*unit 6:*

*Burn Time Considerations and Line-of-Duty Deaths from collapse incidents*

*objectives*

*The students will:*

*1. Given examples of different types of structures and different fire loads, predict the time of collapse.*

*2. Discuss the impact of the primary factor, construction, on line-of-duty deaths (LODDs).*

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wood frame

Abstract

A series of fire tests were 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. 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. 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 and bedroom areas of each structure were ignited simultaneously using electric matches.

Peak temperatures obtained during the tests ranged from approximately 800 °C (1,500 °F) to 1,000 °C (1,800 °F). The roof of each structure collapsed approximately 17 minutes after ignition. In addition to the full scale tests, the plywood and oriented strand board (OSB) roofing materials were tested using a cone calorimeter to characterize the fire properties of the materials.

Introduction

Every year, approximately 100 firefighters die in the line-of-duty, and 90,000 to 100,000 are injured. In 1999, the U.S. Fire Administration (USFA) estimated that slightly more than 30 percent of the firefighter fatalities occurring on the fireground resulted from something other than stress and heart attacks. Stress and heart attacks, which accounting for almost half of the firefighter fatalities, remain the leading cause of death.

The categorization of statistics does not lend itself to easy identification of those deaths that occurred due to structural issues, including failure and collapse. Examination of specific incidents in 1999 indicates that 18 firefighters, or 16 percent, died as a result of being trapped in a structure or involved in a collapse. Based on data obtained from 1979 through 1988, a report prepared by the National Fire Protection Association (NFPA) for the Federal Emergency Management Agency (FEMA) indicates that 93 of the 474 firefighters who were killed at structure fires died as a result of structural collapse. Of these firefighters killed due to structural collapse, 60 percent were caught or trapped in the collapse while 40 percent were struck by collapsing walls or sections of walls. A subsequent report examined 1,150 firefighter fatalities that occurred during the period from 1983 through 1992. Of the 390 deaths that occurred at structure fires, 2 died as a result of being caught or trapped and 26 firefighters were struck and killed by debris from the collapse. In a 2002 report, Dr. Fahy of NFPA indicated that the rate of deaths due to heart attacks at structural fire is decreasing while the rate of deaths due to traumatic injuries is increasing. Structural collapse is identified as one of the major causes of these traumatic injuries.

A recent National Institute of Standards and Technology (NIST) report indicated that deaths resulting from structural collapse have decreased overall during the last 23 years. However, the percentage of those deaths occurring at residential fires has been increasing. As part of a project funded by the USFA, the Building and Fire Research Laboratory (BFRL) at NIST is exploring the feasibility of developing a system for use by firefighters to predict structural collapse during fireground operations. 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, etc., makes the task nearly impossible.

The fire department in the Phoenix, Arizona conducted a series of live fire training exercises in various structures in an effort to better educate firefighters about structural collapse. While some of the structures in this ongoing series of training exercises were scheduled for demolition, other structures such as those described in this training exercise were built specifically for the fire tests. Each structure was allowed to burn until some portion of the structure collapsed.

In collaboration with the Phoenix Fire Department, researchers from NIST provided measurement support during the fire tests. Using video and data obtained from two different fire test series, the Fire Department developed a set of three videotapes dealing with fireground command and collapse issues. This report presents the results obtained from a set of tests that were conducted in single story wood frame residential structures. These structures were constructed for test experiments in order to examine several issues related to firefighter health and safety.

The first goal of the tests was to obtain temperature data from a burning structure during a collapse. Second, various techniques and tools were being evaluated for the use in predicting structural collapse. Specifically, the use of thermal imaging techniques was examined as a means to predict collapse. In addition, the exterior of the building was observed prior to and during collapse to identify any visual indicators of impending collapse. Subsequent reports will provide additional analysis of these fires and will also assess the effectiveness of various methodologies for predicting the onset of structural collapse.

These tests were not designed to evaluate the fire endurance of wood trusses, gypsum wallboard, wood studs, or any other structural elements used in the construction of the four structures. The fire scenario used in this study was designed to reach flashover conditions rapidly to force a partial or complete collapse of the structure. Many factors influence the failure of structural elements including the load on the element, protection of the element, fire intensity, and fire duration. More or less time may be available before failure of the element depending on the particular fire scenario. Kenneth E. Bland provides a review of, and expert procedure for, predicting the failure of wood assemblies when exposed to fire. Using the Component Additive Method (CAM) procedures presented in his report, the fire resistance rating of a wood roof assembly consisting of wood trusses, spaced 0.6 m (24") on center and protected by a 12.7 mm (1/2") thick layer of gypsum board would be at least 20 min. The CAM procedures assume the gypsum board is continuous, unlike the Phoenix fire tests where an attic access hole was located directly above the couch.

The fire resistance and ability of a structural member to maintain its load during an actual fire are influenced by a number of factors. Many of these factors can vary significantly depending on the specific fire scenario. Fire resistance ratings and measured or predicted times to failure or collapse should not be relied upon as absolute indicators of time available for operating on, or within, a burning structure. Each structure must be evaluated and reevaluated during the fire to determine whether or not it is safe for firefighters to remain within any potential collapse zone.

Experimental Configuration

The Phoenix Fire Department built four single story wood frame residential type structures for this series of tests. These structures were identical except for the roof construction. One structure had a roof consisting of asphalt shingles on 1/2" five-ply plywood while a second structure had asphalt shingles on 1/2" oriented strand board (OSB). Both structures had a layer of 15 lb felt paper between the asphalt shingles and 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" by 2" boards to hold the tile in place. The measurements for the materials used to construct the test structures described in this report are approximate nominal dimensions.

Each structure consisted of two rooms and an attic space. The rooms were separated by a wall constructed of 2" x 4" wood studs with a layer of 1/2" gypsum board nailed to each side. There was a doorway, 2.9' wide and 6.5' high, in the wall between the two rooms with its centerline located 14.9' from one exterior wall and 2.4' from the other exterior wall.

The exterior walls of the structures were composed of 2" x 4" wood studs on 1.3' centers nailed to a single sole plate and a double top plate. The exterior surfaces of the walls were covered with 5/8 in T-1-11 wood siding using galvanized nails. Interior walls and ceilings had 1/2" gypsum board nailed to the studs. All of the joints between boards were taped, and the taped joints and nails were covered with joint compound. In addition, the four walls in the back room (bedroom) and the two walls in the front room (living room) were covered with 1/8" pressboard paneling attached using construction adhesive and small brads.

The front wall of the living room had a doorway, approximately 2.9' wide and 6.7' high, located with its centerline 1.9' from one wall and 14.8' from the opposite wall. A hollow core wood door was mounted in the doorway opening. In the living room of each structure, the walls adjacent to the front wall each had an approximately 4' wide by 3' high section removed to let air into the room. One wall in the bedroom had a 4' wide by 3' high section removed, and the rear wall had a 3' by 3' window with glass. Each of the three cutout sections of wall had a piece of plywood on a slide track allowing it to be moved back and forth to regulate the flow of air into the room.

The roof system was built with manufactured trusses on 2' centers. The gable ends were studded with 2" by 3" lumber and covered with 1/2" high density fiberboard. The trusses were nailed on each end and attached to the top plate with metal hurricane ties. All structures had 2" x 6" boards nailed to the truss tails which were cut off at 1.7'. The outside rafts were nailed to 2" x 4" boards and attached to the second truss at 4' intervals.

A 5' long base cabinet made of particle board and a counter top were placed along the front wall of the living room. A second 5' long cabinet was nailed to the wall above the first cabinet.

Electrical outlet boxes were installed in the walls at various locations throughout the two rooms. A 0.8' by 0.8' hole was cut in the center of the ceiling in the living room and covered with a plastic grill to simulate a vent. The location of this vent was selected to facilitate fire spread into the attic space. A 2' by 2.5' hole was cut in the ceiling of the living room to allow access to the attic space. This opening was covered with a 1/2" piece of drywall which was held in place using wooden molding strips. Identical pieces of furniture, typical of a residential occupancy, were placed in each of the four structures. The living room contained a couch, a love seat, and two chairs consisting of wood frames with polyurethane foam cushioning material. Two wooden night tables, a wooden 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. Wooden night tables were placed adjacent to each bed. Two wooden 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 wooden 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.

Two mannequins outfitted in firefighter turnout gear with self-contained breathing apparatuses were placed on the roof of each structure during the test. Each firefighter mannequin had a mass of approximately 280 lb with gear, and they were positioned on the roof using metal stands. One firefighter was placed in a bending position while the second stood upright. Thermocouples were located in contact with the roof surface under the left and right boot of each firefighter mannequin. Tiles were removed from under the mannequins' boots for tests 3 and 4. A roof mounted air conditioning unit was also placed on the roof of each structure.

Each air conditioning unit had an approximate mass of 500 lb and was placed on the sloped portion of the roof opposite the firefighter mannequin locations. Each test was documented using standard video, infrared cameras, and still photographs. Two separate infrared cameras monitoring different portions of the electromagnetic band were used during the tests. One of the infrared imagers, Camera A provided less quantitative temperature data, but was representative of infrared cameras typically used by fire departments. The other infrared imager, Camera B, provided significantly more resolution in temperature data, different measurement ranges, emissivity factors, adjustable sensing spans, and calibration capability, but was not designed for firefighter use. The video and infrared cameras were mounted on a fire department ladder truck. During each fire test, the ladder with the standard video and two infrared cameras was elevated to provide an overhead view of each structure for the three cameras.

Experiments

Full Scale Fire Tests

Two fires were ignited simultaneously in each structure using electric matches. Electric matches are matchbooks with a short length of Ni-Chrome wire wrapped around the match heads. When a small electric current passes through the wire, the wire heats up and ignites the matchbook. One electric match was placed in a slit in the couch in the front room and covered with paper towels and newspaper. A second electric match was positioned in a slit in the chair, located in the back room, and covered with paper towels and newspaper. The fires were ignited in each room simultaneously and allowed to grow to flashover. Flashover occurs when multiple combustible items in a room ignite as a result of being heated by intense thermal radiation from the hot upper layer. At flashover, the room environment is characterized as well stirred, with temperatures throughout the space being relatively uniform. Gas temperatures in the room typically exceed 600 °C (1,110 °F). During this test series, the fire ultimately spread into the attic space and eventually caused collapse of a portion of the roof structure. For this test series, collapse was assumed to occur when the portion of the roof supporting the firefighter mannequins failed and allowed fire to envelope the mannequins. As the roof structure collapsed, the firefighter mannequins were removed using a fire department crane. Once the mannequins were removed, the fire was extinguished using water or a combination of water and a fire suppression foam agent.

**Test No. 1** was conducted using the structure with a roof composed of asphalt shingles over plywood. For the first test, smoke became visible from the structure approximately 60 seconds after ignition. At approximately 3 min after ignition, the living room reached flashover temperatures. The bedroom reached flashover temperatures about 6 1/2-minutes after ignition. After approximately 1 min, the temperatures in the living room dropped to a relatively uniform 500 °C (930 °F). The bedroom temperatures remained near 600 °C (1,110 °F). The fire appears to have penetrated into the attic space at about 7 1/2-minutes after ignition. At 14 minutes, portions of the roof began to burn. Collapse of a portion of the roof and removal of the firefighter mannequins occurred 17 1/2-minutes after ignition. Fire suppression was initiated at 18 minutes, 40 seconds.

**Test No. 2** was conducted using the structure a roof composed of asphalt shingles over oriented strand board. In the second test, smoke became visible from the structure approximately 52 seconds after ignition. At approximately 3 1/2-minutes after ignition, the living room temperatures briefly exceeded flashover temperatures. Temperatures in the bedroom area never exceeded the 600 °C (1,110 °F) flashover threshold until near the end of the test. The living room maintained peak temperatures in excess of 500 °C (930 ºF) while the temperatures in the bedroom remained between 400 °C (750 ºF) and 600 °C (1,110 ºF). The fire appears to have penetrated into the attic space at about 8 minutes after ignition. Flames began lapping the roof 13 minutes after ignition and at this time the front door failed. At 14 minutes, portions of the roof began to burn. Collapse of a portion of the roof and removal of the firefighter mannequins occurred 17 minutes after ignition. Suppression was initiated at 17 minutes, 45 seconds.

**Test No. 3** was conducted using the structure with a roof composed of cementitious tile over plywood. During the third test, smoke became visible from the structure approximately 1 minute, 20 seconds after ignition. At approximately 3 minutes after ignition, the living room reached flashover temperatures of approximately 600 °C (1,110 ºF). The living room continued to maintain temperatures in excess of 600 °C (1,110 ºF) for most of the test period. Temperatures in the bedroom remained below flashover temperatures until 11 minutes after ignition. The fire appears to have penetrated into the attic space again at 8 minutes after ignition. Collapse of a portion of the roof and removal of the firefighter mannequins occurred 16 minutes after ignition. Suppression was initiated at 17 minutes. White smoke was observed coming from the structure at 19 minutes, 40 seconds.

**Test No. 4** was conducted using the structure with a roof composed of cementitious tile over oriented strand board. For the fourth test, smoke was first visible at approximately 56 seconds after ignition. Flashover temperatures were reached in the living room 4 minutes after ignition while the bedroom remained below flashover temperatures until almost 8 minutes after ignition. The fire penetrated into the attic space at about 8 minutes after ignition. Collapse of a portion of the roof and removal of the firefighter mannequins occurred 17 minutes, 10 seconds after ignition. Suppression was initiated at 18 minutes.

Results - Full Scale Fire Tests

Temperature Data

First Test:

As the fire in the living room grows to flashover, the stratified fire environment is evident from the distinct temperature histories obtained at the eight sampling locations. At about 200 seconds, the temperature plots indicate a "well stirred environment" with an average temperature of about 500 °C (930 °F). The fire in the bedroom takes longer to reach flashover temperatures; it reaches the flashover point at about 420 seconds. At this point, the environment becomes well mixed with a temperature of about 600 °C (1,100 °F). Both the north and south thermocouple arrays in the attic indicate a stratified environment until about 700 seconds. The two peaks, one at about 180 seconds and the second at 200 seconds to 250 seconds, are most likely the result of periodic flame penetration into the attic space through the ceiling penetrations. At about 700 seconds, flashover appears to have occurred in the attic with the environment becoming well mixed at an average temperature of 750 to 800 °C (1,380 to 1,470 °F).

The temperature plots suggest that some portions of the ceiling begin failing at about 800 seconds. In addition, the front door failed at about 840 seconds. The roof begins to collapse at 1,050 seconds and suppression is started at 1,120 seconds. Once flashover occurs in the attic at about 700 seconds, the temperatures under the boots increase rapidly to 800 °C (1,470 °F), approximately the temperature within the attic space. Subsequently, the temperatures decrease correspondingly with decreasing temperatures within the attic space, possibly the result of failure of the ceiling. The temperatures gradually increase until roof collapse at which point the mannequins become surrounded by flames until their removal.

Second Test:

In the living room, the fire grows to a temperature indicative of impending flashover, approximately 600 °C (1,100 °F) within 180 seconds after ignition. After this initial period, the fire environment becomes stratified with a temperature gradient of 300 °C (570 °F) to 550 °C (1,020 °F) for a period of about 180 seconds. At approximately 350 seconds after ignition, the entire living room area appears to flashover with a peak temperature of 700 °C (1,300 °F). At this point, the environment in the living room becomes well mixed with a uniform temperature throughout most of the remainder of the test. The decrease in temperature occurring at approximately 400 seconds is the result of failure of some portion of the living room ceiling. After the fire begins spreading into the attic area, temperatures in the living room begin a steady climb to a peak of 1,200 °C (2,200 °F). The front door fails at about 840 seconds leading to a reduction in living room temperatures. Except for a few brief moments, the temperatures in the bedroom area never exceed 600 °C (1,110 °F). With the exception of the point at which the roof section collapsed at 1020 seconds, the environment in the bedroom remains stratified throughout the duration of the test.

The first peak at 180 seconds is most likely the result of flames--momentarily extending into the attic area through the ceiling ventilation louvers. The attic access panel and possibly a portion of the ceiling near the ignition location failed at 400 seconds. The brief peak at 725 seconds is probably the ignition of plastic light boxes in the ceiling. The attic area reaches a flashover condition at about 900 seconds. A portion of the roof under the firefighter mannequins collapses approximately 4 minutes after flashover in the attic area. As the attic space approaches flashover conditions at about 800 seconds, the temperatures under the boots increase to 750 °C (1,380 °F). At approximately 1,020 seconds, the roof structure begins to collapse.

Third Test:

As with the other tests, the temperatures in the living room rise rapidly at the start of the third test. At approximately 120 seconds, the space reaches temperatures indicative of flashover. After flashover, the environment becomes stratified with temperatures ranging from 300 °C (570 °F) to 600°C (1,110 °F). At about 550 seconds, the temperatures in the lower part of the living room increase producing an almost uniform environment of between 550 °C (1,020 °F) and 600 °C (1,110 °F). Just prior to a portion of the ceiling collapsing at about 700 seconds, the temperatures in the living room increase to about 700 °C (1,290 °F). After collapse of a portion of the ceiling, the temperatures initially decrease then increase to 700 °C (1,290 °F) to 800 °C (1,470 °F). Collapse of a portion of the roof occurs at about 960 seconds. Prior to collapse of a portion of the ceiling, the bedroom temperatures remain well below 600 °C (1,110 °F). For the first 400 seconds of the test, the temperatures in both the north and south portions of the attic grow slowly to a peak of about 150 °C (300 °F). The temperature spikes during this period are indicative of flames momentarily extending into the attic area through the louvers and other ceiling penetrations. Once materials located in the attic start burning, the temperatures increase reaching a sustained maximum of 550 °C (1,020 °F) with a momentary peak above 600 °C (1,110 °F). When the roof collapses at 960 seconds, the attic temperatures initially increase then decrease rapidly as suppression is initiated. The temperatures under the firefighter mannequins' boots remain close to ambient until the roof collapses at 960 seconds when the mannequins are enveloped in flame and removed.

Fourth Test:

The temperature data obtained in the living room indicates that the fire grew rapidly producing temperatures in excess of 600 °C (1,110 °F). The environment in the living room remains well mixed at flashover temperatures until about the time of roof collapse.

The environment in the bedroom remains stratified with a peak temperature of 420 °C (790 °F) until some portion of the ceiling fails at 450 seconds. After ceiling failure, the temperatures become somewhat erratic varying between 400 °C (750 °F) and almost 800 °C (1,470 °F). At approximately 800 seconds, the temperatures in the bedroom become uniform and decrease, rapidly increase, and decrease again. The most likely cause of this phenomenon is failure of additional portions of the ceiling as a result of flashover in the attic space. Temperature increases in both the north and south parts of the attic is relatively continuous with only slight discontinuities at about 450 seconds and 850 seconds. These discontinuities indicate ignition of materials in the attic space and failure of the ceiling membrane between the living room/bedroom area and the attic. Once the attic space has flashed over at 900 seconds, the temperatures become uniform at approximately 750 °C (1,380 °F) until collapse at 1,030 seconds. Very little temperature increase is evident on the underside of the firefighter boots until the roof collapses at 1,030 seconds.

Conclusions

In all four tests, some portions in the living room reach flashover temperatures (approximately 600 °C (1,110 °F)) within 180 seconds after ignition. With the exception of test 3, the living room temperatures remained at or above 600 °C (1,110 °F) until roof collapse. Temperatures in excess of 600 °C (1,110 °F) 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 seconds to 450 seconds after ignition during each test. With the exception of the first test, roof collapse appears to be preceded by flashover in the attic space. Even though the noncombustible tile was removed from beneath the firefighter mannequins' boots, no temperature changes were measured under the boots until collapse of the roof during the third and fourth tests. 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 magnetic radiation as a result of electron motion associated with the internal energy of the material. This internal energy is a strong function of the temperature of the substance.

For all four tests, the maximum temperatures in the living room and bedroom areas reached between 540 °C (1,000 °F) and 815 °C (1,500 °F). Flashover occurred in the living room spaces approximately 3 to 4 minutes after ignition. Prior to collapse, peak temperatures in the attic spaces were approximately 500 °C (930 °F). The fires spread into the attic spaces between 6 minutes and 8 minutes after ignition. In all of the tests, collapse occurred approximately 17 minutes after ignition. Flashover in the attic spaces occurred approximately 5 1/2 minutes after the fire spread to the ceiling or 12 minutes after ignition. As the attic space approaches flashover, temperatures under the roof rapidly change (on the order of a few seconds) from near ambient 37 °C (100 °F) to 540 °C (1,000 °F).

The temperature of the roof surface under the firefighter mannequins' boots did not increase significantly prior to collapse. Temperature measurements obtained under firefighter boots would probably not be a useful indicator of potential collapse. Unfortunately, the firefighter 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.

Each of the roofs collapsed between approximately 16 3/4 minutes and 17 1/2 minutes. This limited set of full-scale tests does not demonstrate a significant difference between the performance of the plywood and OSB sheathing. No differences were observed between the asphalt shingles and the cementitious tiles. The other temperature data obtained during the tests did not indicate any difference in performance between the plywood and OSB. OSB releases energy faster, and more of its total energy when exposed to high radiant heat fluxes in the cone calorimeter. While it is heat flux dependent, both materials ignite after about the same exposure time. 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.

Acknowledgements

This information was taken from: Structural Collapse Fire Tests: Single Story Wood Frame Structures

David W. Stroup, Nelson P. Bryner, Jack Lee,

Jay McElroy, Gary Roadarmel, and William H. Twilley

structural collapse fire tests: single story, Ordinary Construction Warehouse

overview

Two fire tests were conducted in a warehouse located in Phoenix, Arizona to develop data for evaluation of a methodology for predicting structural collapse. A firewall was constructed to divide the warehouse into two fire compartments. Temperatures were measured as a function of time in three locations during the first test and in two locations during the second test. In addition, the volume fraction of carbon monoxide was measured at selected locations during each test. Stacks of wood pallets were used as the primary fuel source and were ignited using paper and electric matches. Some combustible debris and building structural elements provided the remainder of the fuel load. Peak temperatures obtained at different elevations ranged from approximately 300 °C (570 °F) to   
800 °C (1,470 °F). Peak carbon monoxide volume fraction reached 4 percent in the first test and 5 percent during the second test. The front half of the structure's roof burned through approximately 18 minutes after ignition of the fire for the first test. The back half of the structure's roof burned through approximately 15 minutes after the start of the second test.

Introduction

Every year, approximately 100 firefighters die in the line-of-duty, and 90,000 to 100,000 are injured. For calendar year 1999, the United States Fire Administration estimated that slightly more than 30 percent of the firefighter fatalities occurring on the fireground resulted from something other than heart attacks. The categorization of the statistics does not lend itself to easy identification of those deaths that occurred due to structural issues.

Examination of specific incidents in 1999 indicates that 18 firefighters, or 16 percent, died as a result of being trapped in a structure or involved in a collapse. As part of a project funded by USFA, the Building and Fire Research Laboratory (BFRL) at the National Institute of Standards and Technology (NIST) is exploring the feasibility of developing a system for use by firefighters to predict structural - collapse during fireground operations. Predicting a potential structural collapse is one of the most challenging tasks facing an IC at a fire scene. Usually the lack of information on the construction of the building, fire size, fire location, fire burn time, condition of building, fuel load, etc., makes the task nearly impossible.

The fire department in Phoenix, Arizona conducted a series of live fire training exercises in various structures in an effort to better educate firefighters about structural collapse. Some of these structures were built specifically for the fire tests while others were existing structures scheduled for demolition. Each structure was allowed to burn until some portion of the structure collapsed. At the invitation of the Phoenix Fire Department, researchers from NIST provided measurement support during the fire tests.

This training exercise presents the results obtained from one set of tests. This test series was conducted to examine several issues related to firefighter health and safety. The first goal of the tests was to obtain temperature data from a burning structure during a collapse. Second, various techniques and tools were evaluated for use in predicting structural collapse. Specifically, researchers from Harvey Mudd College, through a NIST funded grant, measured the building vibrations as a means to predict collapse. In addition, the exterior of the building was observed prior to and during collapse to identify any visual indicators of impending collapse. Finally, carbon monoxide volume fractions were measured at selected locations to obtain information regarding the survivability of conditions within the structure prior to collapse.

Experimental Configuration

For this series of tests, the Phoenix Fire Department obtained a 135' by 50' warehouse that was scheduled for demolition. The building was a single story with a peaked roof composed of rolled roofing material laid over 2" by 8" boards supported on wood trusses. The warehouse was separated into two halves with a wall constructed of 2" x 4" wood studs with 1/2" plywood nailed to one side. The plywood was covered with two layers of 5/8" fire rated gypsum board. The separation wall was built along a truss 90' from the front of the building.

The trusses used 2" x 12" lumber for the top and bottom chords and various lumber sizes for the web members. The trusses were spaced 15' apart and oriented perpendicular to the long dimension of the building. The peak of the roof was 18' above the floor with the bottom chord of the truss located 10' above the floor. The trusses rested on bearing walls composed of brick and block.

Overall, the front half of the building was 50' wide and 90' long. This area was subdivided into several smaller areas. The primary separation was a wall composed of gypsum on wood studs, and was located along the truss 60' from the front of the building. This wall went only to the underside of the bottom chord of the truss. A door, 7.5' high and 6' wide, was located in this wall 12' from the east wall. In addition, there were several 0.79' by 1.5' holes cut through the wall at a height of about 10'. Two small rooms were also located along the east wall. These rooms were located on either side of the wall dividing the front room. The larger room was 24' long and 10' wide and apparently served as an office. There was a door, 3' wide and 6.8' high, in the west wall of the office and a small opening, 3'by 2' in the north wall. The smaller room was 5' by 6' and served as a restroom. It had a single door opening with dimensions of 3 ft wide by 6.8 ft high. The front wall of the warehouse structure had a doorway, approximately 6 ft wide and 10.5' high, located 13' from the east wall. There were two glass doors in this doorway. A glass window 7.7' high and 28' wide was located in the front wall approximate 1' from the east wall. The sill of the window was 2.3' high.

The **second burn** area was 45' by 50' with a single doorway in the east wall. The doorway was 8' wide and 8' high. It was located 96' from the front wall of the building and 6' from the separation wall.

The fuel load for the **first test**, conducted in the front part of the warehouse, consisted of four stacks of ten wood pallets. Each stack of pallets had a mass of approximately 360 lb. Three of the stacks were arranged in a triangle in the front half of the space. A fourth stack of pallets was placed in the center of the second section of the building. Newspaper was placed among the three stacks of pallets, and an electric match was positioned in the newspapers as the ignition source.

For the **second test**, three stacks of ten pallets each were arranged in a triangle in the center of the second section of the building. An electric match and newspaper were again used as the ignition source.

Experiments

A fire was ignited in the newspaper among the three stacks of pallets in the front room of the first test area. Electric matches are matchbooks with a winding of nichrome wire that heats and ignites the matches when an electric current passes through the wire. The fire was allowed to grow to involve a significant portion of the roof structure north of the fire area separation wall. After approximately 25 minutes, the Phoenix Fire Department extinguished the fire.

For the **first test,** the flames reached the top of the pallet stacks 40 seconds after ignition. Smoke became visible coming from a rooftop ventilator approximately 60 seconds after ignition. At approximately 1 1/2 minutes after ignition, flames had reached the ceiling and started spreading along the underside. The entire array of pallets in the front half of the first burn area was involved in fire within 2 minutes. Adjacent items began igniting due to radiant energy 2 1/2 minutes after ignition. At 3 minutes after ignition, flames were observed coming from the rooftop ventilator. The roof area around the ventilator started burning at 4 minutes. At about this time, the interior picture became obscured in smoke and the camera was removed at the 4 minute mark. At approximately 4 1/2 minutes after ignition, the heavy smoke coming from the structure began to diminish, and the roof fires were mostly out by 5 minutes after the start of the test. As the test measurements indicated, the fire became oxygen deficient and the glass in the front door was removed at 8 minutes to provide additional oxygen for the fire.

Within 2 minutes after removing the front door glass, various fires had reignited on the roof. 11 minutes after the start of the test, the northwest portion of the roof was burning and appeared to have burned through in spots. Due to loss of some data signals and possible collapse, the thermocouple and volume fraction measurements were terminated at 13 minutes. At 14 minutes, approximately 1/4 of the roof, primarily the northwest portion, was burning. The entire west side was burning by 17 minutes, and portions collapsed at about 18 minutes after ignition. The northeast part of the **roof collapsed at** **18 minutes, 20 seconds**. By 18 minutes, 35 seconds, all of the plywood covering the front windows had started burning and had fallen out of the windows. One minute later, the upper portion of the front wall collapsed into the street. At 23 minutes, the east section of the roof between the trusses 60' and 75' from the front wall collapsed. The test was terminated approximately 25 minutes after ignition.

**In the second test**, a fire was again ignited in newspaper among three stacks of pallets placed in the center of the second fire test area. The fire was allowed to grow to involve the entire roof over the second test area. After approximately 30 minutes, monitoring of test conditions was terminated.

**For the second test,** the flames reached the top of the pallet stacks 45 seconds after ignition. The entire array of pallets was involved in fire within 2 1/2 minutes. At approximately 3 minutes after ignition, flames had reached the ceiling and started spreading across it. Smoke started coming out of the open doorway at approximately 3 1/4 minutes. Adjacent items began igniting due to radiant energy 3 minutes, 20 seconds after ignition. The smoke layer appeared to reach the top of the pallet stack at 4 minutes. At 5 minutes, the interior picture became obscured in smoke and the camera was removed. Flames started coming out of the doorway at 6 1/2 minutes. At 9 minutes, various edges of the roof started to burn. The roll-up door collapsed at 13 1/2 minutes and partially blocked the open doorway. Data collection was terminated at 14 minutes.

Significant portions of the roof were burning at the 14 minute mark. **A partial collapse of the roof occurred at 15 minutes, and 20 seconds.** At 16 1/2 minutes, additional portions of the roof collapsed, with the roof being mostly destroyed by 19 1/2 minutes. An unused door in the southwest portion of the west wall had been sealed with a single course of cinder blocks. These blocks collapsed into the street 24 minutes after ignition. The upper portion of the rear wall collapsed at 29 minutes and further monitoring was terminated.

Results

The temperature histories indicate a relatively well mixed flashover environment. Approximately 200 seconds into the first test, the fire became oxygen starved. Opening the front door at about 480 seconds into the test produced the second set of peaks. In addition to allowing the fire to resume it's growth, opening the front door lead to the development of a stratified upper layer, as indicated by the divergence of the temperature histories after the 500 second mark. 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 seconds indicates additional significant roof collapse in the area of this thermocouple tree.

The temperatures decrease when the door is opened at approximately 500 seconds. The temperatures begin to increase, but not as rapidly as the ones closer to the door. The dip in the temperature profiles at approximately 650 seconds is another indication of a partial roof collapse. Additional roof failure beyond 700 seconds leads to further temperature reductions. The temperature histories were obtained in the second third of the first section of the warehouse. This part of the warehouse was separated from the other part by a wall that went from the floor to the suspended ceiling. The temperature histories obtained in this area are more stratified than in other parts of the warehouse. The stratification becomes more significant after the front door is opened. In addition, the roof failures occurring in the front part of the warehouse continue to produce increasing temperatures in this area. The concentrations decrease and the temperatures increase after the door is opened.

At this point, flames were observed coming from the open door suggesting a lack of oxygen within the warehouse in the vicinity of the fire near the thermocouples. Initially, the temperature at the ceiling, 19' above the floor, is lower than some of the upper level locations. This effect may be the result of the wood trusses that support the roof and obstruct the flow of hot gases across the ceiling. The carbon monoxide volume fractions correspond with the fire becoming somewhat oxygen starved. Equipment and personnel were evacuated from the area. Unfortunately, data acquisition had to be stopped prior to complete collapse. Further work will evaluate the potential for use of sensors with radio output to allow continued monitoring through the collapse phase of the research activity.

For both tests, the maximum temperatures in the area prior to collapse were 800 °C (1,470 °F). Gas temperatures in the second test remained between about 600 °C (1,110 °F) and 800 °C (1,470 °F) throughout the test. The carbon monoxide volume fractions in the first test exceeded 3 percent approximately 5 minutes after ignition. In the second test, the carbon monoxide volume fraction exceeded 5 percent approximately 7 minutes after ignition. The volume fractions at the 25 mm and 0.9 m locations varied from 0.1 percent to a 0.5 percent. Variation was greater in the first test than in the second test.

The results presented in this report are subject to some uncertainties. Error in gas temperature measurements resulting from radiation effects can be as high as 25 percent during the very early stages of the fire.

Conclusions

Two fire tests were conducted by the NIST in cooperation with the Phoenix, AZ Fire Department in an ordinary construction, single story warehouse. These fire tests were part of a series of tests being conducted to identify potential methodologies for predicting structural collapse. If technology were available to provide a reliable assessment of structural stability or timely warning of impending collapse, then interior fire fighting operations could be conducted with greater safety. The data obtained from these tests is being used to evaluate the applicability of various fire models for predicting structural collapse. In addition, the test data are useful for investigating the use of new measurement technologies in the fire environment. These investigations include the use of infrared cameras to measure temperature, lasers and sonar to measure displacement, and vibration to predict a change in structural integrity. Specifically, these experiments included sensors for obtaining vibration measurements [4].

The results from the vibration studies will be presented in a future report. While work is continuing to evaluate these technologies for use by the fire service, there are some useful conclusions that can be drawn from these two tests.

According to the 2nd edition of the SFPE Handbook of Fire Protection Engineering, exposure of a person involved in light work, such as walking, to a carbon monoxide level of 1 percent for approximately 3 minutes is sufficient to cause unconsciousness while a carbon monoxide level of 4 percent for less than 1 minute will cause death [5]. Within about 5 minutes 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 (120 F) to as much as 150 °C (300 °F). During the second test, the temperature variation between the two locations was as high as 250 °C (480 °F). For reference, unprotected people can tolerate temperatures of 100 °C (212 °F) for approximately 10 minutes and temperatures of 150 °C (300 °F) for about 5 minutes when exposed to convected heat [6]. Flashover, as indicated by gas temperatures in excess of 600 °C (1,100 °F), is reached during both tests about 4 minutes after ignition. After flashover, temperatures - 8 - during the first test decrease but remain about approximately 200 °C (390 °F) throughout the test. Temperatures remain above 400 °C (750 °F) at head height through the second test.

The ability of firefighters to withstand the extreme temperatures associated with typical building fires is directly related to the thermal performance of their protective clothing and equipment.

The National Fire Protection Association standard for interior structural fire fighting clothing requires a minimum Thermal Protective Performance (TPP) rating of 35 [7]. When exposed to a flashover fire, firefighters wearing garments with a TPP rating of 35 have from 10 to 20 seconds to escape before receiving serious burns [8, 9].

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. Eventually, a portion of the wall did collapse. The smoke from a building fire has been suggested as a possible cue to the collapse potential. 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 Depending on the stage of the fire, initial exterior appearances can be deceiving.

Acknowledgements

This information was taken from: Structural Collapse Fire Tests: Single Story, Ordinary Construction Warehouse

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LINE-OF-DUTY DEATHS 1994-2002

Overview

As part of a project funded by USFA, BRFL, and NIST are exploring the feasibility of developing a system for use by firefighters to predict structural collapse during fireground operations.

Predicting a potential structural collapse is one of the most challenging tasks facing an ICat a fire scene.

Usually the lack of information on the construction of the building, fire size, fire location, fire burn time, condition of building, fuel load, etc., makes the task nearly impossible.

They examined records to determine if there were any trends or patterns that could be detected in firefighter fatalities due to structural collapse.

**If so, these trends could be brought immediately to the attention of training officers and the IC, and investigated further to determine probable causes.**

This study examined data from structural collapse incidents that occurred from 1994 to 2002 involving one or more firefighter fatalities where a fire weakened and caused the failure of structural members in a building. This failure resulted in the complete or partial collapse of any part of the structure, excluding the cases described above.

Several data parameters were analyzed for each incident, including

* the time of the incident;
* the property type of the structure;
* the firefighter's age;
* years of experience;
* status (i.e., career or volunteer);
* nature and cause of death; and
* activity at the time of death.

In the case of rank, individuals ranked higher than captain were designated chief officers. **Any dual-trained firefighter (e.g., firefighter/paramedic) was designated as firefighter.**

The 1994-2002 data were also compared to results reported in two earlier NFPA reports addressing firefighter fatalities due to structural collapse. These reports analyzed data from incidents that occurred from 1979-1988 and 1983-1992, respectively. The raw data from these reports were not available. In order to make comparisons, several categories of the data were restructured for the more recent data in order to fit the criteria established in the NFPA reports. For instance, in the historical reports, the category for cause of death only had the two parameters "Caught or Trapped" and "Struck by/Contact with Object."

Data collected for the years 1994-2002 included "Exposure" and "Fell or jumped" as additional causes of death (as designated by the USFA Memorial database). Cases that belonged to the latter two categories were realigned with the criteria established in the NFPA reports. For example, the cause of death of a firefighter who fell through a floor during a fire attack and was unable to escape or be rescued would be designated in the USFA database as "Fell or jumped". Comparing this case to the NFPA reports, the cause of death would be reassigned to **"Caught or Trapped."**

Between the years 1979 and 2002 there were over 180 firefighter fatalities due to structural collapse, not including those firefighters lost in 2001 in the collapse of the World Trade Center Towers. Structural collapse is an insidious problem within the fire fighting community. It often occurs without warning and can easily cause multiple fatalities.

Between the years 1994 and 2002 there were 63 deaths caused by structural collapse in a total of 47 fires.

Figure 1 Fatalities and incident per year (1994-2002) graph

Of these deaths, over two-thirds occurred within the first six months of the year and over one-half occurred in the first three months

figure 2 fatalities by month graph

Over 42 percent of deaths with known incident times occurred in the first eight hours of the day (12:00 A.M. – 7:59 A.M.).

figure 3 fatalities by time of incident graph

Victims of structural collapse were part of several age groups, experience levels, and ranks and were involved in several activities.

**Fatalities by Age**

figure 4 fatalities by age graph

**Fatalities by Years of Experience**

Over 44 percent of deaths involved career firefighters with six or more years of experience.

figure 5 fatalities by years of experience graph

**Fatalities by Rank**

figure 6 fatalities by rank graph

**Fatalities by Activity**

A majority of the victims (over 65 percent) were involved in a fire attack or advancing hose.

figure 7 fatalities by activity graph

**Fatalities by Nature of Death**

The nature of firefighter deaths in collapsed structures is categorized as asphyxiation, burns, internal trauma, and other causes.

Over 42 percent of fatalities (27 deaths) were by asphyxiation.

figure 8 fatalities by nature of death graph

**Fatalities by Activity and Duty Type**

figure 9 fatalities by activity and duty type graph

**Fatalities by Cause of Death and Duty Death**

figure 10 fatalities by cause of death and duty type graph

**Fatalities by Month and Rank**

figure 11 fatalities by month and rank graph

**Fatalities by Activity and Cause of Death**

figure 12 fatalities by activity and cause of death graph

**Fatalities by Cause of Death and Property Type**

figure 13 fatalities by cause of death and property type graph

**Fatalities by Cause of Death and Nature of Death**

figure 14 fatalities by cause of death and nature of death graph

**Fatalities by Property Type and Status**

figure 15 fatalities by property type and status graph

**Fatalities by Activities and Status**

figure 16 fatalities by activity and status graph

**Fatalities by Activity and Property Type**

figure 17 fatalities by activity and property type graph

**Fatalities by Month and Nature of Death**

figure 18 fatalities by month and nature of death graph

**Fatalities Due to structural Collapse per Year (1979-2002)**

figure 19 fatalities due to structural collapse per year (1979-2002) graph

**Fatalities by Cause of Death**

figure 20 fatalities by cause of death graph

another figure 20 fatalities by cause of death graph

**Fatalities by Fixed Property Type**

figure 21 fatalities by fixed property type (1979-1988) graph

figure 21 fatalities by fixed property type (1983-1992) graph

figure 21 fatalities by fixed property type (1994-2002) graph

Acknowledgments

This information was taken from: Trends in Firefighter Fatalities Due to Structural Collapse, 1979-2002.