STRUCTURAL COLLAPSE RESEARCH AT NIST

D. W. Stroup and N. P. Bryner
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD, USA 20899-8661

ABSTRACT

Approximately 20 % of the fire fighters killed at structure fires over the past ten years (not counting the World Trade Center towers) have been as a result of structural collapse. Predicting a potential structural collapse is one of the most challenging tasks facing an incident commander at a fire scene. Usually, the lack of information on the building construction, fire size, fire location, fire burn time, building condition, fuel load, and other factors makes the task nearly impossible. Over the last several years, the National Institute of Standards and Technology (NIST) with funding from the United States Fire Administration (USFA) has been examining potential tools and techniques for predicting structural collapse. During the course of this research project, the effects of thermal exposure and weight loading on various building construction types and materials have been studied. In addition, data on firefighter fatalities due to structural collapse were analyzed. The use of thermal imaging equipment, already in the hands of the fire services, to gather temperature data from roof surfaces and use of that data to provide warning of impending localized structural collapse was an initial focus of the work. The research results showed that there were many ways in which normal fire and fire fighting activities, such as hot fire plumes and water spray, could change surface temperatures significantly and reduce the usefulness of that measurement as a means of determining the safety of structures. Other techniques that have been studied during the course of this project include laser range finding, motion sensing, and acoustic monitoring. Acceleration data obtained from buildings have shown the best potential for providing information concerning building stability and collapse. These data have lead to the development of a prototype for monitoring the health of buildings. Additional research is underway to continue development of the building monitoring system and examine specific construction types and scenarios of concern to fire fighters.

INTRODUCTION

Every year in the United States, approximately 100 fire fighters die in the line of duty and 90,000 to 100,000 are injured[1]. In 1999, the United States Fire Administration estimated that slightly more than 30 % of the fire fighter fatalities occurring on the fire ground resulted from something other than stress and heart attacks[2]. Stress and heart attacks, accounting for almost half of the fire fighter fatalities, remain the leading cause of death. As part of this project, data on firefighter fatalities due to structural collapse (not including those firefighters lost in the 2001 collapse of the World Trade Center) were analyzed using various factors. Among the trends discovered in the data was that the number of fire fighters lost annually in residential collapses has tripled since the 1980’s even though there has been a decrease in the average number of annual fatalities during the same time period[3].

In early 2000, the National Institute of Standards and Technology (NIST) with funding from the United States Fire Administration (USFA) started to examine potential tools and techniques for predicting structural collapse. Predicting a potential structural collapse is one of the most challenging tasks facing an incident commander at a fire scene. Usually, the lack of information on the construction of the building, fire size, fire location, fire burn time, condition of the building, fuel load, and other factors makes it nearly impossible.

During the course of this project, the effects of thermal exposure and weight loading on various building construction types and materials has been studied. In addition, new measurement technologies, such as infrared cameras, lasers, sonar, and ultrasonics, have been investigated for use in the fire environment. Some of these technologies, such as infrared, are currently being used on the fire ground. Initiated prior to the events of September 11, 2001, this project has been focused primarily on residential and light weight commercial construction. The potential collapse of high rise buildings and other mega-structures is being studied separately as part of the NIST research program instituted following the investigation into the collapse of the World Trade Center[4].

EXPERIMENTS – RESIDENTIAL CONSTRUCTION

Wood Frame, Two Room Structures

Four wood frame residential-like structures with different roof constructions were used in a series of fire tests conducted in cooperation with the Phoenix, AZ Fire Department. The roof construction was the primary difference between each structure. The roofing material and underlayment for each building were: asphalt shingles and plywood, asphalt shingles and oriented strand board, cement tiles and plywood, or cement tiles and oriented strand board. Each structure contained an attic space, a furnished living room, and a furnished bedroom. Figure 1 shows the approximate arrangement of furniture and Figure 2 shows the location of instrumentation and dimensions.

Multiple fires were initiated in each structure to facilitate collapse. The fires were allowed to burn until the portion of the roof supporting two firefighter mannequins failed. Temperatures were measured at various locations in the structures. Peak temperatures obtained during the tests ranged from approximately 800 °C to 1000 °C. The roof of each structure collapsed approximately 17 min ±2 min after ignition of the fires[5]. One test structure is shown shortly after ignition in Figure 3 and approximately 16 minutes after ignition in Figure 4.

Figure 1. Plan view of structure showing approximate location of furniture

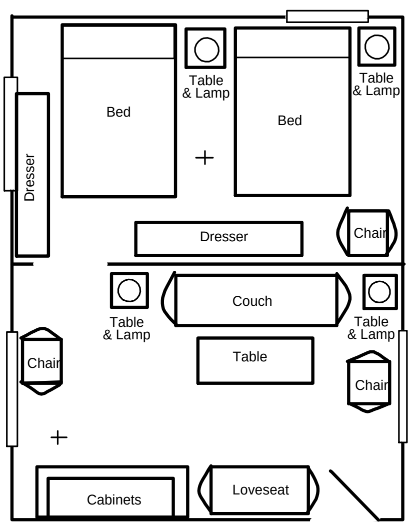
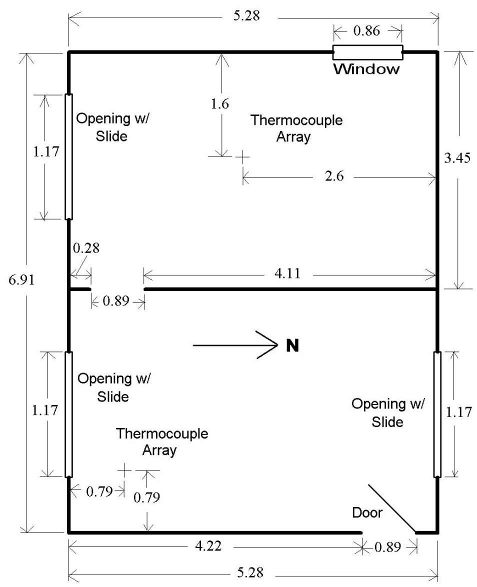


Figure 2. Plan view with instrumentation and dimensions in meters



Ranch Style Houses

Ranch style homes with traditional frame roof construction were used in a series of experiments conducted in Kinston, NC. These structures were existing homes purchased by the US Government as part of a flood relocation program. The US Bureau of Alcohol, Tobacco, and Firearms (ATF) provided technical staff and instrumentation to assist with the experiments. ATF uses buildings of opportunity for fire investigation research and training for agents in the Certified Fire Investigator Program. Using advanced laser range finding technology, the movement of the roof and other parts of the structure were measured during the fire.

Figure 3. Photograph of test structure shortly after ignition

Figure 4. Photograph of test structure 16 minutes after ignition

In one of the tests, a heating oil tank filled with water was placed on the roof for an additional load of approximately 270 kg (Figure 5). The objective was to force collapse of the roof under the tank and the supporting roof structure prior to collapse of the entire roof. The fire in the structure was ignited using 11.3 l of gasoline that produced a large explosion in the front living room of the house. The structure burned for approximately 20 minutes before the tank collapsed through the roof. Wood roof support members were retrieved from this test for further examination. Analysis of these members could provide useful information about the load carrying capacity of burning wood supports. Temperature histories were recorded close to these wood supports to document the history of the high temperature exposure.

Figure 5. Photograph of burning structure showing water filled tank on roof

Figure 6. Photograph showing placement of micro-accelerometers

Another potential method for predicting structural collapse used devices attached to the building to "listen" for signs of failure. As part of this test series, micro-accelerometers were attached to the brick facing on one of the houses (Figure 6). These sensitive instruments measured the vibrations of the exterior wall caused by the pulsating flames from the furniture fire within the structure. Vibration measurements of the house taken during the test indicated that warning signs of collapse could be detected about three minutes before the tank fell through the partially burned roof.

EXPERIMENTS - LIGHT COMMERCIAL CONSTRUCTION

Ordinary Construction Warehouse

Another series of experiments was conducted in Phoenix, AZ using a 46 m long by 15 m wide, brick and block warehouse structure with a "traditional" wood frame roof assembly. This set of two experiments included measurement of temperatures and carbon monoxide inside the structure. Infrared cameras were used on the outside of the building to evaluate their usefulness in structural collapse prediction by incident commanders. In addition, vibration sensors were attached to the structure to monitor for changes that would indicate that structural collapse was imminent.

A firewall was constructed to divide the warehouse into two fire compartments (Figure 7 and 8). Stacks of wood pallets were used as the primary fuel source and were ignited using paper and an electric match. Some combustible debris and the building structural elements provided the remainder of the fuel load. Each portion of the structure was allowed to burn until the roof was completely destroyed (Figure 9). The roof of the front half of the structure burned through approximately 18 minutes after ignition while the roof of the back half began burning about 15 minutes after the start of the second test.

Figure 7. Drawing of warehouse layout showing separation for the two tests (dimensions in m)

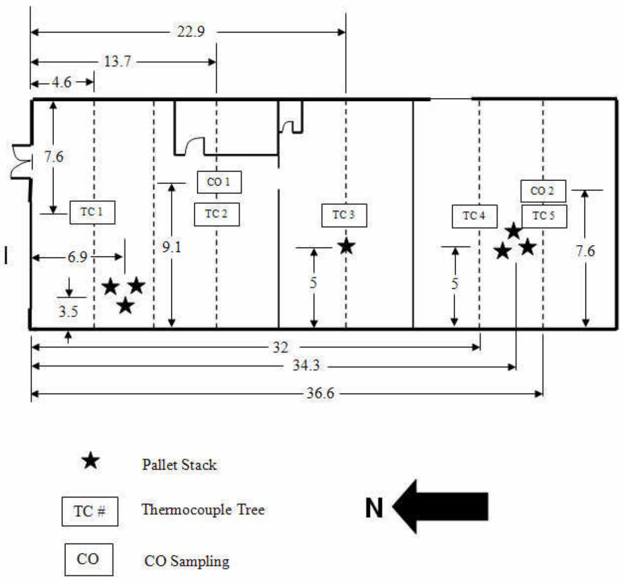
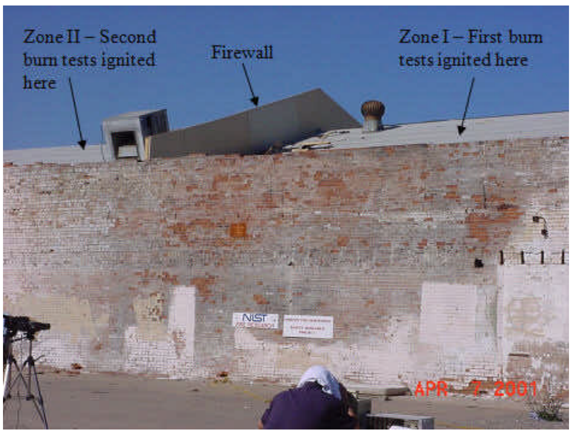


Figure 8. Photograph of warehouse showing firewall separating two fire test areas

Figure 9. Photograph showing fire and smoke coming from the roof during the first test



Lightweight Steel Frame Shopping Mall

An abandoned shopping mall, built in the 1980's and located in Woodbridge, Virginia, was used for a test series examining lightweight steel construction (Figure 10). The shopping mall consisted of several stores constructed with steel studs and gypsum board partition walls (Figure 11). The roof system consisted of a metal deck supported by lightweight open-web steel trusses, a rigid insulation (foam core) covered with a single-ply membrane and topped with gravel. The lightweight open-web steel trusses were of the type widely used in floor and roof systems for commercial and institutional buildings (Figure 12). Thermocouples were placed at appropriate locations with the building to measure temperatures in the stores and in the vicinity of the steel trusses.

Figure 10. Photograph of shopping mall

Figure 11. Shopping mall floor plan showing distribution and size of stores

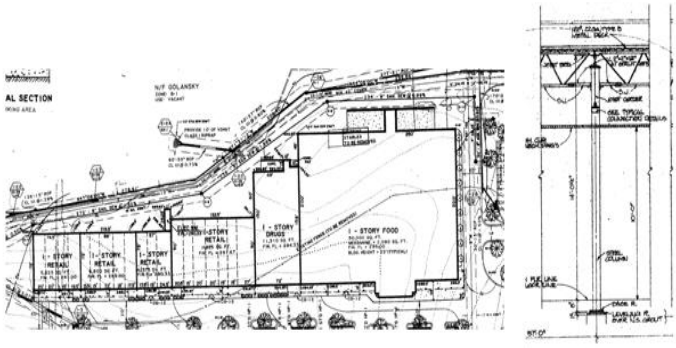


Figure 12. Photograph showing open-web steel trusses supporting roof structure

Figure 13. Photograph showing wood pallet fuel source inside store

A similar collapse scenario to that used during the wood frame residential structure tests was used in the mall tests. Three stores were selected for the three tests to be conducted in the mall. In order to facilitate collapse, the roofs of the three stores were loaded with 200 l barrels filled with water. The first and second test stores each had 4 barrels placed on their respective roofs. When collapse did not occur during either the first or second test, the number of barrels on the roof of the third store was increased to 12. For each test, the fire was remotely ignited at the bottom of a stack of wooden pallets (Figure 13).

Roof collapse occurred within 7 minutes of the start of the third test. Figure 14 shows a photograph of the interior of the store with the pallets fully involved in fire. The store is show in Figure 15 just prior to the onset of collapse and in Figure 16 at the point of complete collapse of the roof and ceiling structure. The damaged steel trusses are shown in Figure 17.

Figure 14. Photograph showing interior of store with burning pallets

Figure 15. Photograph showing complete collapse of the roof

Figure 16. Photograph showing onset of collapse

Figure 17. Photograph showing damage to steel trusses after collapse

DISCUSSION

Residential Structures

In all of the 2-room residential structure tests, some temperatures in the living room reached flashover temperatures (approximately 600 °C) in at least some portion of the room within 180 s after ignition (Figure 18). With the exception of the third test, the living room temperatures remained at or above 600 °C until roof collapse. Temperatures in excess of 600 °C were seldom sustained in the bedroom until after apparent ignition of combustibles in the attic area. Combustible materials in the attic space appeared to ignite 400 s to 450 s after ignition during each test. With the exception of the first test, roof collapse appears to be preceded by flashover in the attic space. Each of the roofs collapsed between 17 min and 17 ½ min. No significant differences were observed in the fire performance of any of the roof constructions.

Even though the noncombustible tile was removed from beneath the fire fighter mannequins' boots, no temperature changes were measured under the boots until collapse of the roof during the third and fourth tests (Figure 19). The increased temperatures obtained during the first and second tests could be the result of burning of portions of the combustible roof structure remote from the mannequin locations. The temperature of the roof surface under the fire fighter mannequins' boots did not increase significantly prior to collapse. Temperature measurements obtained under fire fighter boots would probably not be a useful indicator of potential collapse. Unfortunately, the fire fighter mannequins did not move. Therefore, the influence of impact or dynamic loading from walking on the roof could not be evaluated. Impact loads on these roof structures could result in significantly less time to collapse.

Figure 18. Graph showing temperatures measured in the living room

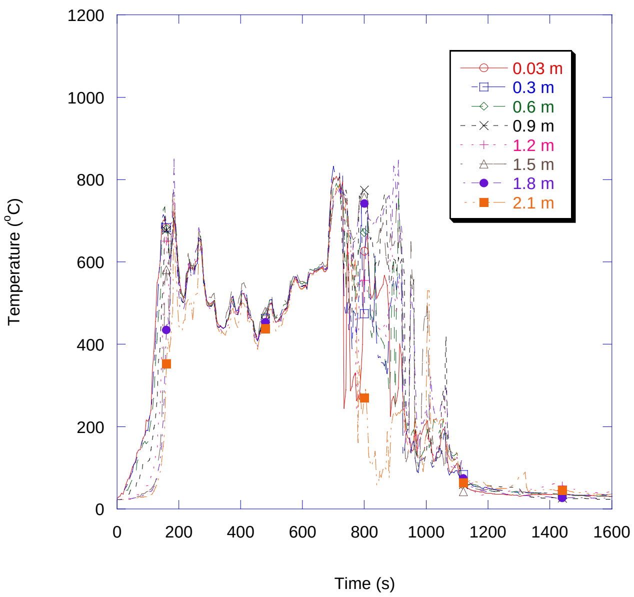
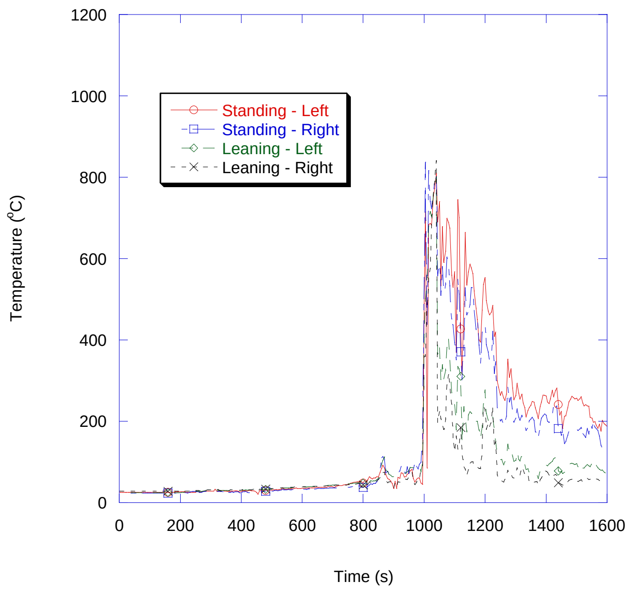
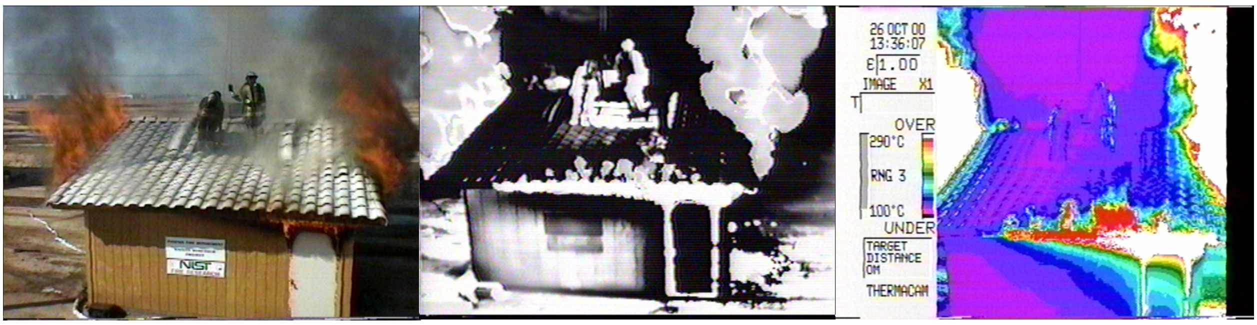


Figure 19. Graph showing temperatures measured under firefighter boots



During each fire test, two infrared cameras and one standard video camera were used to record similar views. One infrared camera was typical of what fire fighters might employ and utilized a focal plane array technology. This camera was capable of detecting infrared radiation in the 8 µm to 14 µm range. The other infrared camera was used for research applications, operated using focal plane array technology and detected radiation in the waveband 3.4 µm to 5 µm. The scene shown in Figure 20 is approximately 10 s prior to collapse of the roof structure. The left-side image is from the standard video camera, the middle image is from the fire fighter infrared camera, and the right-side image is from the research application infrared camera.

Figure 20. Test structure shown approximately 10 s before collapse of the roof (left – normal video, middle – fire department thermal imager, right – high end, radiometric IR camera)

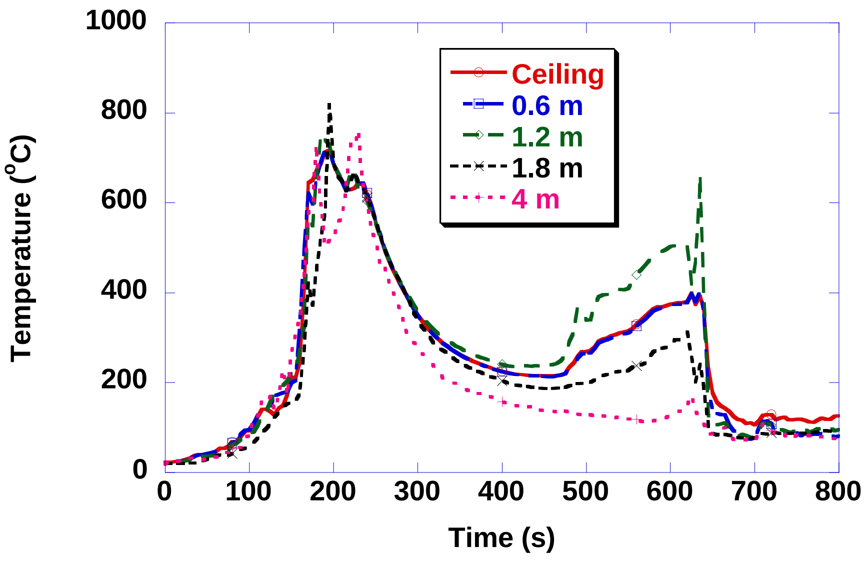


During these tests, the standard video camera documented that the roof began to sag or drop slightly just before failing completely. The time between the first appearance of a noticeable depression on the roof and the complete collapse of the roof appeared too short to allow any personnel on the roof to escape safely. The thermal images provided by the infrared cameras were also examined for evidence of an imminent collapse. The thermal images did not provide any warning of the roof collapse. The thermal radiation from the smoke plumes on both ends of the roof was radiated back to the surface of the roof. This re-radiated energy appeared to wash out any thermal signature of the energy being conducted through the roof. Another factor which could make it difficult to see via thermal imager the energy being conducted through the roof would be the presence of water on the shingles or tiles. The presence of hot smoke plumes or water from suppression activity or rain make it very difficult to see the thermal signature of the fire through the roof. For this limited set of burn experiments, the thermal imagers did not appear to provide sufficient warning to allow fire fighters to escape before the roof collapsed. Typically, roof collapse would be indicative of failure of the trusses supporting the roof while burn through of the sheathing mater (plywood or oriented strand board) would produced localized holes in the roof.

Commercial Structures

Two fire tests were conducted in the warehouse shown in Figure 7. The warehouse, constructed of masonry walls with wood trusses and a wood roof, was a single story approximately 5.8 m high. Temperature data from thermocouples located 4.6 m from the front door are shown in Figure 21 (locations are relative to ceiling so a 0.6 m thermocouple was located 0.6 m from the ceiling). The temperature history indicates a relatively well-mixed flashover environment. Approximately 200 s into the test, the fire became oxygen limited. Opening the front door at about 480 s produced the second set of peaks. The lower temperatures at the ceiling and 0.6 m positions indicate the possibility of roof failure in this location allowing cold air to flow into the building. The sudden decrease of temperature histories after approximately 650 s indicates additional significant roof collapse in the area of this thermocouple tree. The volume fractions of carbon monoxide and temperature obtained at two locations above the floor and 15 m from the front door are shown in Figure 22. The temperatures and gas concentrations are consistent with the fire being oxygen limited by the 300 s point. The volume fractions decrease and the temperatures increase after the door is opened.

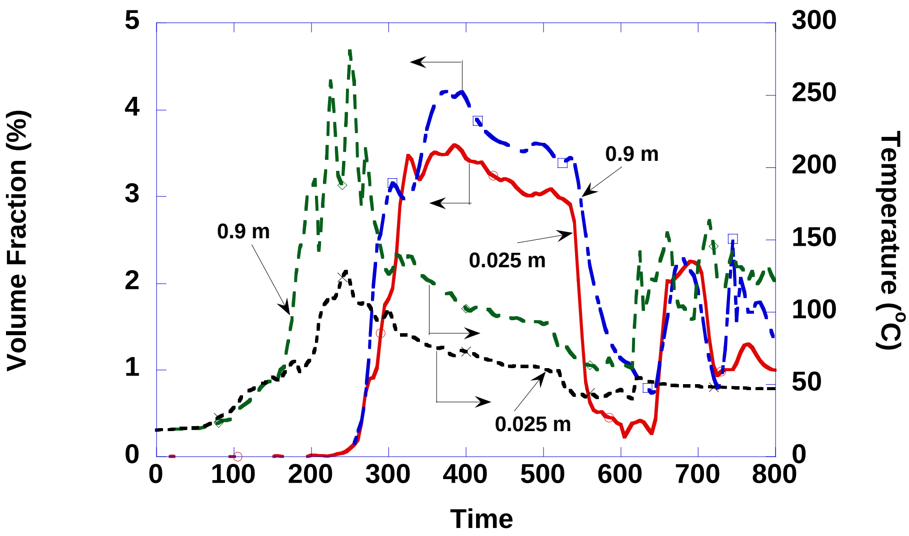
Figure 21. Graph showing temperatures approximately 4.6 m inside front door during first test



For both tests, the maximum temperatures in the area prior to collapse were 800 °C. Gas temperatures in the second test remained between about 600 °C and 800 °C throughout the test. The carbon monoxide volume fractions in the first test exceeded 3 % approximately 5 min after ignition. In the second test, the carbon monoxide volume fraction exceeded 5 % approximately 7 min after ignition. The volume fractions at the 25 mm and 0.9 m locations varied from 0.1 % to a 0.5 %. Variation was greater in the first test than in the second test.

Within about 5 min after ignition, the carbon monoxide levels in both tests rapidly increased to lethal levels. Very similar carbon monoxide volume fractions were measured at the 25 mm and 0.9 m locations during both tests. The temperature measurements at the two locations were not as similar. The temperatures obtained at the two locations during the first test varied from 50 °C to as much as 150 °C. During the second test, the temperature variation between the two locations was as high as 250 °C. Flashover as indicated by gas temperatures in excess of 600 °C is reached during both tests about 4 min after ignition. After flashover, temperatures during the first test decrease but remain about approximately 200 °C throughout the test. Temperatures remain above 400 °C at head height through the second test. In addition to the technical report[6], a DVD containing several NIST structural collapse research reports and video clips of some of the fire experiments is available from the authors[7].

Figure 22. Graph showing carbon monoxide volume fractions and temperatures 15 m from front during first test



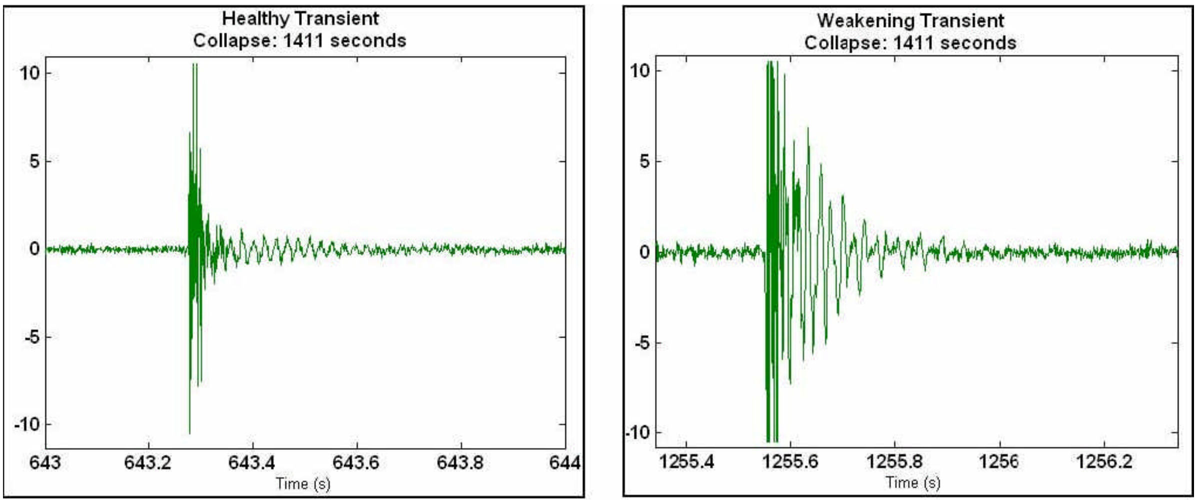
Some indication of potential collapse became evident during the tests. Some of these signs have been documented previously in building construction and collapse related textbooks written specifically for the fire service. For example, one text describes signs of potential wall collapse that can be seen in the bricks and mortar of the exterior walls[8]. Early during the first test smoke and then flames were observed coming from a roof top ventilator. As the fire progressed, the ventilator collapsed, the flames disappeared and only smoke could be seen coming from the ventilator (Figure 23).

Figure 23. Photographs of roof top ventilator before and after collapse of the ventilator due to heat exposure

Vibration Monitoring for Building Collapse

Vibration sensing data obtained during several of these test series have provided the foundation for development of a system to monitor the structural health of a building. Under grants funded by the Building and Fire Research Laboratory, researchers at Harvey Mudd College have demonstrated that dynamic fire loads induce significant responses in burning structures[9]. During various burn tests, it was determined that the transient response of the structures changed as they lost stability over time. In Figure 24, the decay of a transient event from the initial stages of a burn is compared to the longer decay time of an event near collapse. This response suggests that ability of the structure to damp out vibrations decreases toward collapse.

Figure 24. Examples of a healthy and weak transient response from the beginning and end of a burn



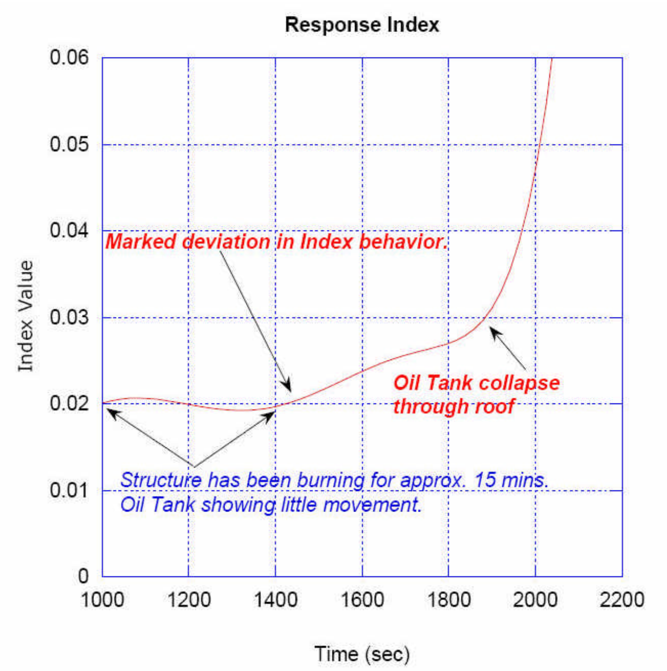
Attempts to track the change in damping of a structure over time have proven inconclusive. Currently, the effort is focused on monitoring the health of a burning structure by tracking the natural frequencies of the structure as they change over the life of a fire. A downward shift in the natural frequencies corresponds to a loss in strength. Additionally, the rate of change of this loss in strength shows potential as a key indication of pending collapse. Previously, it was assumed that a structure had a single dominant frequency that could be tracked through the life of the fire. However, due to the complex modal response of real structures, changes in loading, and shifts in power distribution over the modes that were observed during experiments, new methods were developed to track the progression of multiple modes simultaneously[10].

The Health of Burning Structures (HOBS) monitoring system, developed at Harvey Mudd College, provides a tool for acquiring and analyzing fire-induced vibration measurements obtained in the field. This vibration based health monitoring was demonstrated in tests conducted on a single-family wood frame structure in Kinston, NC. In those tests, a heating oil tank was mounted on the roof of the structure in an effort to induce roof collapse. Those tests demonstrated that fire was capable of exciting dynamic structural vibration responses providing real-time indication of impending collapse. The measured response was acquired on the exterior wall and captures ignition, steady burn and collapse of the tank through the roof. The measured behavior was analyzed after the test, and a response index (Figure 25) based on response variance was developed.

SUMMARY

Several full scale fire tests have been conducted to develop data for evaluating different tools and techniques for predicting structural collapse. Two different generic categories of structures were utilized: single story residential and single story light commercial. Temperatures were measured in each structure during the tests. In addition, the volume fraction of carbon monoxide was monitored during two warehouse tests. Roofs supported by wood trusses collapsed approximately 15 to 20 minutes after ignition. Steel bar joist supported roofs collapsed 10 to 20 minutes after ignition. Various devices were utilized as part of these tests to examine their potential for use to predict structural collapse.

Figure 25. Collapse index behavior for a burning wood frame structure



To date, this research has examined the use of thermal imaging equipment, already in the hands of the fire services, to gather temperature data from roof surfaces and use of that data to provide warning of impending localized structural collapse. That work showed that there were many ways in which normal fire and fire fighting activities, such as hot fire plumes and water spray, could change surface temperatures significantly and reduce the usefulness of that measurement as a means of determining the safety of structures. An attempt to use laser based motion detection was also unsuccessful. Very little or no motion of the roof could be measured during the test burns. There were many technical difficulties associated with obtaining reliable position measurements.

The use of vibration signals has shown good potential for providing early warning of structural failure. Additional development and testing will be required before this system can become a practical tool for fire fighters.

FUTURE RESEARCH

With the exception of the vibration sensing system, the techniques tested to date have shown little to no ability to provide information concerning potential structural collapse. Additional research in this project will focus on identification and testing of construction techniques of concern to fire fighters. In addition to lightweight steel construction, the fire service is interested in the fire performance of lightweight and engineered wood construction. A test series is planned to investigate the impact of basement fires on current residential flooring systems. Other test scenarios will be developed and examined as funding permits. Work by Harvey Mudd College on the Health of Burning Structures monitoring system will also continue.

ACKNOWLEDGEMENT

The authors would like to thank present and former staff of the Building and Fire Research Laboratory, especially Daniel Madrzykowski, Roy McLane, Jay McElroy, Doug Walton, Jack Lee, William Twilley, and Gary Roadarmel. In addition, Dr. Dave Evans, currently the Executive Director of the Society of Fire Protection Engineers, served as the project leader for some of these test series while at BFRL. The authors are also grateful to the agents from the Bureau of Alcohol, Tobacco, and Firearms (ATF) and the staff of the ATF Fire Research Laboratory who provided measurement support for several experiments. The authors express appreciation for the support of the Phoenix, AZ; Kinston, NC, and Prince William County, VA fire departments and other municipal agencies involved in this project. Professor Ziyad Duron and his students from Harvey Mudd College in Claremont, CA have participated in many of these tests while developing the health of burning structures monitoring system. Finally, this research program would not have been possible without financial support from the Department of Homeland Security and the U.S. Fire Administration.

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