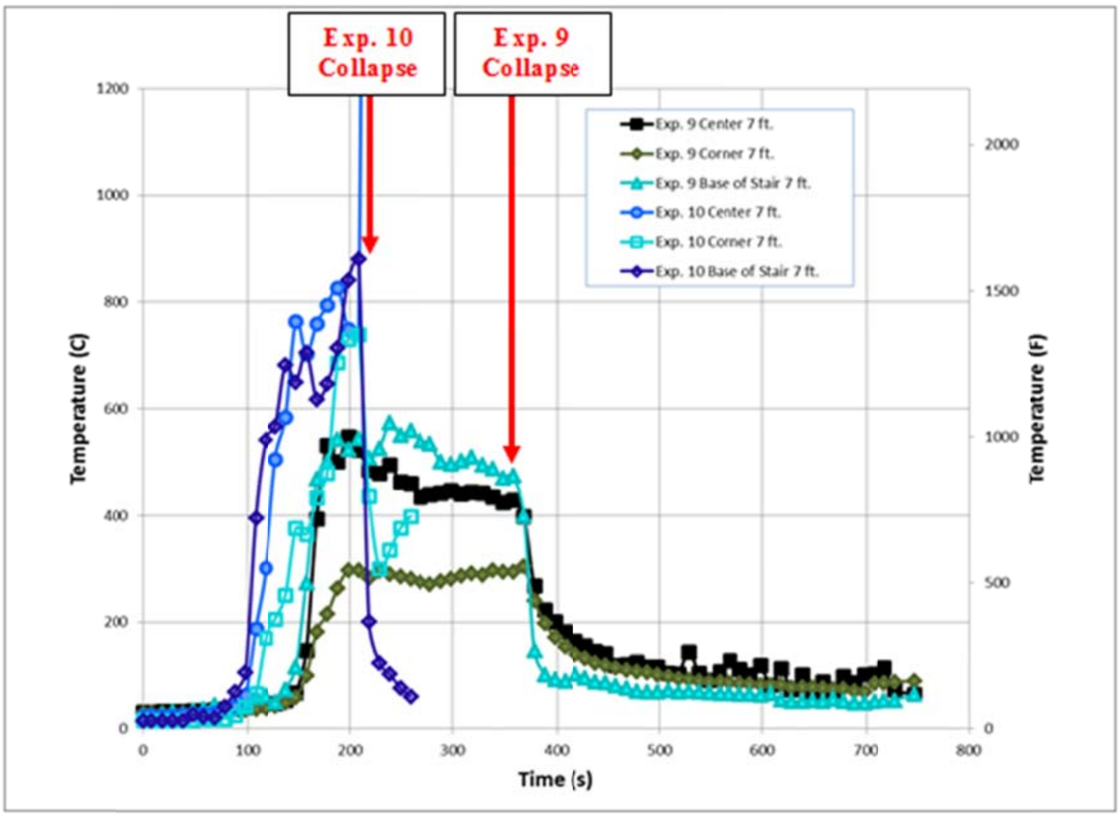

Figure 406. Experiment 9 and 10 Comparison of Basement Temperatures at 7 ft. above the floor

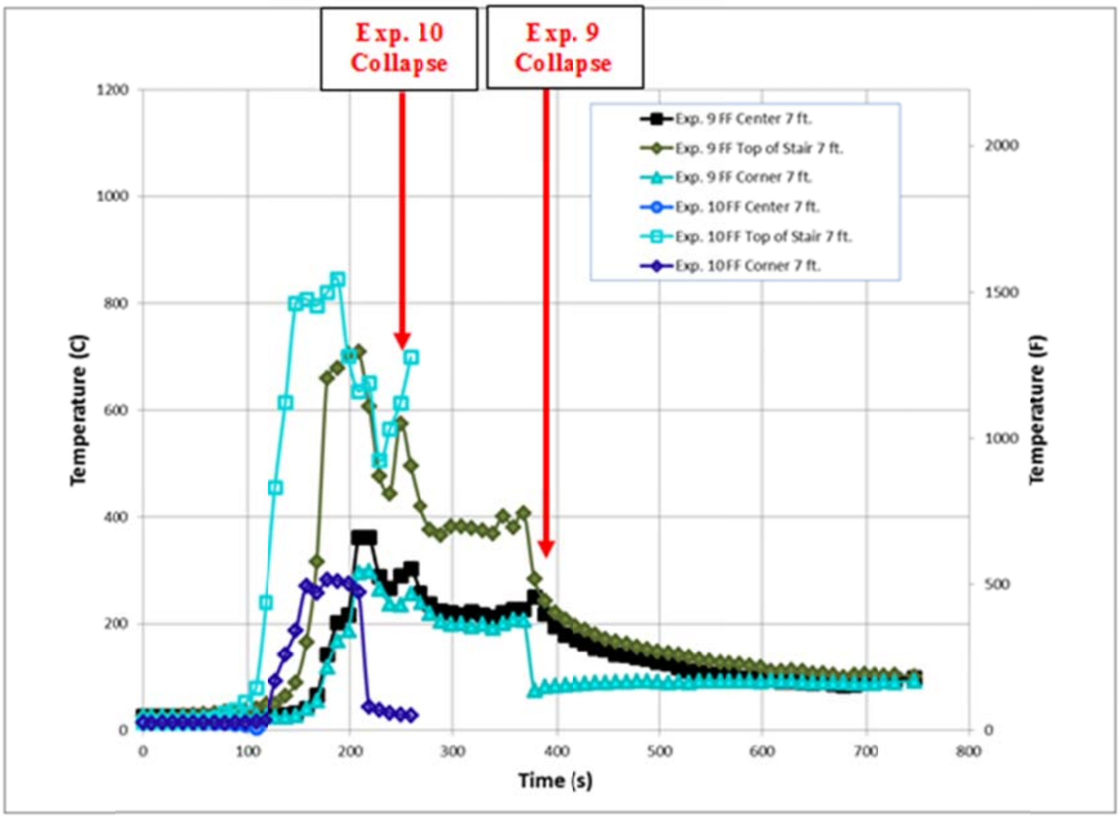

Figure 407. Experiment 9 and 10 Comparison of First Floor Temperatures at 7 ft. above the floor

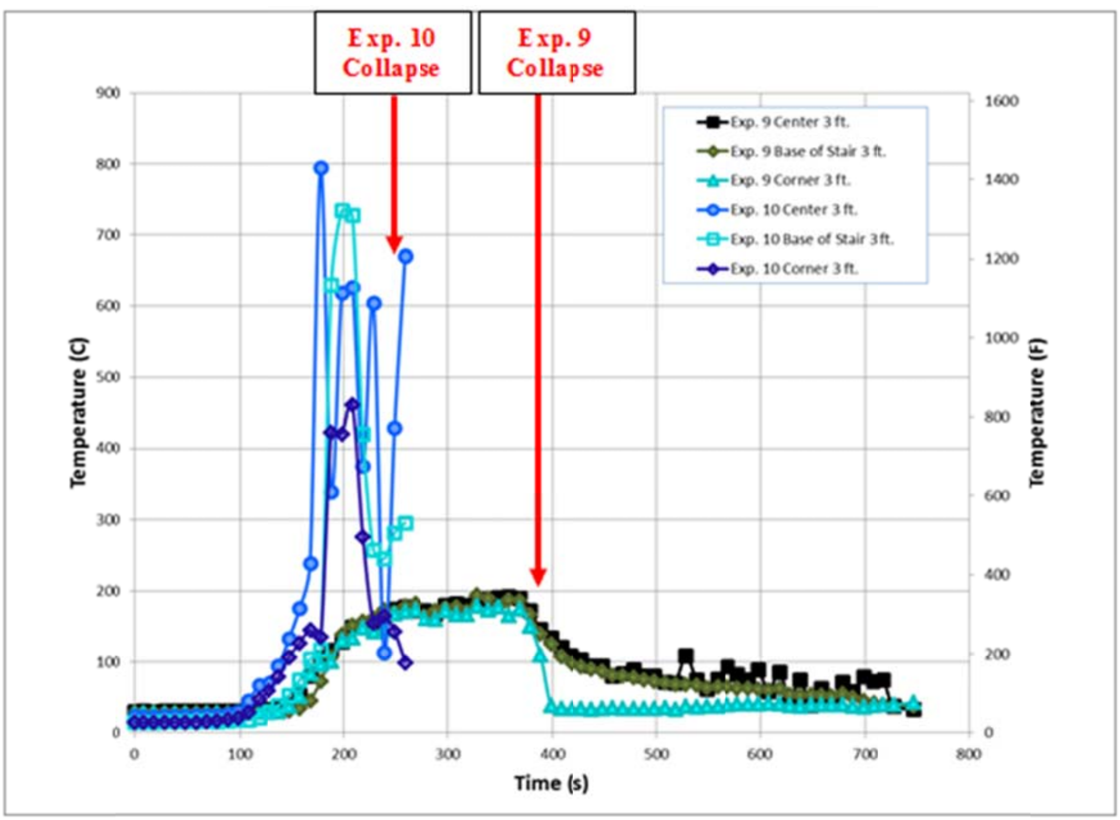

Figure 408. Experiment 9 and 10 Comparison of Basement Temperatures at 3 ft. above the floor

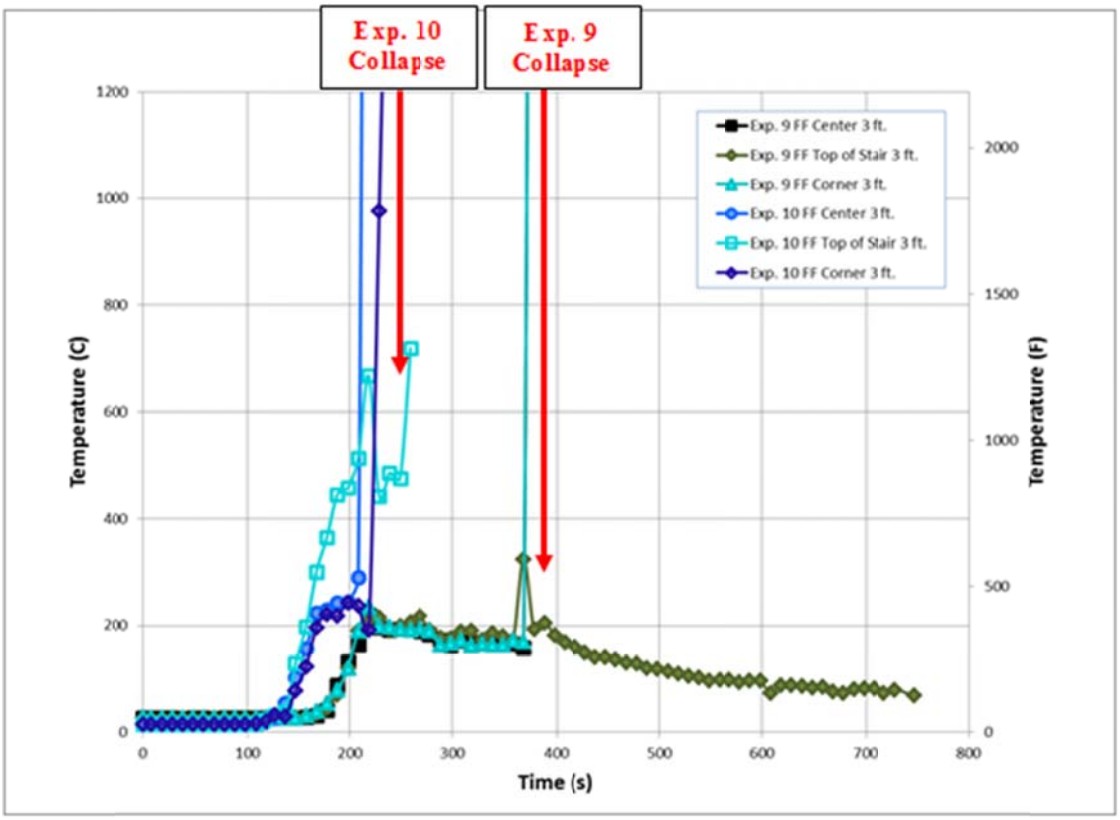

Figure 409. Experiment 9 and 10 Comparison of First Floor Temperatures at 3 ft. above the floor

Examining these 4 comparisons it can be concluded that the floor systems in the ventilated experiments collapsed an average of 22% faster than the non-ventilated or sequenced ventilated experiments. This is not a significant difference and it shows the ability of the floor system exposed to elevated temperatures to degrade to the point of collapse, without ample amounts of oxygen. These comparisons also point out the extreme hazard that firefighters can be exposed to when they approach a basement fire from the top of the basement stairs.

10.4. Load

In Experiment 6 the load placed on the top of the floor system was decreased to examine the impact of the loading. This experiment was compared to Experiment 3 which had the design load of 65% which was used in all of the other experiments as well. Both experiments utilized an engineered I-joist floor system, a standard fuel loading and maximum ventilation scenario. Experiment 6 had a modified load that was substantially less than the load used for the other experiments. It consisted of barrels loaded to 40 lb/ft^2 along the back and side walls to simulate furniture and two barrels filled to 300 lb to simulate two firefighters in the center of the floor.

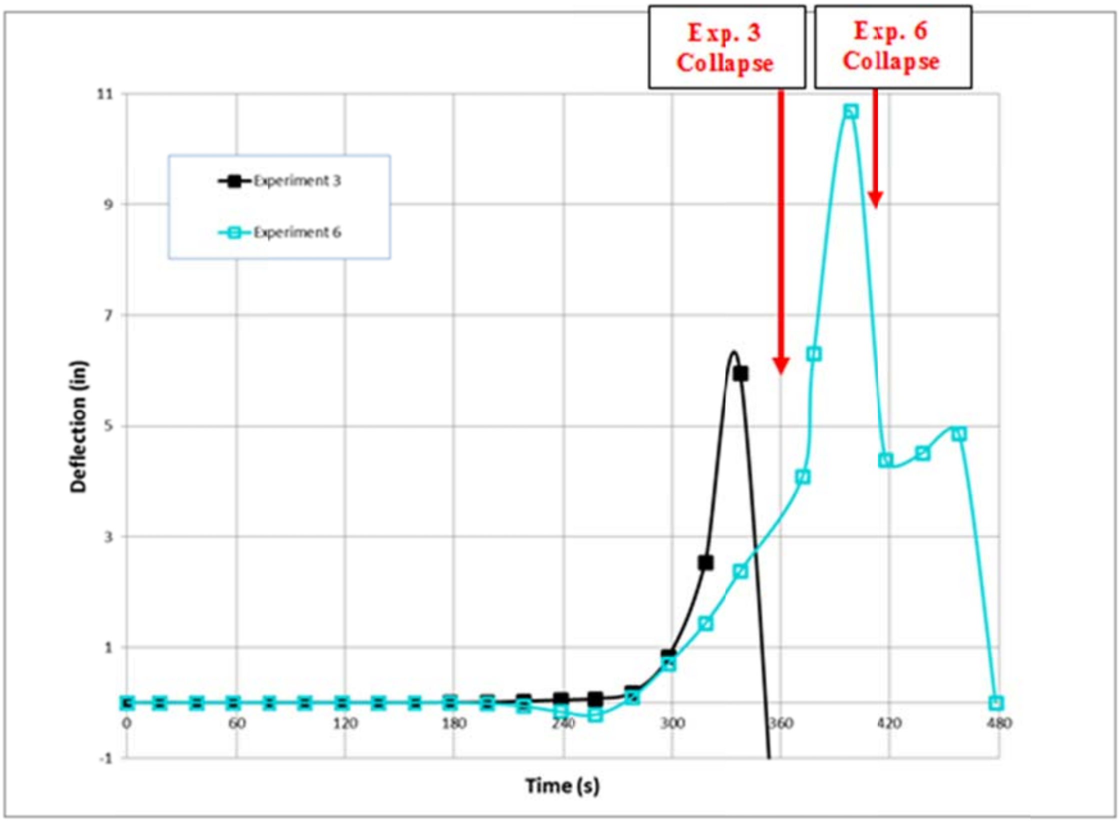

Figure 410 shows the deflection during Experiments 3 and 6. Both Experiments have approximately the same time to onset of deflection. Due to the smaller load Experiment 6 had a slightly slower rate of deflection leading up to collapse which accounts for the 49 seconds difference in collapse times. Ultimately 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.

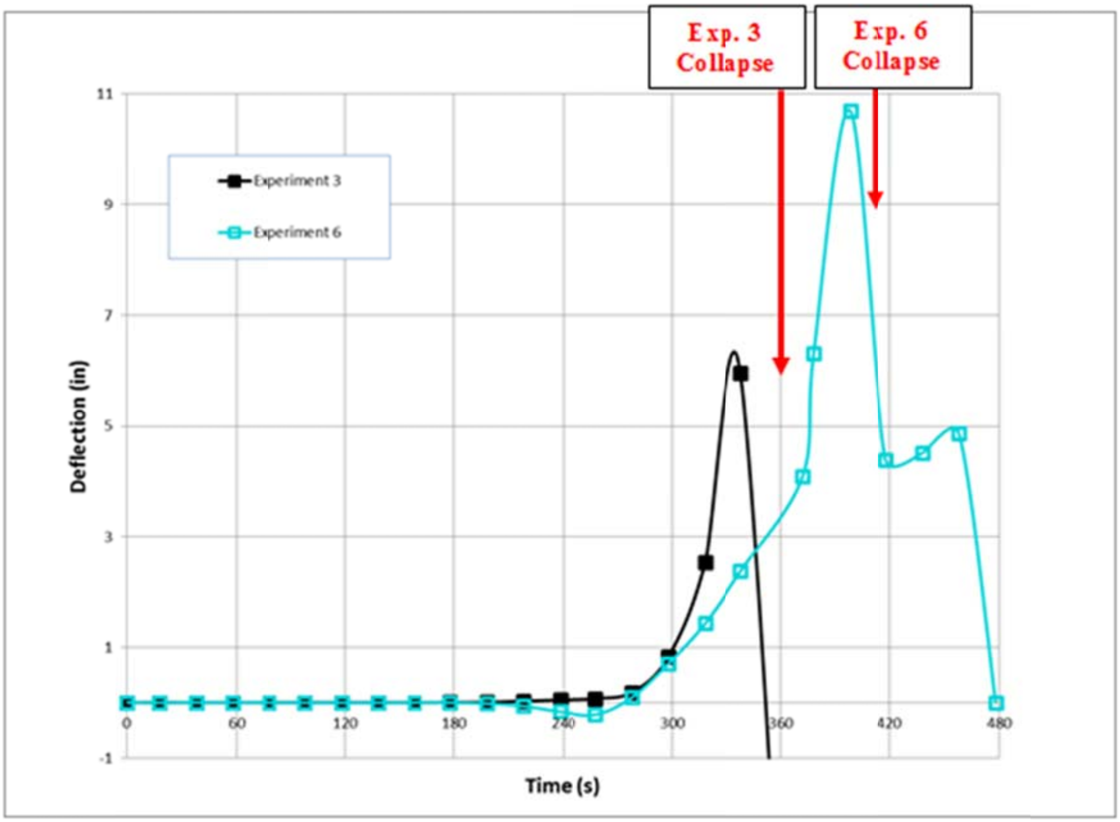

Figure 410. Deflection versus time for Experiments 3 and 6

10.5. 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.

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 that 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.

10.5.1. 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) The start of the operational timeframe for the sequenced ventilation experiments coincides with the 75% response time of 8 minutes from the USFA study.

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 occurs simultaneously with the start of the response time. Figure 411 shows the response times from the USFA study and how they compare with the collapse times from the field experiments. It is clear that even with the quickest notification of the fire department and the fastest response times that fire departments have to seriously consider collapse in their initial operations because regardless of the flooring type, ventilation configurations, fuel load or mechanical load collapse could occur within 8 minutes of fire department arrival.

In the best case, the slowest collapsing floor system was the dimensional lumber floor that was ventilated in the sequence that could be done by the fire service. The simulated operations of the fire department began at 8 minutes after ignition and the collapse occurred at 12 minutes and 45 seconds. 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 emphasizes the importance of protecting all types of flooring systems, including dimensional lumber. However, note that 5 of the 8 engineered floor assemblies collapsed prior to the 8 minute mark, which emphasizes the importance of size-up by the arriving fire department.

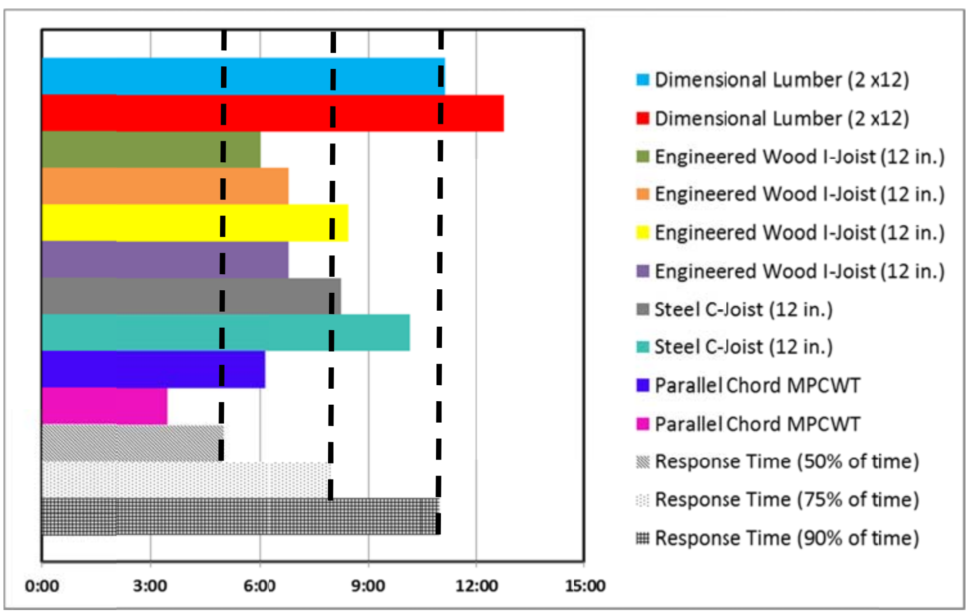

Figure 411. Collapse Time versus Response Time, assuming dispatch at the time of flaming ignition.

10.5.2. Size up

During all of these experiments it was evident that the floor section over top of the initial fire was the section to collapse first in every experiment. Second, the amount of ventilation provided to the fire allowed the floor system to collapse faster. While there are not many interior clues as to when the floor system was going to collapse, such as sag may not be noticeable or temperatures may not be predictive. One thing that could go a long way in increasing firefighter safety at basement fires is to conduct a 360 degree walk around of the structure and look for the location of the fire and the amount of ventilation, prior to the fire fighters making entry to the building. These two factors, while important to many other factors on the fire ground, are two that can lead to firefighters falling through the floor into a basement fire.

10.5.3. 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 412 shows the temperatures at the top of the stairs, 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 experiments have temperatures in excess of the threshold indicating 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.

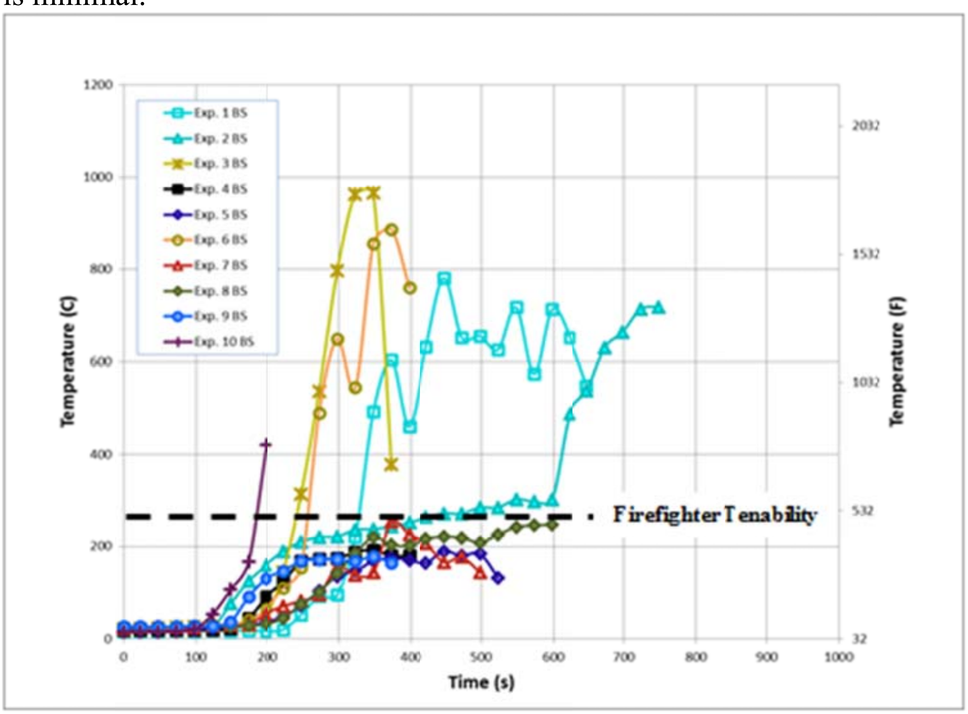

Figure 413 shows the temperatures at the bottom of the stairs up through the time of floor system collapse. It also demonstrates that if the fire is ventilated then the temperatures at the bottom of the stairs are also not tenable for firefighters. The thought that if it is hot at the top of the stairs 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.

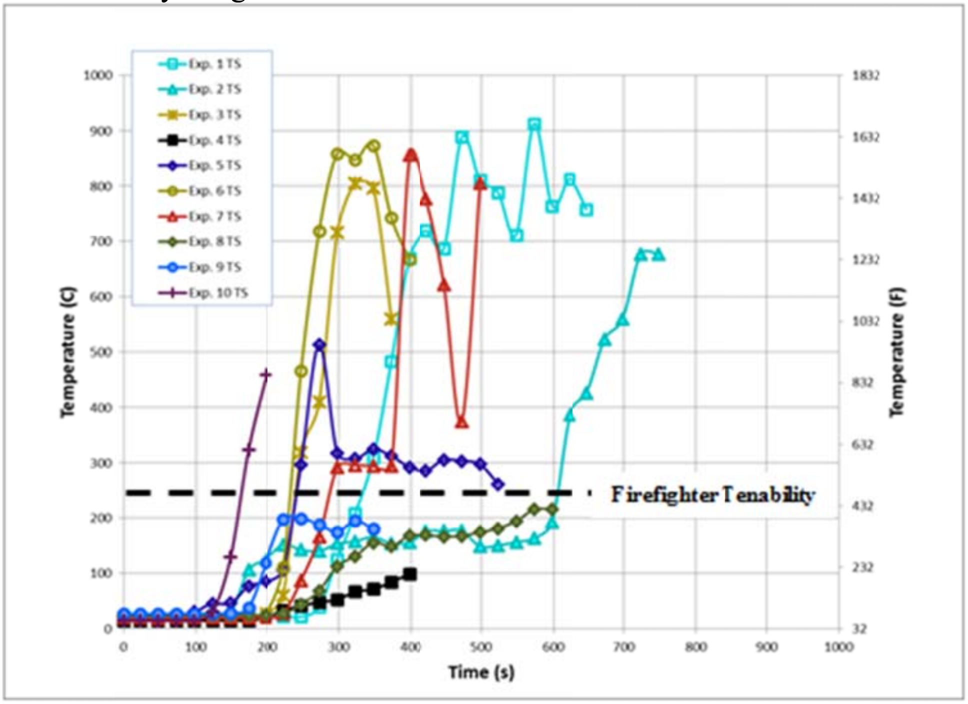

Figure 412. Temperatures 3 ft. above the floor at the top of the stairs

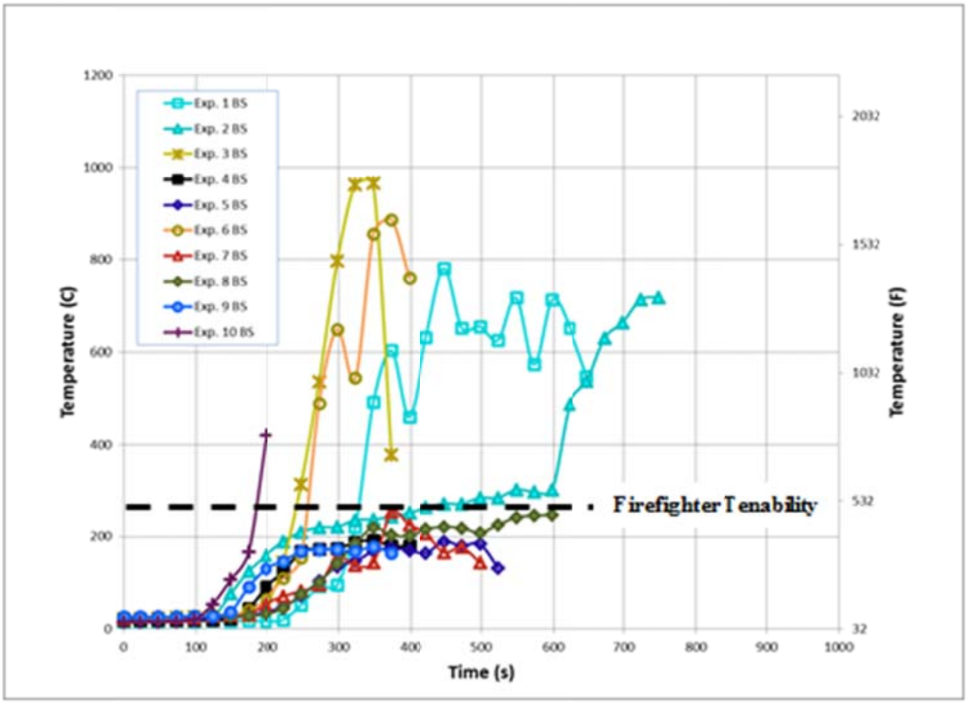

Figure 413. Temperatures 3 ft. above the floor at the bottom of the stairs

10.5.4. Ventilation

This series of experiments demonstrates the importance of coordinated ventilation. While most of the floor systems collapsed prior to fire department intervention, experiment 2 did not and it highlights the importance of flow paths. As the ventilation openings in the basement were made it created a flow path from the basement to the front door of the structure. Anyone in this path would have to move quickly to survive. Figure 414 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 415 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.

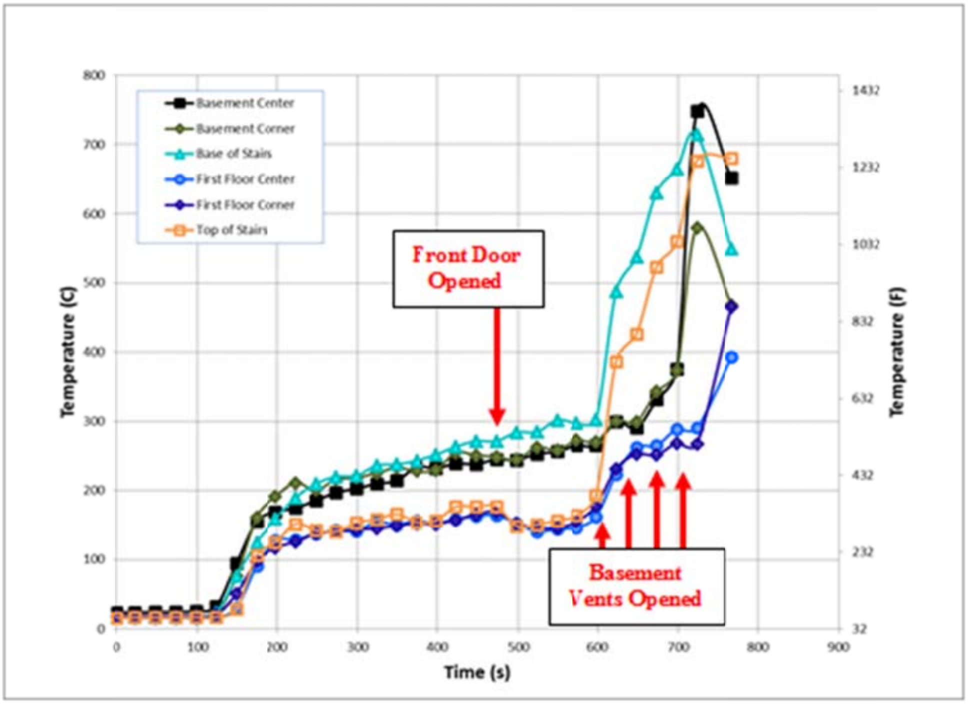

Figure 414. Experiment 2 Temperatures at 3 ft. above the floor

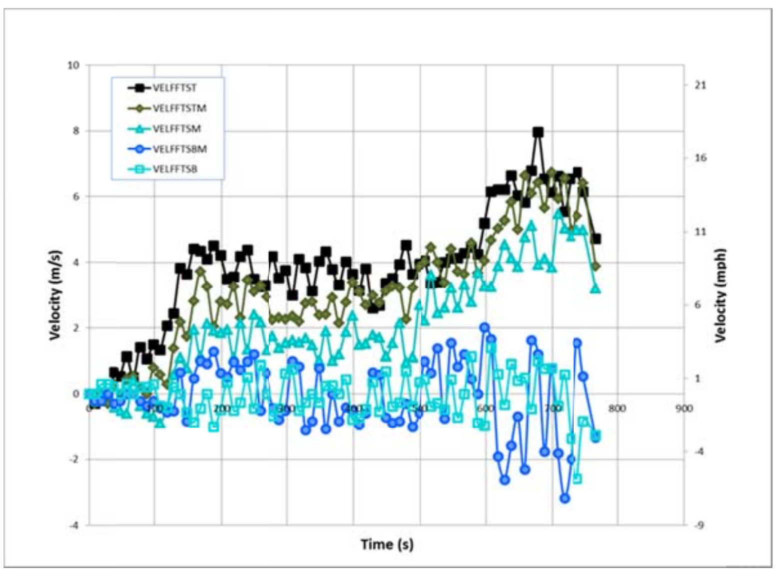

Figure 415. Experiment 2 Velocities at the top of the stairs

10.5.5. 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 situation 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 one 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 49 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 416 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 49. 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

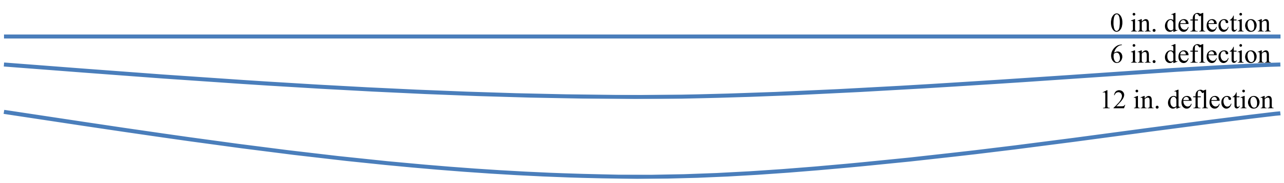

Figure 416. Relative depiction of 0, 6 and 12 in. deflections on a 20 ft. span

10.5.6. 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 417. 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 418 through Figure 420). 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.

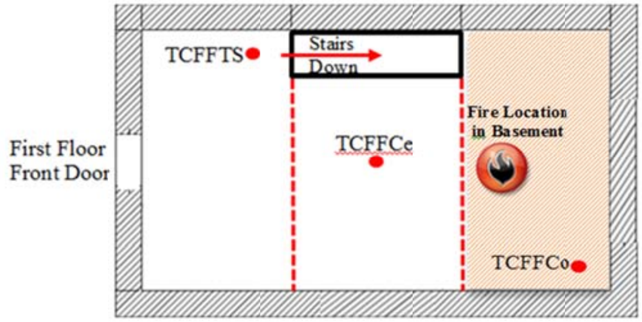

Figure 417. First floor temperature locations and collapse zone

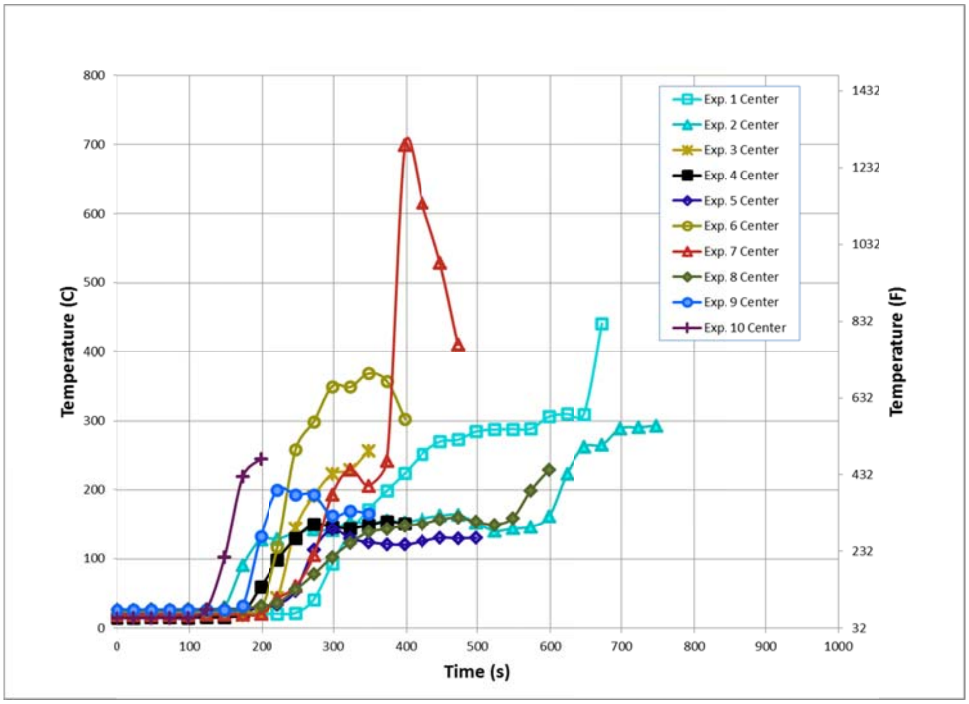

Figure 418. First floor center temperatures 3 ft. above the floor

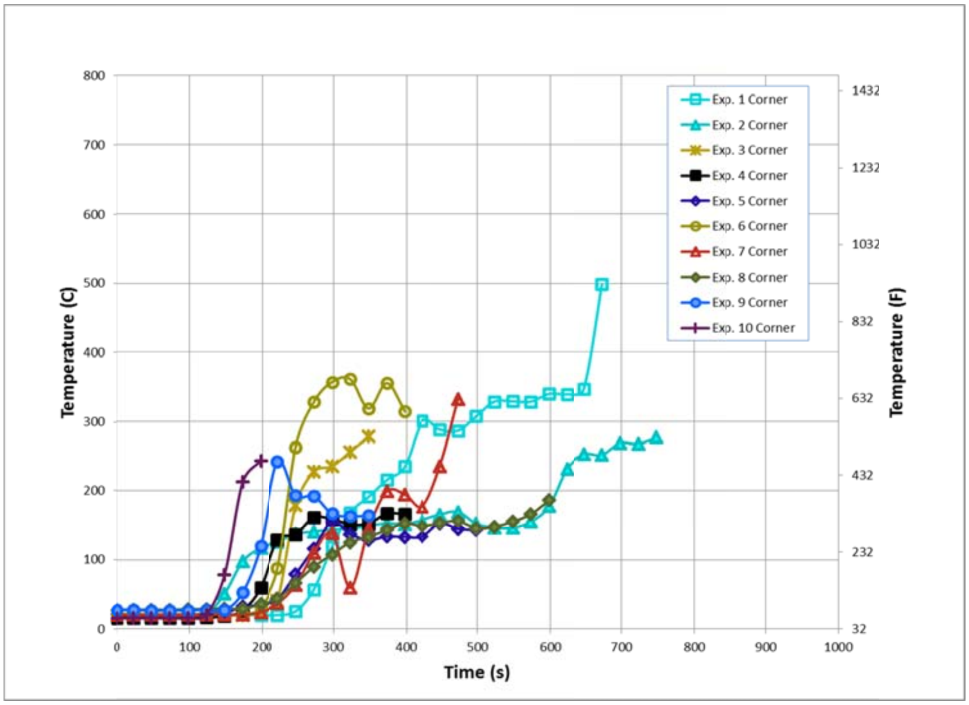

Figure 419. First floor corner temperatures 3 ft. above the floor

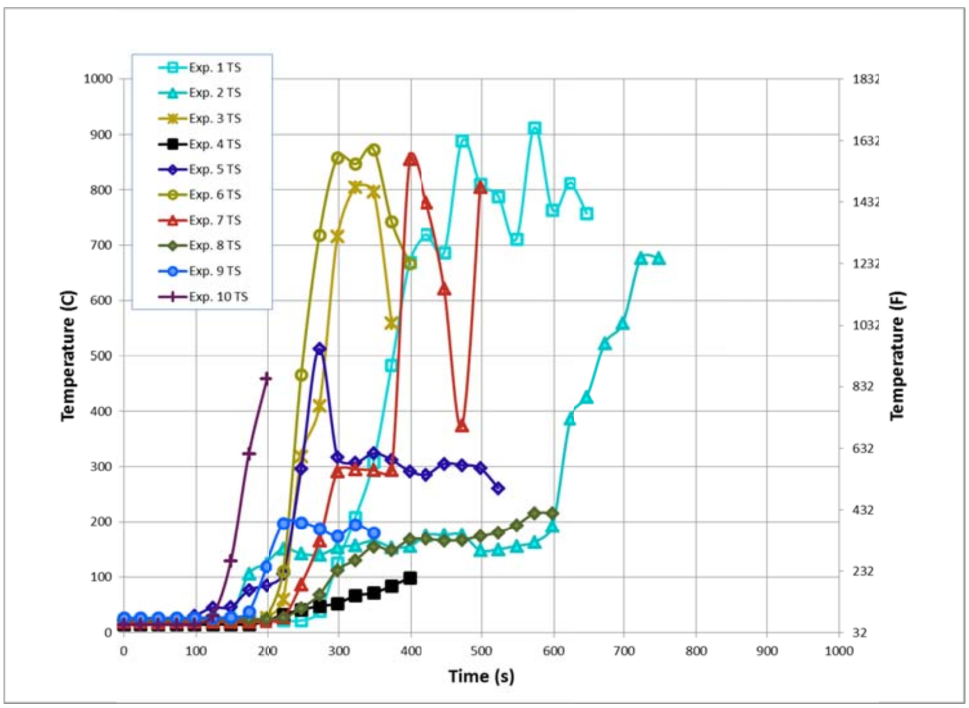

Figure 420. First floor stair temperatures 3 ft. above the floor

10.5.7. 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 421 through Figure 428 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.

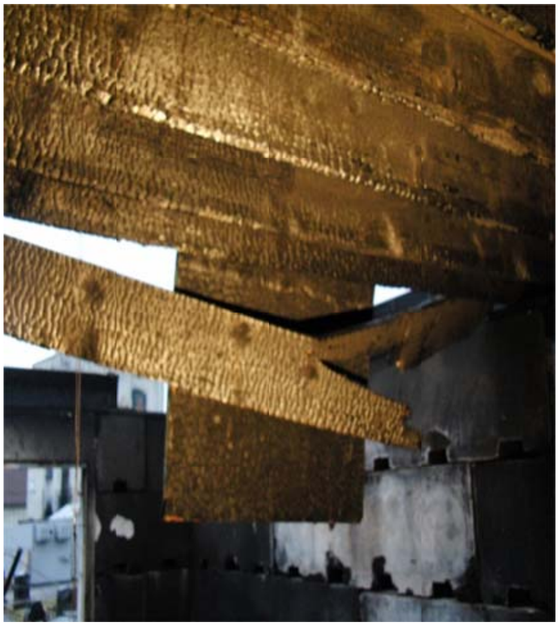

Figure 421. Dimensional Lumber Joist Fracture

Figure 422. Dimensional Lumber Complete Joist Burn Through

Figure 423. Engineered I-joist Web Burn Through

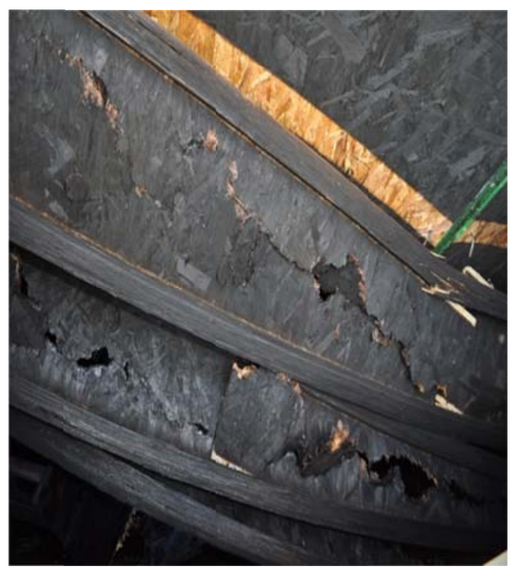

Figure 424. Engineered I-joist Web Failure and Sheathing Separation

Figure 425. MPCWT Steel to wood panel point connection failure

Figure 426. MPCWT Detail of Connection Failure

Figure 427. Steel C-joist Loss of strength inducing progressive joist deformations, sheathing connection failure, joist bracing and lateral bracing strap failure

Figure 428. Steel C-joist deformation detail

10.5.8. Overhaul

In 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 429). The resulting fire grew differently with the available oxygen, eventually leading to collapse. Figure 430 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.

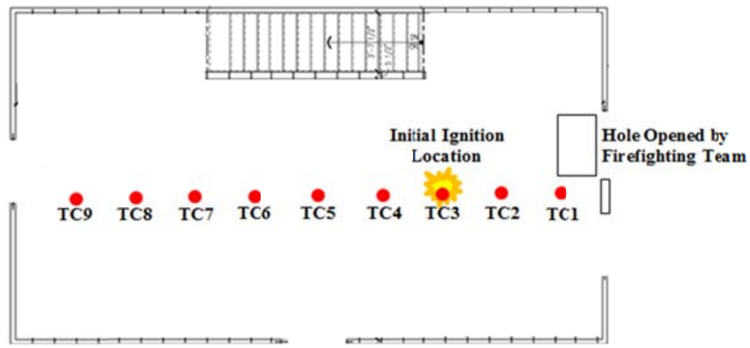

Figure 429. Experiment C Void Thermocouple and Hole Location

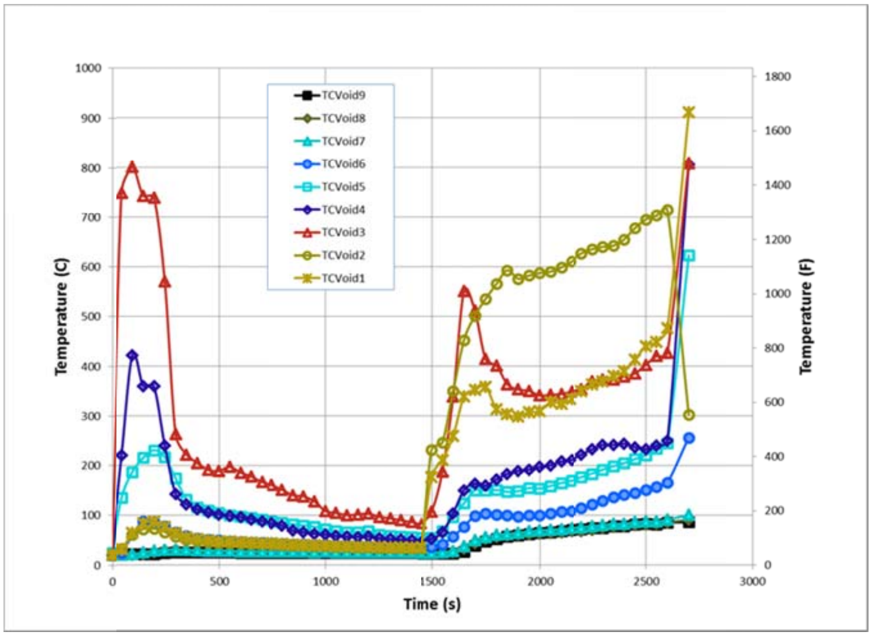

Figure 430. Experiment C void space temperatures.

10.6. Code Implications

Based on some previous research by UL and others as well as concerns from the fire service a code change was developed by an ad hoc group consisting of fire service and building industry representatives. 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.

Section 4 of the floor fire protection code indicates that exposed dimensional lumber does not need to be protected. In these experiments the dimensional lumber outperformed all of the engineered 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 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. 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 at the time of ignition, called into the fire department, the fire department is dispatched at the first sign of flames in the structure, 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.

The exception in Section 3.1 of the floor fire protection 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 431 and Figure 432). The exposed area was located on the centerline of the room toward the back of the stairwell location (

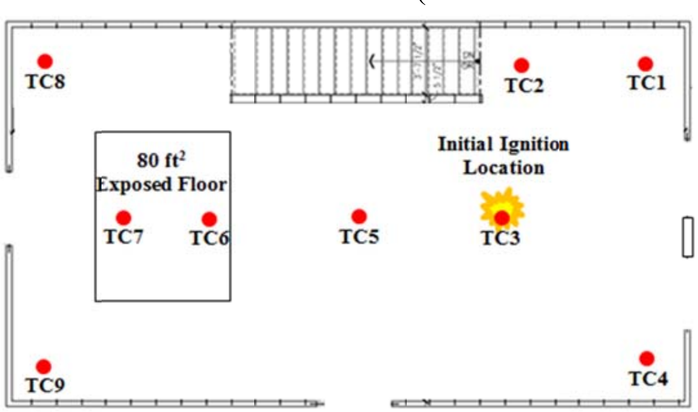

Figure 433). The fire was ignited at the end of the basement near the doorway as shown in

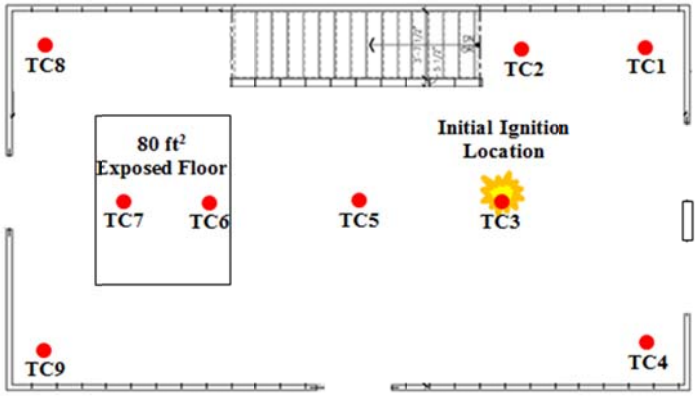

Figure 433. Thermocouples were placed in the void space as well as on the decking in the exposed joist area. Figure 434 shows the temperatures throughout the experiment. The thermocouples in the exposed joist area were the first to reach elevated temperatures and they increased in temperature throughout the experiment. At approximately 6 minutes the temperatures in the void space just above the fire source increased to over 600 °C (1100 °F) indicating that the fire breached the gypsum ceiling. 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. Even though the exposed floor section burned and collapsed the thermocouples in the corners of the basement above the remainder of the protected basement, less than 6 feet away from the exposed floor, never exceeded 180 °C (360 °F) (Figure 434).

Figure 431. Close view of exposed trusses

Figure 432. Detailed image showing draft stopping of the exposed trusses

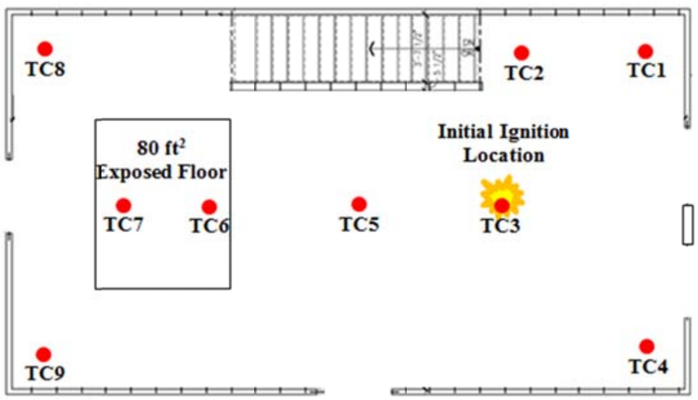

Figure 433. Experiment D Void Thermocouple and Exposed Floor Location

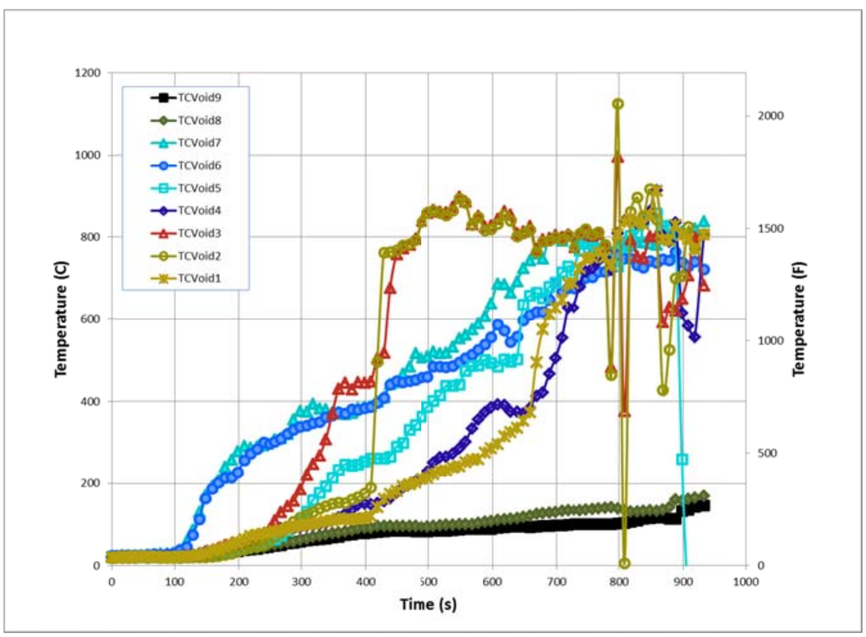

Figure 434. Experiment D void space temperatures

11. Future Research

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.

12. Summary

UL conducted a series of 17 full-scale fire experiments. Three characterized the fuel by measuring the heat release rate of the fuel package. Ten full-scale simulated basement fire experiments were conducted 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.

This research project expanded the current body of knowledge of floor system behavior under fire conditions by assessing other typical scenarios including: longer floor span lengths, more realistic fire loads, different ignition locations, more realistic ventilation scenarios, additional engineered floor system products, code change implications and most importantly the impact of firefighter operations on floor system failure times and mechanisms.

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.

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 (Experiment 4 and 5) resulted in collapse times within 100 seconds of each other.

Ventilation or the amount of air available to the fire can play 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. The topics of Operational Timeframe, Size-up, Basement Fire Attack, Ventilation, Floor Sag as a Collapse Indicator, Temperatures on the First Floor Prior to Collapse, and overhaul were examined for their impact on firefighter safety. The overriding safety message is that a well-ventilated basement fire that has involved the floor system is inherently dangerous to operate on top of regardless of the construction method or members involved. The longest time to collapse of an unprotected floor system during this series of experiments was 12:45 after ignition. Since the fire department does not typically know when the fire started there is no guaranteed safe operational timeframe to be operating on top of a residential basement fire.

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14. Acknowledgements

UL would like to acknowledge the staff at the Delaware County (PA) Emergency Services Training Center for their generous support and use of their facility for the full-scale field experiments. The authors would also like to thank NIST for funding this work through the 2009 American Reinvestment and Recovery Act Grant.

Appendix A. Framing Details

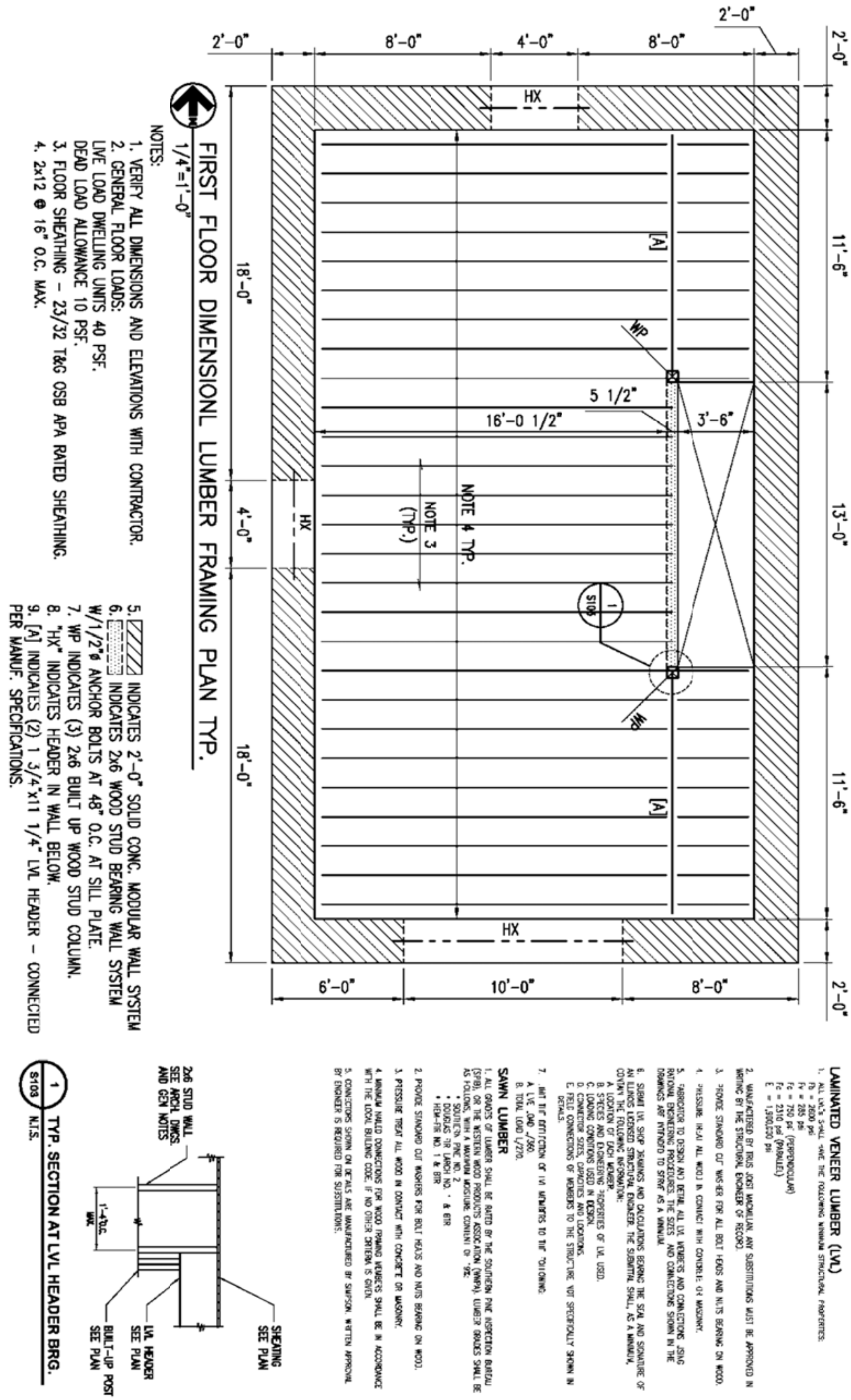


Figure 435. Dimensional Lumber Framing Detail

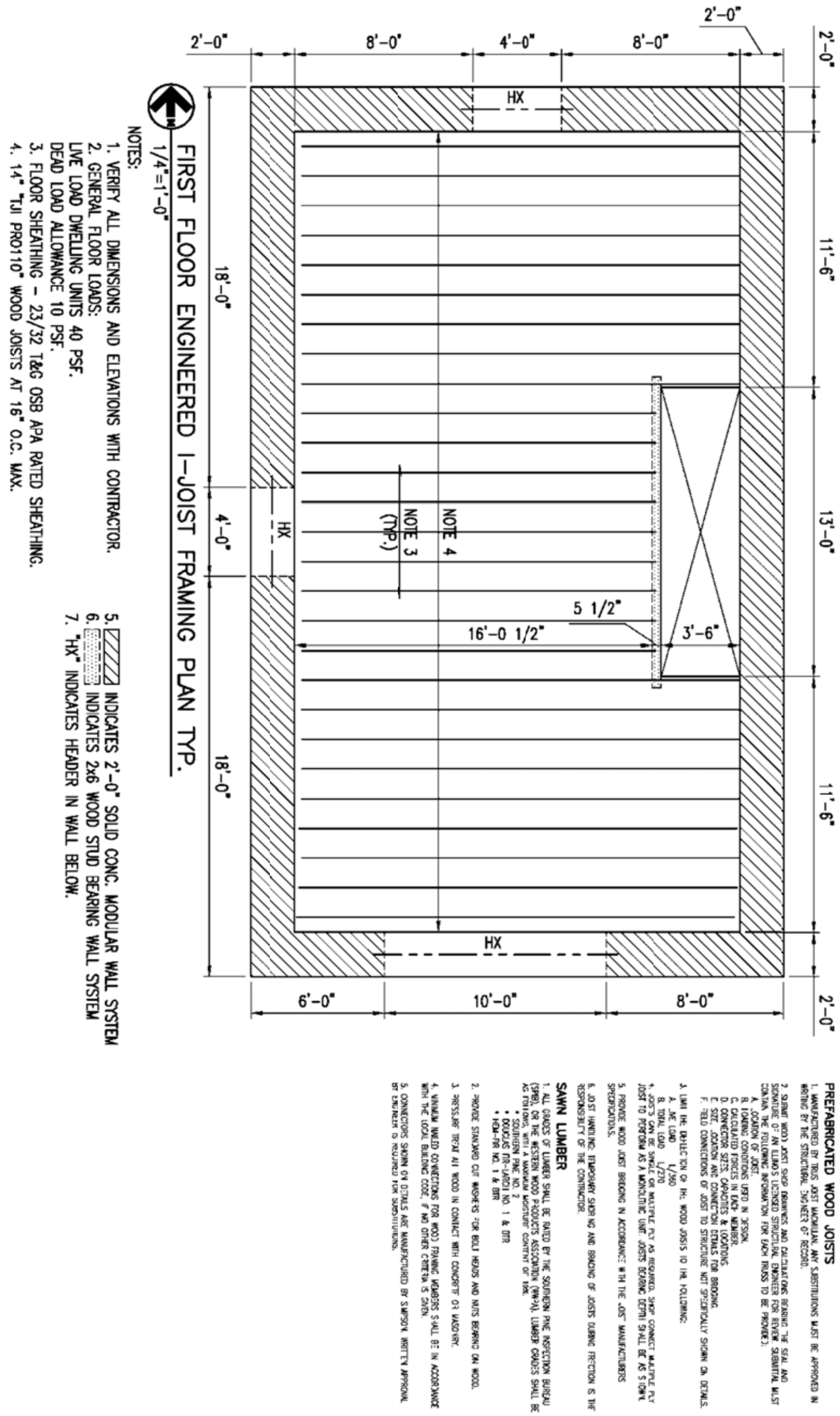


Figure 436. Engineered Wood I Joist Framing Detail

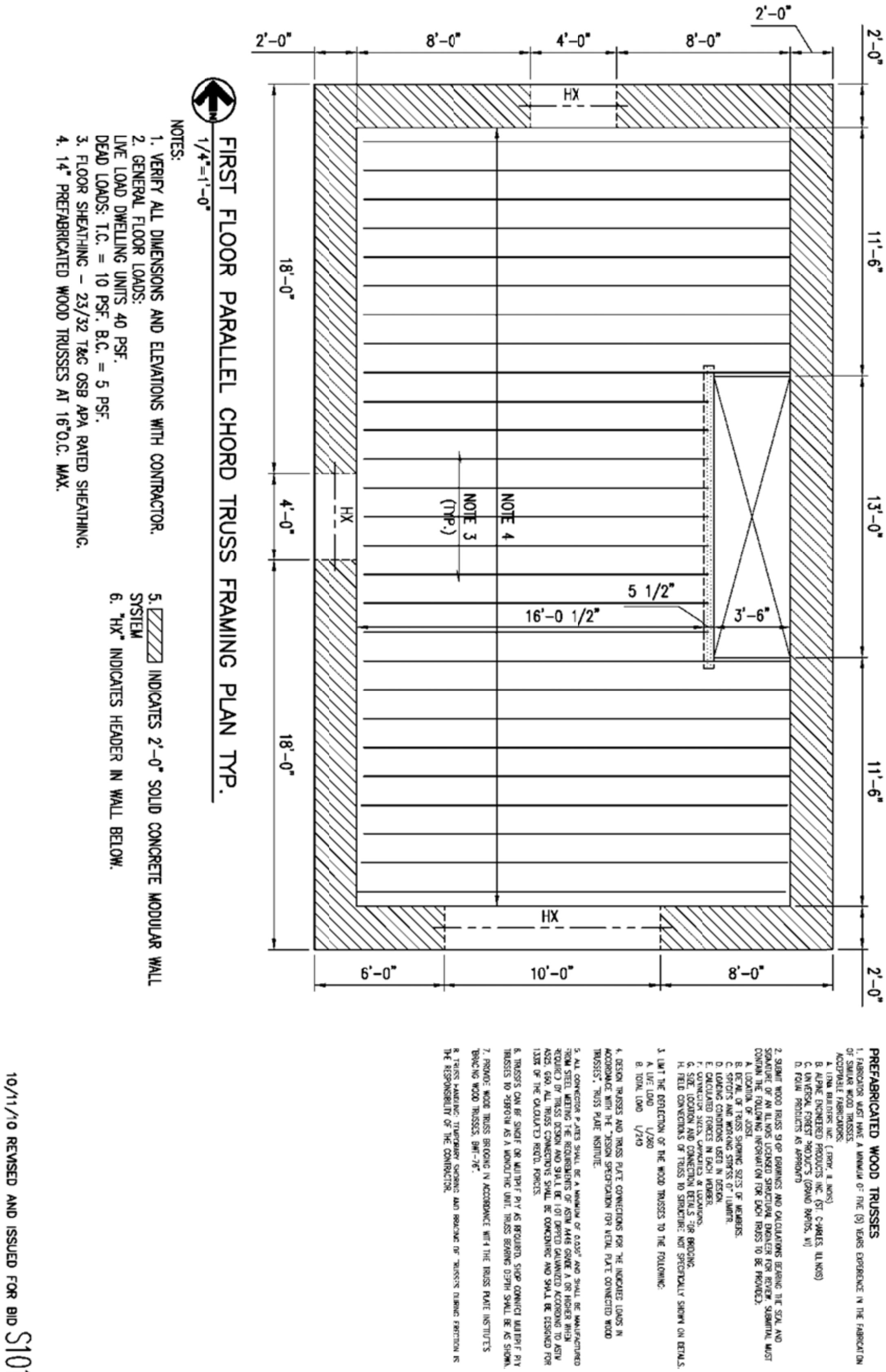


Figure 437. Parallel Chord Wood Truss Framing Detail

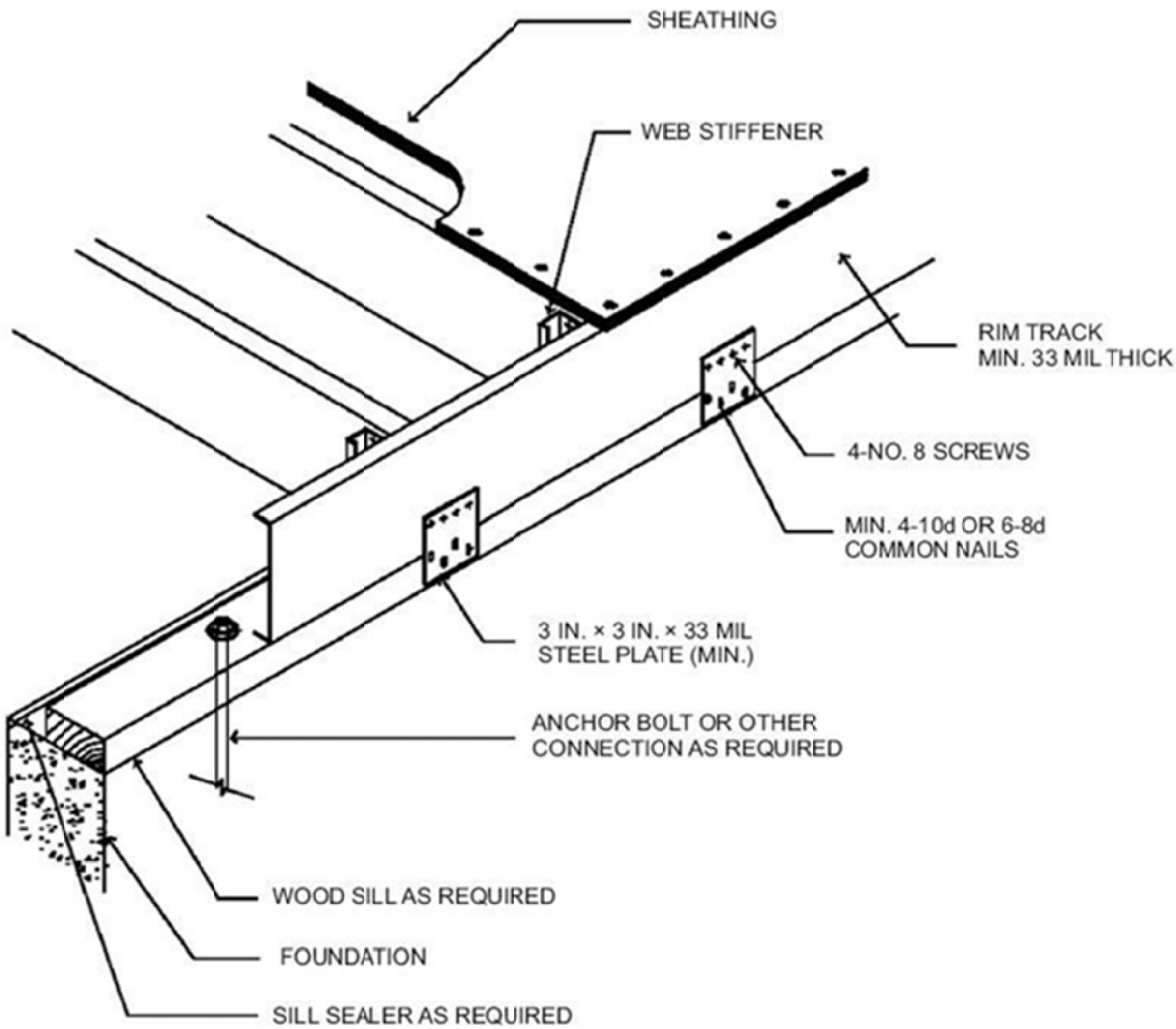


Figure 438. Steel C Joist Detail

Appendix B. Field Experiment Load Calculations

Experiment 1 and 2

Boise Cascade

Single 2 x 12 HF #2 | **Joist\16' span\2x12_Hem-fir**

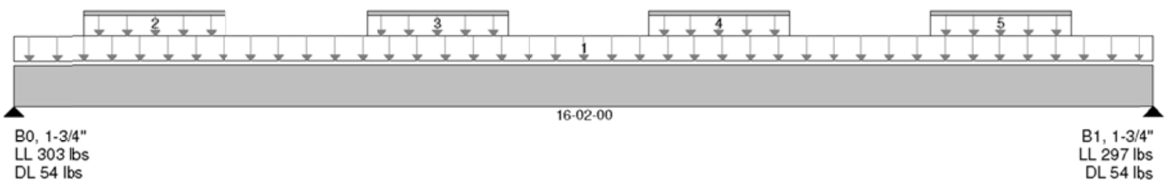
BC CALC® 3.0 Design Report - US
Build 440

1 span | No cantilevers | 0/12 slope
16 OCS | Non-Repetitive | Member construction

Wednesday, October 20, 2010

Job Name:
Address:
City, State, Zip: ,
Customer:
Code reports: WCLIB/WWPA

File Name: UL_Fire_Test_10-20-2010
Description: 16' span\2x12_Hem-fir
Specifier:
Designer:
Company:
Misc:



Total of Horizontal Design Spans = 16-02-00

Load Summary

Tag	Description	Load Type	Ref.	Start	End	Live 100%	Dead 90%	Snow 115%	Wind 133%	Roof Live 125%	OCS (in.)
1	Standard Load	Unf. Area (psf)	L	00-00-00	16-02-00	0	5				16
2	Barrel	Unf. Lin. (plf)	L	01-00-00	03-00-00	75	0				n/a
3	Barrel	Unf. Lin. (plf)	L	05-00-00	07-00-00	75	0				n/a
4	Barrel	Unf. Lin. (plf)	L	09-00-00	11-00-00	75	0				n/a
5	Barrel	Unf. Lin. (plf)	L	13-00-00	15-00-00	75	0				n/a

Controls Summary	Value	% Allowable	Duration	Case	Span
Pos. Moment	1,444 ft-lbs	64.4%	100%	1	1 - Internal
End Shear	349 lbs	20.7%	100%	1	1 - Left
Total Load Defl.	L/651 (0.298")	36.9%		1	1
Live Load Defl.	L/765 (0.254")	47.1%		1	1
Span / Depth	17.2	n/a			1

Notes

Design meets Code minimum (L/240) Total load deflection criteria.
Design meets Code minimum (L/360) Live load deflection criteria.
Minimum bearing length for B0 is 1-1/2".
Minimum bearing length for B1 is 1-1/2".
Entered/Displayed Horizontal Span Length(s) = Clear Span + 1/2 min. end bearing + 1/2 intermediate bearing

User Notes

WATER DEPTH IN BARRELS = 11"

Disclosure

Completeness and accuracy of input must be verified by anyone who would rely on output as evidence of suitability for particular application. Output here based on building code-accepted design properties and analysis methods. Installation of BOISE engineered wood products must be in accordance with current Installation Guide and applicable building codes. To obtain Installation Guide or ask questions, please call (800)232-0788 before installation.

BC CALC®, BC FRAMER®, AJS™, ALLJOIST®, BC RIM BOARD™, BCI®, BOISE GLULAM™, SIMPLE FRAMING SYSTEM®, VERSA-LAM®, VERSA-RIM PLUS®, VERSA-RIM®, VERSA-STRAND®, VERSA-STUD® are trademarks of Boise Cascade, L.L.C.

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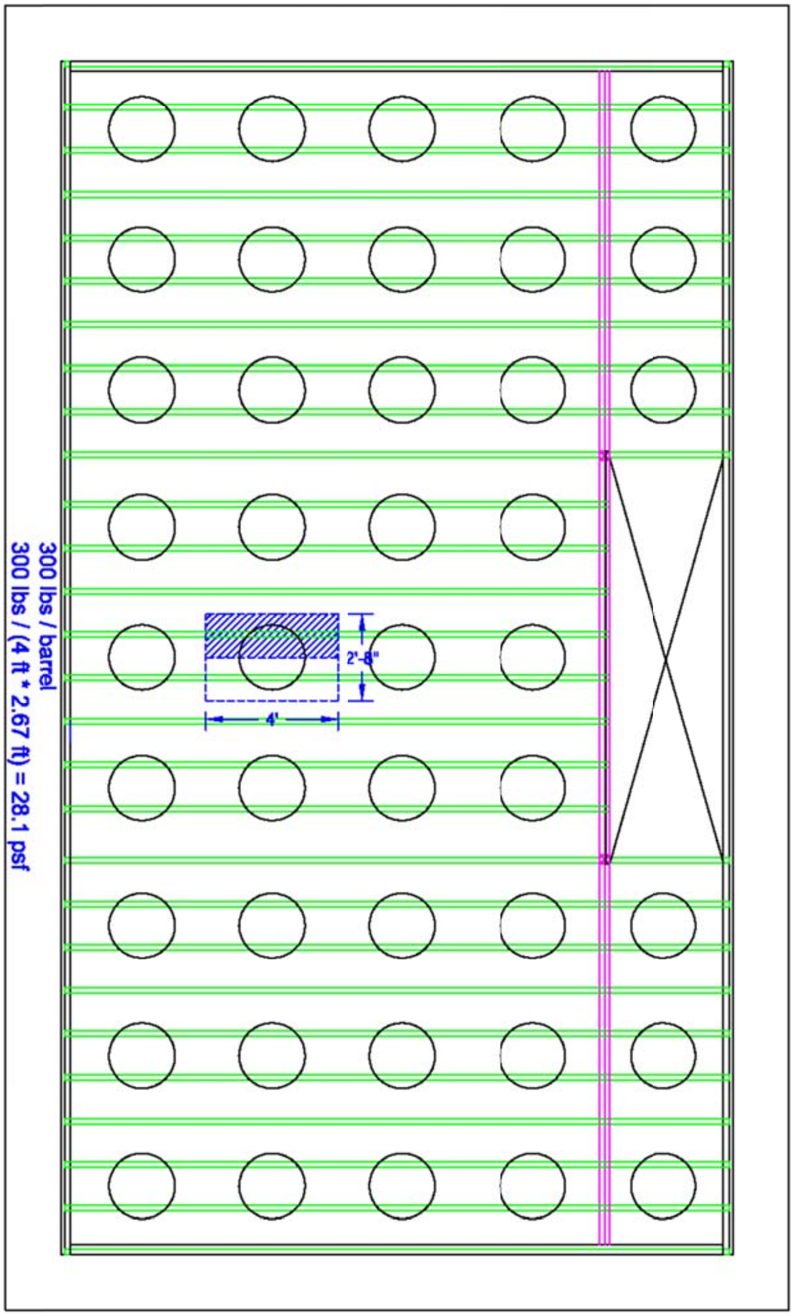


Constant - Span - Distributed Loading
2x12 Solid-Sawn = #2 HF KD @ 16" o.c.

Experiments 3, 4 and 5

Boise Cascade

Single 11-7/8" BCI® 60s-2.0 SP Joist\20' span\Deflection Control 20 ft.

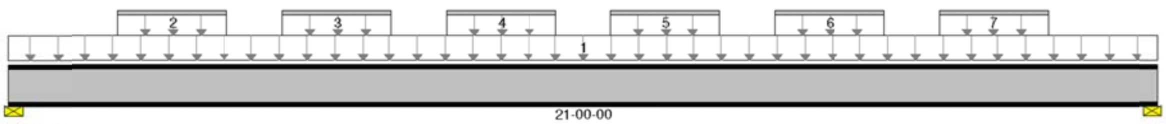
BC CALC® 3.0 Design Report - US
Build 440

1 span | No cantilevers | 0/12 slope
16 OCS | Non-Repetitive | Member construction

Wednesday, October 20, 2010

File Name: UL_Fire_Test_10-20-2010
Description: 20' span\Deflection Control 20 ft.
Specifier:
Designer:
Company:
Misc:

Job Name:
Address:
City, State, Zip: ,
Customer:
Code reports: ESR-1336



Lt. Brg., 4-3/8"
LL 432 lbs
DL 70 lbs

Rt. Brg., 4-3/8"
LL 432 lbs
DL 70 lbs

Total Horizontal Product Length = 21-00-00

Load Summary

Tag	Description	Load Type	Ref.	Start	End	Live 100%	Dead 90%	Snow 115%	Wind 133%	Roof Live 125%	OCS (in.)
1	Standard Load	Unf. Area (psf)	L	00-00-00	21-00-00	0	5				16
2	Barrel	Unf. Lin. (plf)	L	02-00-00	04-00-00	72	0				n/a
3	Barrel	Unf. Lin. (plf)	L	05-00-00	07-00-00	72	0				n/a
4	Barrel	Unf. Lin. (plf)	L	08-00-00	10-00-00	72	0				n/a
5	Barrel	Unf. Lin. (plf)	L	11-00-00	13-00-00	72	0				n/a
6	Barrel	Unf. Lin. (plf)	L	14-00-00	16-00-00	72	0				n/a
7	Barrel	Unf. Lin. (plf)	L	17-00-00	19-00-00	72	0				n/a

Controls Summary	Value	% Allowable	Duration	Case	Span
Pos. Moment	2,313 ft-lbs	45.1%	100%	1	1 - Internal
End Reaction	502 lbs	33.5%	100%	1	1 - Right
Total Load Defl.	L/482 (0.509")	49.8%		1	1
Live Load Defl.	L/550 (0.446")	65.5%		1	1
Span / Depth	20.6	n/a			1

Bearing Supports	Dim. (L x W)	Value	% Allow Support	% Allow Member	Material
Lt. Brg. Wall/Plate	4-3/8" x 2-5/16"	502 lbs	n/a	n/a	Unspecified
Rt. Brg. Wall/Plate	4-3/8" x 2-5/16"	502 lbs	n/a	n/a	Unspecified

Notes

Design meets Code minimum (L/240) Total load deflection criteria.
Design meets Code minimum (L/360) Live load deflection criteria.

Disclosure

Completeness and accuracy of input must be verified by anyone who would rely on output as evidence of suitability for particular application. Output here based on building code-accepted design properties and analysis methods. Installation of BOISE engineered wood products must be in accordance with current Installation Guide and applicable building codes. To obtain Installation Guide or ask questions, please call (800)232-0788 before installation.

BC CALC®, BC FRAMER®, AJS™, ALLJOIST®, BC RIM BOARD™, BCI®, BOISE GLULAM™, SIMPLE FRAMING SYSTEM®, VERSA-LAM®, VERSA-RIM PLUS®, VERSA-RIM®, VERSA-STRAND®, VERSA-STUD® are trademarks of Boise Cascade, L.L.C.

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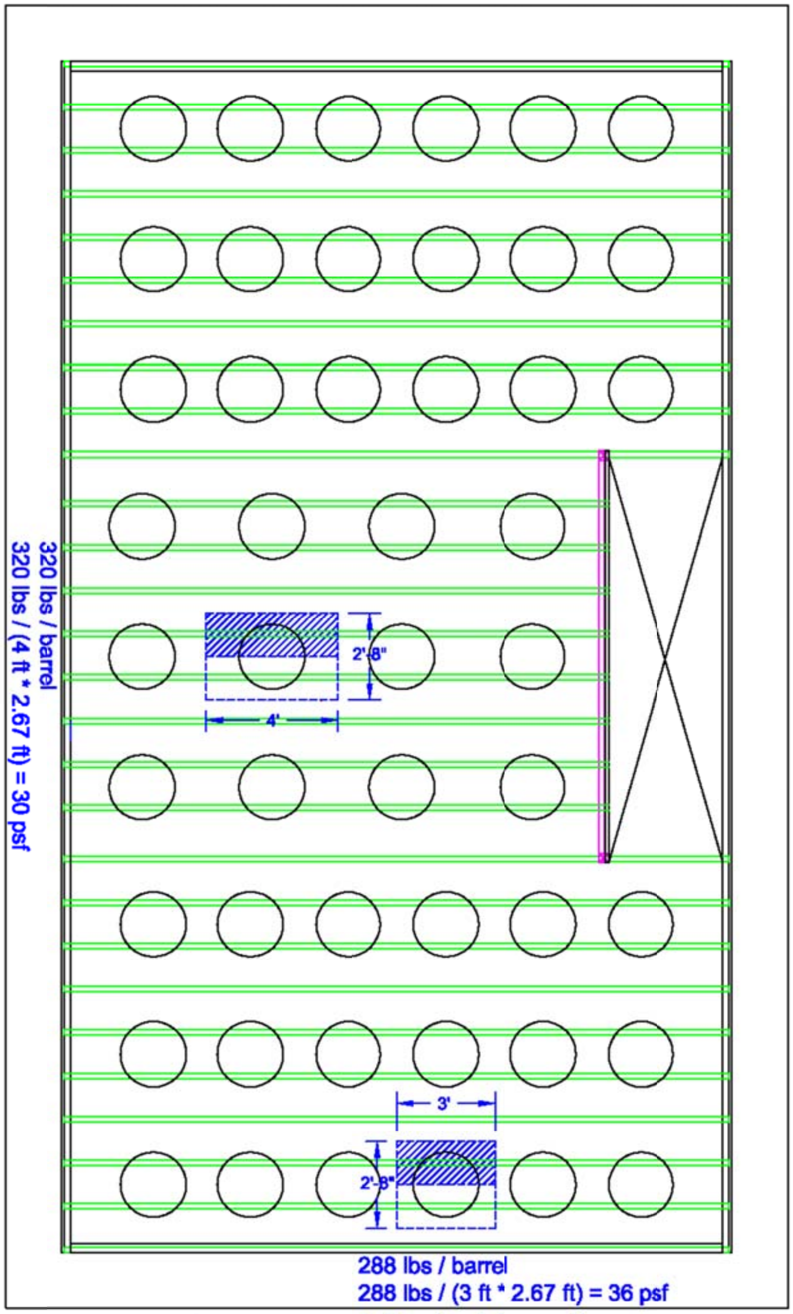


Multi-Span - Distributed Loading
I-Joist = 11-7/8 BCI 60s - 2.0 @ 16" o.c.

Experiment 6

Boise Cascade **Single 11-7/8" BCI® 60s-2.0 SP Joist\20' span\Uniform Load**

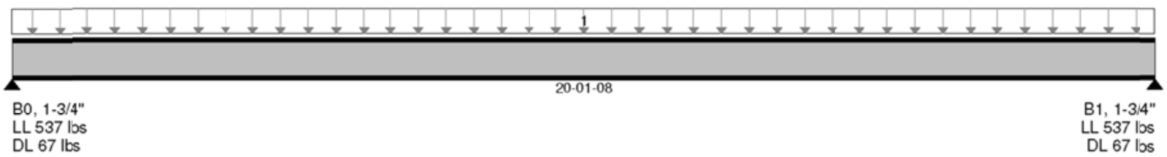
BC CALC® 3.0 Design Report - US
Build 440

1 span | No cantilevers | 0/12 slope
16 OCS | Non-Repetitive | Member construction

Saturday, October 23, 2010

Job Name:
Address:
City, State, Zip: ,
Customer:
Code reports: ESR-1336

File Name: 2010_10_19_UL_Fire_Test_10_15 (3).BCC
Description: 20' span\Uniform Load
Specifier:
Designer:
Company:
Misc:



Total of Horizontal Design Spans = 20-01-08

Load Summary

Tag	Description	Load Type	Ref.	Start	End	Live 100%	Dead 90%	Snow 115%	Wind 133%	Roof Live 125%	OCS (in.)
1	Standard Load	Unf. Area (psf)	L	00-00-00	20-01-08	40	5				16

Controls Summary	Value	% Allowable	Duration	Case	Span
Pos. Moment	3,038 ft-lbs	48.7%	100%	1	1 - Internal
End Reaction	604 lbs	49.3%	100%	1	1 - Right
Total Load Defl.	L/452 (0.534")	53.0%		1	1
Live Load Defl.	L/509 (0.474")	70.7%		1	1
Span / Depth	20.3	n/a			1

Notes

Design meets Code minimum (L/240) Total load deflection criteria.
Design meets Code minimum (L/360) Live load deflection criteria.
Entered/Displayed Horizontal Span Length(s) = Clear Span + 1/2 min. end bearing + 1/2 intermediate bearing

Disclosure

Completeness and accuracy of input must be verified by anyone who would rely on output as evidence of suitability for particular application. Output here based on building code-accepted design properties and analysis methods. Installation of BOISE engineered wood products must be in accordance with current Installation Guide and applicable building codes. To obtain Installation Guide or ask questions, please call (800)232-0788 before installation.

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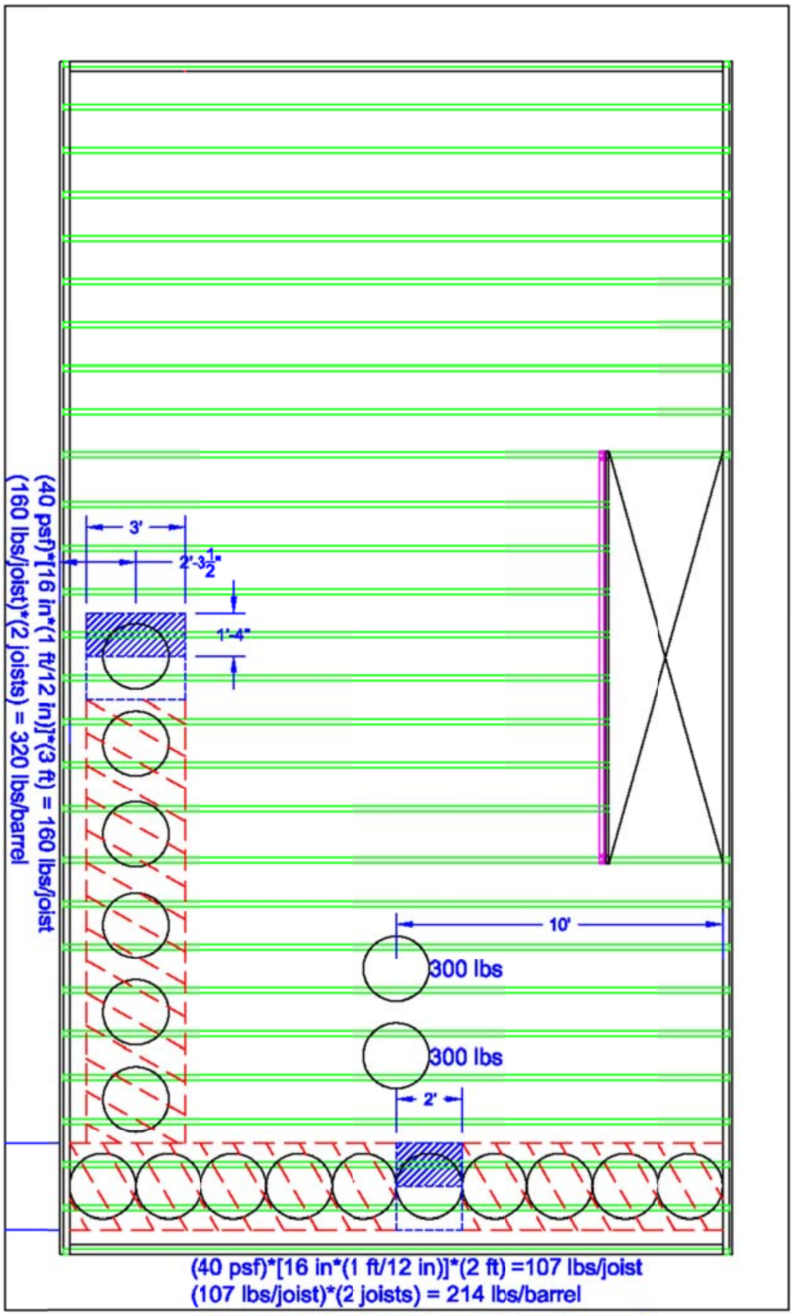

Multi-Span - Perimeter Line Loading
I-Joist = 11-7/8 BCI 60s - 2.0 @ 16" o.c.

Experiments 7 and 8

For the C-joist assembly as built, with 20'-8" span, and joist steel grade of 50 ksi

Nominal bending moment capacity (50 ksi steel grade) = 95,700 in-lb
Factor of safety for bending, Ω_b = 1.67
Allowable bending moment capacity (50 ksi steel grade) = 57,300 in-lb
Gross moment of inertia (used for effective moment of inertia) = 15.7 in^4

The Allowable (100%) Total Load (based on bending strength) = [(8) (57,300)] / [$(20.67)^2$ (16)]= 67.1 psf
The Allowable (100%) Life Load (based deflection limit of span/480) = [(0.16) (29,500,000) (15.7)] / [$(20.67)^3$ (12) (16)]= 43.7 psf

If you choose to use 65% of the combined strength and deflection limits for test loads:

*** 65% of the total allowable load (based on bending strength) = (0.65) 67.1 = 43.6 psf
*** applied test load based on the total allowable load (based on bending strength) = 43.6 – 5 = 38.6 psf
*** 65% of the allowable live load (based on deflection limit of span/480) = (0.65) x 43.7 = 28.4 psf
*** applied test load based on the allowable live load (based on the deflection limit of span/480) = 28.4 psf

*** applied test load based on the combined strength and deflection criteria above = 28.4 psf
*** percentage of the allowable bending strength = (28.4) / (67.1) = 42.3 %

*** To simulate the joist mid-span bending moment equivalent to the bending moment generated by 28.4 psf of uniformly distributed load, using 5 barrels (each resting on 2 joists; tributary area 4.13'x2.67' per barrel) spaced along the 20.67' span @ 4.13' o.c., the weight of one barrel should be = (0.125/0.130) (28.4) (4.13) (2.67) = 301 lbs

Experiments 9 and 10

Job	Truss	Truss Type	Qty	Ply	
TRIMEND	F01A	FLOOR	1	1	Job Reference (optional)

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ID:7Y1vQQeUnWTKDNiLKc8XldyPUxC-lJ8xxEF9F4x2SYX_rTdxFWtT0SPLnh?UpnH2OFyPFUj

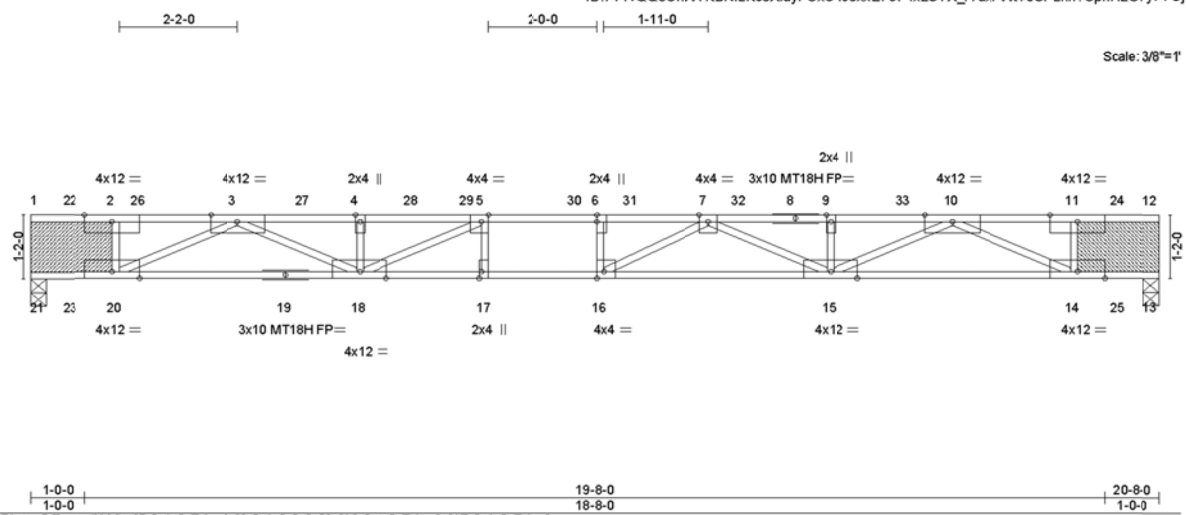

Plate Offsets (X,Y): [5:0-1-8,Edge], [6:0-1-8,0-0-0], [16:0-1-8,Edge], [17:0-1-8,Edge]

LOADING (psf)		SPACING	1-4-0	CSI		DEFL	in	(loc)	l/defl	L/d	PLATES	GRIP
TCLL	1.0	Plates Increase	1.00	TC	0.33	Vert(LL)	-0.45	15-16	>539	360	MT20	197/144
TCDL	2.0	Lumber Increase	1.00	BC	0.65	Vert(TL)	-0.50	15-16	>484	240	MT18H	197/144
BCLL	0.0	Rep Stress Incr	NO	WB	0.36	Horz(TL)	0.07	13	n/a	n/a		
BCDL	2.0	Code IRC2000/ANSI95		(Matrix)							Weight: 72 lb	

LUMBER
TOP CHORD 4 X 2 SPF 1650F 1.5E
BOT CHORD 4 X 2 SPF 1650F 1.5E
WEBS 4 X 2 SPF Stud
OTHERS 1-6-0 X 0-11-0 X 18' I-Joist

BRACING
TOP CHORD Sheathed. [P]
BOT CHORD Rigid ceiling directly applied or 10-0-0 oc bracing.

REACTIONS (lb/size) 21=500/0-3-8 (min. 0-1-8), 13=537/0-3-8 (min. 0-1-8)

FORCES (lb) - Max. Comp./Max. Ten. - All forces 250 (lb) or less except when shown.
TOP CHORD 2-22=-510/0, 2-26=-706/0, 3-26=-706/0, 3-27=-2260/0, 4-27=-2260/0, 4-28=-2260/0, 28-29=-2260/0, 5-29=-2260/0, 5-30=-2739/0, 6-30=-2739/0, 6-31=-2739/0, 7-31=-2739/0, 7-32=-2329/0, 8-32=-2329/0, 8-9=-2329/0, 9-33=-2329/0, 10-33=-2329/0, 10-11=-753/0, 11-24=-550/0
BOT CHORD 20-23=0/474, 19-20=0/1603, 18-19=0/1603, 17-18=0/2739, 16-17=0/2739, 15-16=0/2690, 14-15=0/1678, 14-25=0/514
WEBS 3-20=-990/0, 3-18=0/725, 5-18=-526/0, 10-14=-1021/0, 10-15=0/718, 7-15=-399/0

NOTES
1) The bottom chord dead load shown is sufficient only to cover the truss weight itself and does not allow for any additional load to be added to the bottom chord.
2) Dead loads shown include weight of truss. Top chord dead load of 5.0 psf (or less) is not adequate for a shingle roof. Architect to verify adequacy of top chord dead load.
3) All plates are MT20 plates unless otherwise indicated.
4) WARNING: Top chord live load is below 12.0psf. Architect and/or engineer of the overall structure to verify adequacy of top chord live load.
5) Load case(s) 1 has/have been modified. Building designer must review loads to verify that they are correct for the intended use of this truss.
6) This truss is manufactured with a prefabricated I-Joist trimmable end. I-Joist flange minimum Ft: 3x2=535psi, 4X2=383psi. The reaction limit for bearing size shown without a web stiffener must be greater than or equal to reactions shown.
7) Recommend 2x6 strongbacks, on edge, spaced at 10-0-0 oc and fastened to each truss with 3-10d (0.131" X 3") nails. Strongbacks to be attached to walls at their outer ends or restrained by other means.

LOAD CASE(S)
1) Floor: Lumber Increase=1.00, Plate Increase=1.00
Uniform Loads (plf)
Vert: 13-21=-3, 1-26=-4, 3-26=-79, 3-27=-4, 27-28=-79, 28-29=-4, 29-30=-79, 30-31=-4, 31-32=-79, 8-32=-4, 8-33=-79, 10-33=-4, 10-11=-79, 11-12=-4

Job	Truss	Truss Type	Qty	Ply	
TRIMEND	F01A	FLOOR	1	1	

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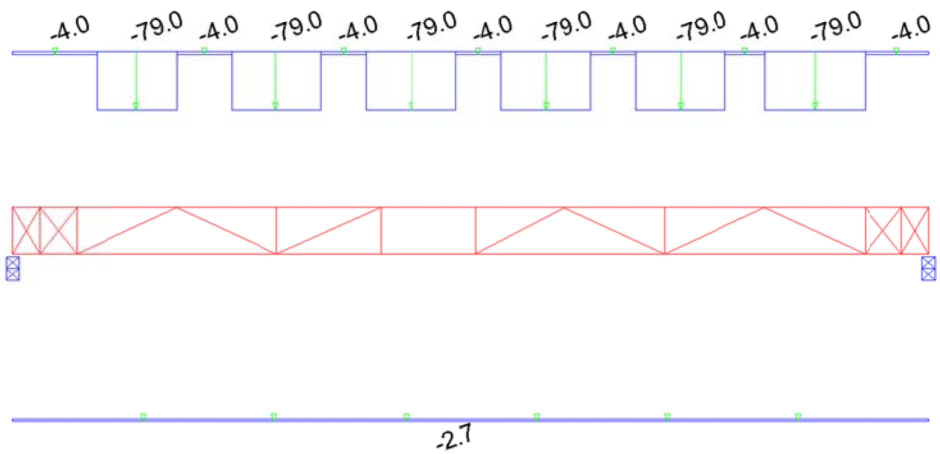
ID:7Y1vQQeUnWTKDNiLKc8XldyPUxC-bTes64yXbuFpPSy7FffYclHNNqCvMwM19pL6QuyPFTp

Load Diagram (plf)



LOAD CASE No 1 : (1) Floor

Appendix C. Lab Experiment Load Calculations

Job	Truss	Truss Type	Qty	Ply	UL Fire Test
UL FIRE TEST	F3*	FLOOR	16	1	Job Reference (optional)

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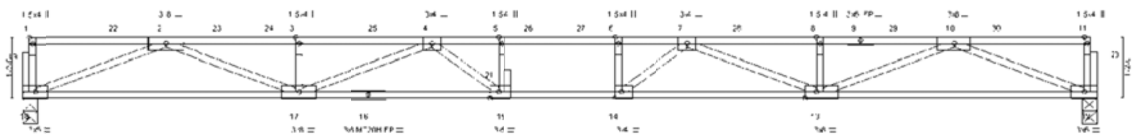
0-1-8

2-6-0 1-3-4 2-0-0 1-3-4 0-1-8



9-4-12 10-4-12 11-4-12 20-8-0

9-4-12 1-0-0 1-0-0 9-3-4

Plate Offsets (X,Y): [1:Edge,0-0-12], [13:0-3-0,Edge], [14:0-1-8,Edge], [15:0-2-0,Edge]

LOADING (psf)		SPACING	1-4-0	CSI		DEFL	in	(loc)	l/defl	L/d	PLATES	GRIP
TCLL	0.0	Plates Increase	0.90	TC	0.37	Vert(LL)	n/a	-	n/a	999	MT20	197/144
TCDL	5.0	Plt.Metal Increase	0.90	BC	0.44	Vert(TL)	-0.68	14-15	>362	240	MT20H	148/108
BCLL	0.0	Lumber Increase	0.90	WB	0.63	Horz(TL)	0.09	12	n/a	n/a		
BCDL	5.0	Rep Stress Incr	YES	(Matrix)							Weight: 77 lb	
		Code IBC2003/TPI2002										

LUMBER
TOP CHORD 4 X 2 SPF No.2
BOT CHORD 4 X 2 SPF 2100F 1.8E
WEBS 4 X 2 SPF Stud

BRACING
TOP CHORD Structural wood sheathing directly applied or 6-0-0 oc purlins, except end verticals.
BOT CHORD Rigid ceiling directly applied or 10-0-0 oc bracing.

REACTIONS (lb/size) 18=606/0-3-8 (min. 0-1-8), 12=618/0-3-8 (min. 0-1-8)

FORCES (lb) - Max. Comp./Max. Ten. - All forces 250 (lb) or less except when shown.
TOP CHORD 2-23=-2494/0, 23-24=-2494/0, 3-24=-2494/0, 3-25=-2494/0, 4-25=-2494/0, 4-5=-3240/0, 5-26=-3234/0, 26-27=-3234/0, 6-27=-3234/0, 6-7=-3234/0, 7-28=-2547/0, 8-28=-2547/0, 8-9=-2547/0, 9-29=-2547/0, 10-29=-2547/0
BOT CHORD 17-18=0/1455, 16-17=0/3067, 15-16=0/3067, 14-15=0/3234, 13-14=0/3088, 12-13=0/1489
WEBS 2-18=-1564/0, 2-17=0/1121, 4-17=-619/0, 10-12=-1601/0, 10-13=0/1142, 7-13=-584/0

NOTES
1) Dead loads shown include weight of truss. Top chord dead load of 5.0 psf (or less) is not adequate for a shingle roof. Architect to verify adequacy of top chord dead load.
2) As requested, plates have not been designed to provide for placement tolerances or rough handling and erection conditions. It is the responsibility of the fabricator to increase plate sizes to account for these factors.
3) All plates are MT20 plates unless otherwise indicated.
4) Attach ribbon block to truss with 3-10d nails applied to flat face.
5) WARNING: Top chord live load is below 16.0psf. Architect and/or engineer of the overall structure to verify adequacy of top chord live load.
6) This truss is designed in accordance with the 2003 International Building Code section 2306.1 and referenced standard ANSI/TPI 1.
7) Recommend 2x6 strongbacks, on edge, spaced at 10-0-0 oc and fastened to each truss with 3-10d (0.131" X 3") nails. Strongbacks to be attached to walls at their outer ends or restrained by other means.
8) In the LOAD CASE(S) section, loads applied to the face of the truss are noted as front (F) or back (B).

LOAD CASE(S) Standard
1) Floor: Lumber Increase=0.90, Plate Increase=0.90 Plt. metal=0.90
Uniform Loads (plf)
Vert: 12-18=-7, 1-22=-7, 22-23=-85(F=-78), 23-24=-7, 24-25=-85(F=-78), 4-25=-7, 4-26=-85(F=-78), 26-27=-7, 7-27=-85(F=-78), 7-28=-7, 9-28=-85(F=-78), 9-29=-7, 29-30=-85(F=-78), 11-30=-7

Job	Truss	Truss Type	Qty	Ply	Ul Fire Test
UL FIRE TEST	F01	FLOOR	16	1	

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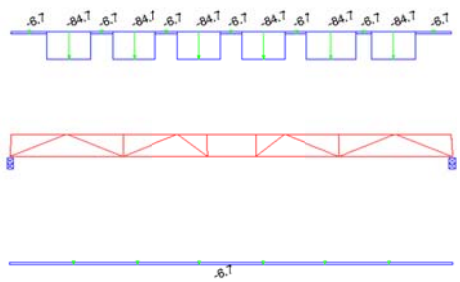
Load Diagram (plf)



LOAD CASE No 1 : (1) Floor