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Early Warning Capabilities for Firefighters: Testing of Collapse Prediction Technologies

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Notice

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Executive Summary

This report details a two-year effort to develop and evaluate an early warning capability for firefighters to detect structural collapse in a burning structure. The methodology developed is based on monitoring vibrations in the structure induced by the fire and using these measurements to define indices that provide warning of impending collapse. Field test procedures and instrumentation were developed and shown to be effective in measuring structural vibrations during full-scale burn tests on wood and steel frame structures. Attempts to correlate measured responses with changes in structural behavior during burn have shown that trends in response magnitude, response statistics and in changing system parameters can all be used to track changing structural conditions leading to collapse.

Acknowledgements

It is rare when, during the course of a research program, external events occur that provide a profound context for the effort and its outcomes. Each year, firefighters are injured or lose their lives in structural fires, and the events associated with the collapse of the World Trade Center Twin Towers only served to sharpen the focus of the current effort. Apart from the technical contributions to the current state of the art in collapse monitoring of burning structures, this effort has provided a unique opportunity to expose undergraduate students to the need for, and the importance of, fire protection research. Needless to say, this program would not have been possible without the collaborative efforts of the academic, government and private agencies that were involved. The author is indebted to a number of organizations and individuals.

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1.0 Introduction and Background

Injury or loss of life to firefighters from structural collapse during operations may be mitigated if reliable monitoring of changing conditions in a burning structure can be achieved. Further, if real-time monitoring indices that predict impending collapse can be developed from field measurements of changing conditions, information currently not available to firefighters during operations could enhance firefighter safety.

This report presents the major findings and conclusions from a NIST funded study that included full-scale burn tests on wood frame and lightweight steel frame structures. Details associated with the type of field measurements obtained, characteristics associated with the burning structures and with the criteria used to evaluate the procedures are discussed. Video files are available that provide visual evidence of observed collapse events and of predictive capabilities of indices derived from field measurements during the burn tests.

The research effort originally proposed focused on the use of acoustic measurements obtained from inside a burning structure to develop an early warning indicator of impending collapse. The idea, although not new to NIST, was essentially based on developing field test procedures and instrumentation that could withstand the hostile environment of a burning structure and still provide reliable measurements of acoustic emissions that could then be correlated to physical changes in the structure. Ultimately, the goal was to develop suitable indices based on these measurements that could be used by firefighters to monitor and predict impending collapse. If successful, indices of the type shown in Figure 1 might result in which collapse would be indicated by the rapidly changing index value. With this in mind, a series of training exercises were observed and are described below.

1.1 Phoenix Fire Department and NIST Training Exercise

In October 2000, the Phoenix Fire Department, in collaboration with the NIST and BFRL (Building Fire Research Laboratory), conducted a series of training exercises in which four small wood frame structures were burned to collapse. Figure 2 is a picture of the one of the structures prior to test that shows two firefighter mannequins and a HVAC unit mounted on the roof. The mannequins were tethered to a crane that was used to extract them at the moment of roof collapse. Inside the structure, wood framed walls were covered with drywall sheeting or wood paneling. The roof was instrumented with thermocouples in an effort to characterize the thermal environment during burn, and the aluminum covered instrumentation harnesses used by NIST can be seen at the bottom left in Figure 2. Four structures were available for these exercises, differing primarily in roof material and in the use of plywood or oriented strand board (OSB) shear walls. Fire was ignited remotely inside the front room and the structure was allowed to burn well after roof collapse occurred. Thermal imaging infrared cameras were used during these exercises and videos of the tests were also taken. The pictures in Figure 3 were taken during one of the burn tests.

During these tests, the PI had an opportunity to discuss the merits of acquiring acoustic measurements in a burning structure with firefighters who reported that they could often hear nails being pulled out of connections inside burning wood frame structures. As the training exercises continued, however, it became clear that even if reliable acoustic measurements could be obtained, identification of a single or even dominant acoustic source would prove to be a difficult task. Significant environmental noise associated with firefighting gear (e.g. trucks, engines, generators) and operations (e.g. water, demolition) could easily mask acoustic signatures associated with changing structural conditions. While photographing the burning structures, large roof motions that appeared to be fire-induced were observed. This seemed to suggest that the fire was able to generate a random excitation sufficient to excite structural response.

Prior to this research effort, the PI had developed a number of field test procedures based on detecting ambient (i.e. naturally occurring) responses in large civil structures (e.g. dams, bridges, buildings and tunnels). These procedures were based on ability to measure low-level responses induced by a variety of sources including wind, water waves, micro-seismic events and traffic flow. Levels as low as 80micro-g's (approximately 0.1 micron for a typical structural response at 10 Hz) have been reported with acceptable signal-to-noise ratios. Based on these experiences and the fact that roof motion was visible on a burning structure, it seemed likely that fire-induced vibration responses could be obtained if suitably protected sensors could be attached to the structure.

1.2 Revised Research Objectives

As a direct result of the observations made during the Phoenix training exercises, the objectives for the proposed research effort were revised as follows.

1. Can fire induce structural vibrations in a burning structure?
2. Can fire-induced vibrations be measured during burn?
3. Can fire-induced vibrations be used to monitor and perhaps predict impending collapse in a burning structure?

Sections 2.0 and 3.0 of this report describe the development of field test procedures demonstrated during actual burn tests in order to address the first two objectives listed. Analyses of the measured responses are described in Section 4.0 and correlations to observed and documented collapse mechanisms are also discussed in order to address the third objective listed. Outcomes and implications of the research findings are presented in Section 5.0 and recommendations for future work are discussed in Section 6.0. Summary and conclusions are presented in Section 7.0. Appendices at the end of the report contain specifications of the sensor and thermal blanket utilized during the burn tests and describe an ignition timing and location analysis based on measured responses acquired during the test of a steel frame structure.

2.0 Description of Field Test Procedures for Measuring Fire-Induced Structural Vibrations

The field-test procedures for measuring fire-induced structural vibrations were based largely on procedures that have proven effective in the ambient and transient monitoring of large civil structures. Measurements acquired from tests on structures such as dams, bridges, buildings and tunnels, are typically characterized as low-level responses "surrounded" by environmental noise not directly associated with the structure under test or even indicative of structural behavior. For example, in the ambient testing of the bridge overpass shown in Figure 4, the ambient response (Figure 4, middle) contains transients associated with structural behavior that result from passing vehicular traffic underneath the bridge. Even in the presence of environmental and other noise, ambient responses of the type shown yield reliable information on the dynamic behavior of the structure. As an example, ambient responses acquired on the bridge were used to extract the fundamental vibration shape shown (Figure 4, bottom).

2.1 Description of Sensor and Mounting Technique

Expecting that fire-induced vibration measurements would exhibit characteristics similar to those associated with ambient bridge behavior, the sensor selected for monitoring vibrations in a burning structure was a servo-balance accelerometer. The accelerometer is a small, lightweight, hermetically sealed unit with a noise threshold of 1 micro-g and a flat response over a broad frequency range 0-300 hz. The accelerometer is shown in Figure 5 and specifications are included in Appendix I. The sensor is typically flown in aircraft guidance and control units and has been used to monitor wave-induced vibrations in large offshore platforms, and in many low-level tests conducted on large civil structures.

The accelerometer is a current output device with a sensitivity of approximately 1.3 ma/g. This allows extended cable lengths to be used with the accelerometer and a load resistor can be placed at the data acquisition location (described later) to obtain (virtually) any desired v/g sensitivity rating. A 10 v/g sensitivity was used during the burn tests described in Section 3.0. These units have been used to monitor large concrete dams and cable lengths approaching 2000 ft have been used without loss of signal quality or strength. During the conduct of a burn test, the measurement center may be located at distances greater than 500 ft from the structure and long cable lengths may be required. Sensors that are voltage output devices can experience significant signal loss over long cable lengths and often require additional cable amplifiers to maintain acceptable signal levels.

Operating temperatures of the unit are limited to 205 degF, well below the more than 1000 degF attainable in a burning structure. A method of thermal protection, therefore, was developed to maintain temperatures below 205 degF at the unit and to protect from smoke and water damage. A commercially available thermal insulation blanket (see Appendix II) was determined to be suitable for the current application. The blanket is a foil-encapsulated, non-combustible, inorganic, flexible fireproofing wrap capable of providing 2300 degF insulating capability. Although no data were made available, the manufacturer reported tests in which the blanket was used to wrap standard schedule 40 PVC pipe subjected to high temperature and protection to 2000 degF was achieved. The blanket is shown in Figure 6 and is easily cut using a drywall or gypsum knife.

The accelerometer installation procedure allows attachment at a selected measurement location and protects the sensor during burn. In the sequence shown in Figure 7, installation begins by drilling and placing a concrete anchor (0.25 in. diameter, approximately 0.75 in. long) into the brick at the measurement location. A section of the thermal blanket is centered over the hole and held in place with concrete nails. A mounting aluminum block that contains the accelerometer is then bolted in place. The high sensitivity of the accelerometer allows the unit to merely be placed snug against the mounting surface. In addition, direct attachment to wood frame members should be avoided since the sensor could fall away from the structure during test. Once mounted, the accelerometer is covered with a layer of the thermal blanket that is held in place with concrete nails. The final step in the installation procedure requires that the unit be covered with aluminum foil and sealed around the edges using aluminum duct tape to help protect against smoke and water impingement.

As can be seen in Figure 7, the accelerometer cable is left hanging from the sensor at the mounting location and must also be protected during the burn tests. Protection is achieved by wrapping the cable with aluminum foil as shown in Figure 8. The cable can also be buried underground adjacent to the structure. This technique has been used effectively by NIST to protect instrumentation harnesses and was adopted for this application.

The thermal blanket, if foil-encapsulated on both sides, must have at least one foil layer removed prior to covering the sensor to avoid electrical short circuits across exposed sensor pins. The sensor cables are routed back to the measurement center (see Figure 9) where acquisition is controlled via computer that acquires and plots measured responses and can produce real-time collapse indices (described in Section 4.0) derived from actual measurements.

2.2 Signal Conditioning and Acquisition Requirements

Ensuring adequate signal quality in terms of signal strength and frequency content is critical to the success of the proposed field test procedures. A typical block diagram of the signal conditioning circuitry utilized for capturing fire-induced responses is shown in Figure 10. The sensor's signal is first high-pass filtered to remove unwanted signal drift, amplified, low-pass filtered to limit frequency content and then amplified again. The low-pass cutoff is selected to ensure that unwanted high frequency content beyond the analysis range (present due to the broad-band energy of the fire excitation) is removed. A second stage of amplification is provided to ensure signal levels entering the analog-to-digital converter, or A/D, are on the order of 1v – 5v for a 16-bit A/D. Amplifier gains are selectable, and values ranged from 30 to 55 in the tests described in Section 3.0.

Measurements are acquired using a computer controlled A/D that digitizes the signals at a predetermined rate and then stores the time records to disk. Typical sampling rates ranged from 200 to 1000 samples per second, with the higher rates used to acquire responses exhibiting significant transient characteristics. Acquisition times varied depending upon the length of time required for the structure to collapse, but measurements have been acquired over intervals of 20 mins or more.

3.0 Description of Field Tests Performed

The field test procedures described above have been evaluated during a series of burn tests on full-scale structures that are listed in Table I. These tests are believed to be the first of their kind in which fire-induced structural vibrations were acquired for the purposes of monitoring and predicting impending collapse burning structures. The first tests, conducted on a large wood frame warehouse, were designed to evaluate test procedures, instrumentation and, quite frankly, to see whether or not measurable responses could be acquired during a burn test. Subsequent testing on wood frame and lightweight steel frame structures provided opportunities to correlate measured responses with observed collapse behavior. Descriptions of each test, objectives and significant outcomes are presented below.

3.1 Phoenix Warehouse Burn Tests

In conjunction with NIST and the Phoenix Fire Department, burn tests were conducted on a large warehouse (see Figures 11 and 12) 50 ft wide, 135 ft long and constructed with 50 ft long wooden trusses supported on masonry brick and concrete block walls. For these tests, a firewall was constructed in order to divide the warehouse into two zones, I and II, and two burn tests were conducted. The first burn was ignited in Zone I and vibration measurements were acquired at locations indicated by the red dots in Figure 11. Responses were acquired at the top of the truss (oriented in the vertical direction) behind the firewall and at the west end support (2 sensors oriented in the vertical and horizontal directions) on the truss located 15 ft south of the firewall. No measurements were acquired in Zone I during this test. A second burn test was conducted in which Zone II was ignited, however, no measurements were acquired during this test.

3.1.1 Sample Measurements and Evaluation of Test Objectives

The measurements shown in Figure 13 acquired during the warehouse burn tests are believed to be the first of their kind to be reported. The test provided an opportunity to evaluate the proposed field test procedures and instrumentation and was helpful in designing and implementing modifications in subsequent tests. Data acquisition was unexpectedly halted during the Zone I test when radiant heat levels required that all personnel and equipment be moved back from the structure. At that time, all electrical power to the measurement center was cut off and no further monitoring was performed. Nonetheless, a sufficient amount of data was recorded with which to evaluate test procedures, instrumentation and data quality.

Data were acquired digitally at a sample rate of 200 samples per second, amplified with a gain of 55 and low-passed filtered at 25 hz. With these parameters, aliasing was prevented since the Nyquist frequency (or, highest frequency that can be reproduced) was 100 hz and filtering at 25 hz was performed. Amplification gains were selected based on previous experiences with ambient testing of large civil structures (not burning), but it was not known prior to this test if satisfactory signal-to-noise ratios would result. Data quality was evaluated based on time and frequency domain criteria as well as on structural behavior content.

Time domain criteria for evaluating data quality included reviewing for the presence of offsets, sharp transitions and saturated levels. Offsets are typically not a desired feature of an acceleration-based measurement since an offset implies a constant acceleration at the measurement location. Since the burn test is expected to yield low-level responses, offsets would more likely result from signal conditioning circuitry and would not be considered indicative of actual structural behavior during burn. Sharp transitions are often observed in measurements where a sudden impact, loss of signal ground or other intermittent electrical failure occurs. In addition, these sharp transitions will produce broadband frequency content typically not associated with large civil structural response behavior.

Saturated levels or clipped responses should be avoided whenever possible. Saturation occurs in a response when levels are allowed to exceed the full dynamic range of the A/D. Perhaps the most common cause of saturated response is improper selection of sensor sensitivity. If the sensitivity of the sensor is too high, even a relatively small impact or shock could saturate the sensor itself. The problem is compounded when saturation is not detected at the time it occurs and the signal is subsequently filtered. What results is a measurement whose amplitude and frequency content has been artificially truncated. Also, if improper (i.e. too high) gains are selected in the signal conditioning amplifiers, saturation will occur and although the sensor itself might have produced a well-behaved signal, the end result will contain artificially truncated response characteristics. Using a single sensor to capture low-level response behavior as well as large transient responses that may be present nearing collapse can also result in saturated or clipped levels. Ideally, sensor sensitivity should be selected to allow accurate measurements of both low-level random and larger amplitude impact type responses.

The signal acquired at the top of the truss behind the firewall (top signal, Figure 13) contains significant saturation starting at about 950 secs. Inspection of the accelerometer at that location revealed significant smoke damage that probably elevated temperatures above the 205 degF operating limit of the senor and caused saturation to occur. No other instrumentation failures occurred this test.

Evaluation of signal quality can also be made in terms of an assessment of the signal information that indicates fire-induced structural behavior. A measurement can be expected to include information associated with behavior at ignition, during burn, and should contain information related to changing conditions as collapse develops. For example, a transient response is observed at each measurement location in Figure 13 near 100 secs that correlates well with the time of ignition. Close-up views shown in Figure 14 reveal a transient behavior that is typical of a mechanical system response to an impulse load. The response is characterized by a transition from (relatively) low to elevated amplitudes, and a return to pre- ignition levels. The longer response periods in the transient (near 103.5 secs, top trace Figure 14) are normally associated with resonant characteristics of the structure, and the decay (observed after ignition) is indicative of the structure's ability to dissipate energy. Important system identification parameters, namely resonant frequency and damping, can be determined by examining transient behavior. Typical random behavior recorded during burn is shown in Figure 15.

An attempt was also made to evaluate the fire-induced responses in terms of energy content typically observed in large civil structures. To do this, a spectral analysis was carried out using traditional Fast Fourier Transform techniques to determine the power spectral density (PSD) response functions associated with the measurements. Elevated PSD response occurs at resonant peaks and the frequencies of these peaks are referred to as resonant frequencies. The importance of the PSD lies in the fact that it provides indications of elevated structural response and can be interpreted as the change in mean squared value (MSV) with frequency. MSV, and more commonly root mean square ($RMS = \sqrt{MSV}$) is obtained by integrating the area under the PSD and can be used to evaluate a fire's ability to excite measurable structural behavior.

The PSD response functions shown in Figure 16 are based on an analysis of the entire record for each measurement. As a result, the effects of signal saturation dominate the response at the top of the truss evidenced by the fairly uniform, broadband PSD response (Figure 16, top trace). The absence of resonant behavior, however, does not imply that the fire was incapable of exciting structural response at that location. By comparison, fire-induced structural behavior is indicated in the PSD responses at the truss support. Resonant peaks are observed beyond 5 hz whose amplitudes and width suggest adequate signal-to-noise ratios and the presence of energy dissipation or damping in the structure. The spike at 0 hz results from signal bias imposed by the instrumentation and does not represent actual structural behavior. The noise floor for this measurement approaches a level 4 orders of magnitude below the largest resonant peaks and is further evidence of satisfactory data quality.

Of particular interest are the presence of 2 resonant peaks between 5 and 10 hz seen in the lateral response not seen in the vertical response, and the presence of spectral peaks between 10 and 15 hz in the vertical response not seen in the lateral response. Since the lateral truss responses occur within the lower frequency range, this suggests that the truss exhibits greater lateral flexibility. This is as expected since a roof truss is designed for minimal vertical deflections with greater in-plane stiffness that would be characterized by higher frequency response peaks.

Another interesting characteristic in the PSD responses is seen at 17.5 hz where the narrow peak response at the truss support (both directions) is indicative of forced response behavior. The narrow peak suggests that the structure is responding to an external steady-state, single frequency sinusoidal excitation. During the Zone I burn tests, a fire truck was positioned near the warehouse (actually closer to the Zone II measurement locations than to the Zone I burn area) that was idling during the test. Fire truck engines typically operate in the range of 1000 rpm and the 17.5 hz narrow band response actually corresponds to an operating speed of 1050 rpm. Thus, the instrumentation designed for these tests was also able to detect forced structural response associated with energy transmitted by an idling fire truck engine through the foundation of the warehouse and into the structure itself.

3.1.2 Significant Outcomes from the Phoenix Warehouse Tests

The presence of the transient response at ignition, the random response behavior observed during the burn and the numerous transients that appear in the responses at the truss support are strong indications that the fire was able to excite measurable structural vibrations in the warehouse. The sensor thermal protection procedures employed during these tests, however, were deemed to be unsatisfactory in light of the smoke damage to one sensor. Furthermore, the firewall did not allow a complete evaluation of test procedures since all sensors were (essentially) isolated from the fire in Zone I.

Perhaps the most significant outcome from this test was the realization that sensors placed at remote locations in the structure beyond the burn area were capable of detecting fire-induced vibrations. Responses at the truss support present strong evidence of the fire’s ability to generate global behavior in the warehouse. Being able to place the sensor away from the burn area also reduced the thermal protection requirements for subsequent tests.

3.2 Kinston Burn Tests

Experience gained from the Phoenix warehouse tests provided enhanced confidence in the field test procedures and instrumentation for gathering fire-induced vibration measurements. In collaboration with the Kinston Fire Department, the ATF and NIST, researchers participated in a series of burn tests in Kinston, North Carolina in which 5 single-family wood frame homes were burned to collapse. Of the 5 homes, 3 were monitored for fire-induced vibration response behavior leading to collapse. The following is a description of the tests conducted at 302, 304 and 312 Holloway Drive. Objectives for these tests included

1. To evaluate modifications in sensor installation and thermal protection techniques.
2. To evaluate fire-induced vibration response behavior in a burning wood frame structure
3. To induce and capture a collapse event in a burning wood frame structure.
4. To correlate changing response characteristics to collapse in a wood frame structure.

3.2.1 Sample Measurements and Evaluation of Test Objectives

Pictures of the homes at 302 and 304 Holloway Drive are shown in Figures 17 - 18 and sample acceleration responses acquired during the burn tests are shown in Figures 19-21. Typical PSD response curves are shown in Figure 22 for each house. Evaluation criteria used to evaluate data quality and the ability to detect structural vibration response characteristics were the same as those employed in the evaluation of the Phoenix warehouse data. Overall, the fire-induced response measurements at 302, 304 and 312 Holloway Drive were determined to be of high quality, and contained spectral characteristics indicative of structural behavior. Sensors were attached to the brick veneer on the exterior walls of each house. Unlike the Phoenix warehouse tests where the sensors were not directly affected by the fire due to the firewall, the sensors at Kinston were exposed to fire and falling debris. Data were acquired at 200 samples per second and gains of 30, 55 and 55 were used during the 3 tests, described below, respectively.

3.2.2 302 Holloway Drive

The responses at 302 Holloway Drive shown in Figure 19 and the top response in Figure 20 were acquired over the entire duration of the test. The data appear to be of high quality and no instrumentation failures were experienced during this test. Ignition occurred at approximately 330 secs and is characterized by an acceleration spike and a subsequent transient response. Apart from ignition, other events observed during burn included blown out windows, fire in the attic, and front porch collapse all of which appear as response transients. Although external coverings (e.g. siding) and appendages including the front porch overhang fell during burn, no dominant event (e.g. roof collapse) was recorded. Still, the spectral content in the PSD (Figure 24, top trace) indicates structural response was induced during burn between 10 hz and 15 hz with peak widths and amplitudes consistent with structural behavior. Harmonics associated with operating machinery were also detected as indicated by the narrow peak responses present.

3.2.3 304 Holloway Drive

Test procedures and instrumentation employed during this test were the same as those used in the test at 302 Holloway Drive. However, it is clear from the measured responses shown (Figures 20 and 21) that portions were lost during acquisition as evidenced by the dead-band regions in the measurements. During the test, portions of the eve above one sensor (at Channel 3) impacted and ignited the cable causing the main power fuse to blow in the signal conditioning box that also provides power to the sensors. The fuse was replaced and acquisition restarted, however, the response on Channel 3 remained down due to the burned cable. After acquisition was restarted, responses on Channel 1 and 2 remained active throughout the remaining portion of the test, and the response at Channel 4 was interrupted when falling debris disconnected the sensor from its cable. No significant collapse event occurred during this test and the PSD shown in Figure 24 (middle trace) is comparable to that obtained from the test at 302 Holloway Drive.

The failure to collect a contiguous set of response measurements was due primarily to the harsh test environment and as a result, not all of the original test objectives could be achieved. Still, based on the experience gained, modifications were implemented to reinforce cable connections and to provide additional cable protection in the subsequent test at 312 Holloway Drive.

3.2.4 312 Holloway Drive

The test conducted at 312 Holloway Drive was designed specifically to monitor and predict an artificially imposed collapse mechanism in the structure. After a review of the tests at 302 and 304 Holloway Drive, it became apparent that the absence of a dominant collapse event made it difficult to attempt correlations between measured responses and changing structural conditions during burn. As a result, a collapse mechanism leading to one measurable (i.e. large) event was designed for the 312 Holloway Drive test in order to acquire response information that could be correlated to an actual collapse event.

A heating oil tank (steel, capacity 250 gals) was mounted on the roof (see Figure 22), strapped in place, and filled with water to achieve a load of approximately 600 lbs. The objective was to induce tank collapse through the roof at some time during burn but prior to total structural collapse while recording vibration responses prior to, during, and after collapse. Fire in the structure was ignited using 3 gals of gasoline that produced a large explosion in the front living room of the house (located on the right side of the picture shown in Figure 22). The structure burned for approximately 1200 secs (20 mins) before the tank collapse through the roof.

Measured responses are shown in Figure 23 and excellent data quality was obtained at all locations. The large acceleration spike at 773 secs easily identifies ignition, and the response prior to ignition was associated with firefighters making preparations to ignite the structure. The majority of the response is characterized by random behavior that masks a series of small amplitude transient events that are not readily observed in the traces shown. Large acceleration spikes at the end of the records coincide with tank collapse through the roof and also indicate structural response after the tank impacted the floor. Spectral content (Figure 24, bottom) is consistent with behavior seen in the previous tests at 302 and 304 Holloway Drive.

3.2.5 Significant Outcomes from the Kinston Tests

These tests are believed to be the first of their kind in which fire-induced responses were acquired from a series of burning wood frame structures. In addition, responses were obtained using sensors that were mounted to exterior surfaces but that were not actually attached to the wood frame itself. Sensor locations at door and window heights provided clear indications of fire-induced behavior and thermal protection of both sensors and cabling was improved significantly during these tests.

The most significant outcome, however, was the ability to introduce a collapse mechanism that was captured by the response measurements, on videotape and in event logs describing eyewitness accounts. High data quality was once again demonstrated by the ability to capture low-level random and transient behavior associated with activities in and around the structures prior to burn. Although dynamic tests on wood frame structures have not been widely reported in the literature, the spectral content shown in the PSD responses appears to indicate structural behavior was excited during burn.

3.3 Smoketown Mall Burn Tests

The Kinston burn tests provided researchers with valuable experience that helped refine sensor installation and protection techniques and produced a data set of measured responses that captured a collapse event during burn. Buoyed by the apparent success of those field tests, a third series of tests was planned in October 2001 at a strip mall in Woodbridge, Virginia. The mall was constructed in the late 1980's using lightweight open-web steel trusses and would be the first attempt at monitoring fire-induced vibrations in a burning steel frame structure.

The events of September 11, 2001 and the collapse of the World Trade Center Twin Towers and WTC 7 brought heightened interest to the current research effort. The Twin Towers and WTC 7 are the only known cases of total structural collapse in which fire played a significant role. The collapse of WTC 7 is of particular interest since it resulted primarily from fire, and apparently not from impact or other damage associated with the collapsed towers. Multiple postponements of the mall burn tests resulted in the aftermath of September 11th in large part because of the environmental assessments that were required prior to gaining approval for these tests.

3.3.1 Sample Measurements and Evaluation of Test Objectives

The burn tests at the Smoketown Mall took place in May 2002 and three stores in the mall were burned. A portion of the front of the mall is shown in Figure 26, and a plan view is shown in Figure 27. Objectives for these tests were

1. To evaluate fire-induced vibration response behavior in a burning steel frame structure.
2. To induce and capture a collapse event during burn.
3. To correlate changing response characteristics to collapse in a steel frame structure.

An inspection of the mall was performed in February 2002 for the purposes of evaluating ambient response characteristics of the mall structure, and the roof system and roof trusses were of particular interest. The roof system consisted of a metal deck, a rigid insulation (foam core) covered with a single-ply membrane and topped with gravel. The lightweight open-web steel trusses (schematic shown in Figure 28) were of the type widely used in floor and roof systems for commercial and institutional buildings nationwide and are similar in design to the floor trusses used in the WTC Twin Towers. Since no previous field experience with this type of structure was available, response levels and frequency content needed to be evaluated in order to properly select signal conditioning parameters (i.e. amplifier gains and filter cutoffs). A review of ambient accelerations acquired at Store #1 during the inspection suggested that gains of 30 and a low-pass filter cutoff at 25 hz would provide adequate signal quality.

A similar collapse scenario to that used during the wood frame burn tests was used in the Smoketown tests by placing 55 gal barrels filled with water on each of the store roofs. Stores #1 and #2 were loaded with 4 barrels and Store #3 was loaded with 12 barrels. For each test, fire was remotely ignited using gunpowder placed at the bottom of a stack of wooden pallets and no accelerants were used. An interior view of Store #1 prior to burn and a snapshot taken during burn are shown in Figure 26. Similar pictures of the Store #2 burn test are shown in Figure 27, and a snapshot taken during the test at Store #3 is shown in Figure 28 (top). The picture shown in Figure 28 (bottom) was typical of the type of structural damage observed after each test.

3.3.2 Store #1

The Store #1 (17.5 ft wide by 75 ft long) measurements (see Figure 29) include a fairly long period of structural response prior to ignition in order to assess static deflections and the load capacity of the roof system. This information was used to determine subsequent loading configurations for the Store #2 and Store #3 tests.

The measurements acquired are of high quality and contain many of the characteristics previously observed during the wood frame burn tests. The PSD shown in Figure 32 (top) indicates significant resonant behavior up to 30 hz, and the attenuated response beyond 25 hz coincides with the low-pass filter cutoff. As in previous tests, resonant peaks associated with response due to operating machinery (e.g. fire trucks) are present (e.g. at 20 hz). In order to identify the exact nature of the spectral behavior seen in the PSD, a detailed dynamic survey of the structure would be required. Still, the PSD indicates the fire was able to excite measurable structural resonances during burn and data quality based on spectral content is high. Distinguishing features include the fairly uniform random response throughout the record and the appearance of a series of acceleration transients starting near 600 secs that remain throughout the test. Roof collapse did not occur during burn, however, and acquisition was halted prior to the start of firefighting operations.

The large amplitude response transients suggest that the dominant effect on the structure during burn may have been related to weakened welds and softening members in the roof trusses. The picture in Figure 28 (bottom) gives a clearer view of the truss and roof system that suggests sagging occurred during test. No weld inspections were made in the aftermath of these tests, but it is quite possible that weld integrity was also reduced by exposure to elevated temperatures that exceed 1400 degF during burn. The sensor is capable of detecting "pops" that could be associated with weakening welds, and can certainly capture sudden changes in truss positioning that would result as the members soften. Both scenarios result in measurable transient responses. This behavior is in contrast to that observed in burning wood frame structures that are consumed by the fire and produce predominately random responses.

3.3.3 Store #2

A second test was conducted on Store #2 (20 ft wide by 75 ft long), and even though the roof did not collapse during the Store #1 tests, 4 barrels filled with water were used to load Store #2. Measured responses are shown in Figure 30, and an attempt was made to monitor the back of Store #1 to assess the fire's ability to excite structural response at a remote location.

Even though the measurement at the storefront seems to indicate reasonable behavior (even in the presence of what appear to be one-sided acceleration transients between 500 secs and 600 secs), the response at the back of the store is saturated and of poor quality. By comparison, the response at the remote location behind Store #1 does not contain adequate signal strength and a higher gain for this measurement was probably needed. The poor quality in the measured responses coupled with the fact that roof collapse did not occur made it difficult to evaluate structural behavior during burn.

A PSD was estimated from the measured responses and is shown in Figure 32 (middle trace). The response is dominated by the presence of 3 narrow peaks associated with response due to operating machinery at the site. The wide base at 17.5 hz and the small variations on both sides of the peak suggest that structural behavior was captured by the measured responses, however. Even though advanced signal processing techniques could improve this spectral estimate, this test is considered to have produced unsatisfactory results. Water is believed to have penetrated at least one cable connection and may have contributed to the poor quality in response measurements for this test.

3.3.4 Store #3

Determined to induce a roof collapse during burn, the load at Store #3 (20 ft wide by 90 ft long) was increased by placing 12 barrels filled with water on the roof. Roof collapse occurred within 7 mins of the start of this test and was captured in the measurements at each end of the store. The measurements are shown in Figure 31 and are, by all criteria previously applied, of high quality. The PSD response shown in Figure 32 (bottom) provides further evidence of high data quality and of the significant structural behavior induced by the fire.

The acceleration response at Store #3 is similar to the behavior seen during the Store #1 test, except for the presence of transient responses that seem to increase in number and amplitude as collapse occurs. Motivated by the high data quality of these measurements, an analysis of ignition timing and location was performed and is presented in Appendix III.

3.3.4 Significant Outcomes from the Smoketown Mall Tests

These tests are believed to be the first of their kind in which fire-induced responses were acquired from a steel frame structure. More importantly, the set of measured responses is believed to be the first set that contains recorded structural behavior associated with a known collapse event in a burning steel structure.

4.0 Derivation of Collapse Indices Based on Fire-Induced Vibration Measurements

The series of field experiences described above produced two data sets of measured vibration responses from burning structures that collapsed where fire played a significant role. One set of responses was acquired on a wood frame structure and the other was obtained during tests on a steel frame structure. In addition to the measured responses, video recordings and event logs of eyewitness accounts were also acquired for these tests.

Analyses aimed at developing a response or collapse index, that not only could indicate collapse, but more importantly, might provide an early warning of the collapse event have been performed. Collapse indices were developed based on response magnitude, response statistics and on system identification parameters. An index's ability to track changing conditions in the structure leading to collapse is evaluated on trends in the index behavior. Evaluations based on index response levels (i.e. index magnitude) require that additional field tests be conducted on both wood and steel frame structures in order to assess the importance of relative and absolute index levels.

4.1 Response Magnitude based Collapse Indices

Perhaps the simplest collapse index that can be developed is one based on the response measurements themselves. For instance, the character of the measured wood frame response shown in Figure 33 (top) is generally random during a large portion of the burn, although large transients exist primarily at ignition and at collapse. In the case of the measured steel frame response, also shown in Figure 33 (bottom), the response is dominated by transient spikes that increase in magnitude and number as collapse occurs. Close-ups of the wood frame response at ignition, post ignition and prior to collapse are shown in Figure 34, and similar close-ups are shown in Figure 35 for the steel frame response. Although noticeably different in overall character, both wood and steel frame responses exhibit changing behavior approaching collapse.

Response magnitude collapse indices are obtained by enveloping the absolute value of the measured responses and are shown for both structures in Figure 36. Although index characteristics differ for each structure, envelopes (denoted by the solid black lines) of each index can be described by a low-level, uniform region that includes ignition followed by a transition region and the onset of collapse. The significance of these indices could lie in the relationship between the trends in the index and structure type. For instance, it would prove significant if the plateau region in the wood frame collapse index was characteristic of all similar structures to the extent that the duration of the transition region could be used to predict collapse. Likewise, the sloped transition region seen in the steel frame collapse index could prove invaluable in predicting collapse for this structure type.

4.2 Statistically Based Collapse Indices

A series of analyses was performed in an attempt to develop collapse indices based on response statistics. In particular, moment statistics ranging from standard deviation to Kurtosis and Skewness were examined, but not all of these indices provided clear correlations with recorded events and few provided clear indications of impending collapse.

It was determined that interpretation of statistically derived collapse indices could be enhanced by first filtering the response measurements. The intent was to reduce frequency content leaving only low frequency behavior to indicate collapse. This is consistent with the notion that while actual collapse may appear to occur suddenly, collapse cannot occur in the absence structural changes that probably include sagging of main load carrying members and failed connections – changes that typically are associated with low frequency response behavior.

Selection of a suitable low-pass filter frequency cutoff was based on making sure that the filtered result retained important response characteristics. These characteristics included transient behavior at ignition, during burn and, especially, at collapse. For the wood frame structural response, frequency content was limited to 1 hz and the filtered response is shown in Figure 37. Retained response characteristics are indicated by evidence of ignition and collapse (middle and bottom traces, Figure 37). A particularly interesting result was obtained from the 2nd Moment centered about the origin for this filtered response.

The 2nd Moment centered about the origin is defined by

$$M_2 = \frac{1}{N}\sum_{i=1}^{N} x_i^2$$

where N is the total number of points in the response, and x_i is the i^{th} value of the response. The collapse index is shown in Figure 38. The top trace is the collapse index that results from the analysis of the 1 hz filtered response, and the bottom trace is a smoothed version of the index obtained by fitting a polynomial function to the top trace. Significant features include a jump in response at ignition, level response between 900 secs and 1300 secs, and a steady increase in response leading to collapse near 1900 secs. The smoothed index function is particularly impressive in its character and ability to provide warning associated with the sloped or transition region indicated prior to collapse. The resemblance to the hypothetical index function described in the original proposal (see Figure 1) is also striking.

A similar analysis was performed on the steel frame response. In this case, however, frequency content up to 25 hz was retained since filtering below 25 hz removed a significant portion of the critical behavior at ignition and collapse. Analysis was carried out after ensuring that all frequency content was removed beyond 25 hz using a digital filter and the filtered response is shown in Figure 39 (top). The resulting collapse index based on the 2nd Moment centered about the origin is also shown in Figure 39 (bottom).

The index is essentially a series of peaks increasing in amplitude as collapse occurs. The absence of index response at ignition is consistent with the manner in which the fire was ignited for this test (remote ignition of gun-powder at the base of wooden pallets) in contrast to the explosion associated with use of accelerants in the wood frame test. Additional testing is required to determine whether the presence and amplitudes of the index peaks are capable of predicting collapse.

4.3 System Identification Based Collapse Indices

Damage detection based on changes in system identification parameters is well documented in the literature, and a particularly good summary is presented in Ref [1]. A considerable number of attempts were made in the late 1990's to develop damage detection algorithms based on the premise that system parameters, being functions of the physical properties of the structures, change as changes in structural stiffness occurred. Early work focused on examining changes in resonant frequencies and damping to detect damage in large civil structures (i.e. bridges). However, these parameters proved to be insensitive to lower levels of damage and did not provide clear indications of the location or extent of damage.

Since the goal was to develop techniques suitable for detecting structural damage in order to mitigate high repair costs and loss of function, tracking changes in parameters that were weakly related to damage, but that might change rapidly for "significantly large" amounts of damage was not particularly useful. In fact, a study of the bridge overpass in Figure 4 showed a less than 5% change in resonant frequency after introducing a number of increasingly damaged conditions in the structure.

Since the current effort is aimed at developing indices for monitoring collapse in a burning structure, damage is already assumed. In fact, the process by which the structure is undergoing damage can be assumed to be irreversible and, if left unchecked, will ultimately result in collapse. As a result, the following hypothesis is proposed.

Although parameters such as resonant frequency and damping appear to be insensitive to low-level damage in structures, measurable changes in these parameters can be expected as collapse mechanisms develop and may lead to the development of an index for tracking changes leading to collapse.

4.3.1 Extracting System Parameters from Measured Responses

A simple physical model of a structure is proposed and shown in Figure 40. The model consists of a spring mass damper oscillator and is intended to motivate the discussion of the proposed analysis technique. The model is not intended for use as a predictor or to reproduce responses from a burning structure.

The governing equation written in canonical form is given as

$$\ddot{x}(t) + 2\zeta\omega_n\dot{x}(t) + \omega_n^2 x(t) = f(t)$$

where $x(t)$ represents the response, ζ and ω_n are system parameters damping and resonant frequency, respectively, and $f(t)$ is the random fire excitation. The response can be expressed as

$$x(t) = e^{-\zeta\omega_n t}\left(A\sin(\omega_d t + \phi)\right) + x_f(t)$$

where the first portion of the response is associated with the free vibration of the structure with amplitude A determined by initial conditions of displacement and velocity, and the second portion of the response is associated with forced random excitation of the fire. The parameters $\omega_d = \omega_n\sqrt{1-\zeta^2}$ and ϕ are the damped resonant frequency and phase of the free vibration response.

As expressed, a direct relationship between system parameters ζ and ω_n and the envelope of the free vibration portion of the response exists, and if the free vibration can be extracted from the measured response, a collapse index based on changes in the product $\zeta\omega_n$ during burn can be examined.

4.3.2 Application of Random Decrement Analysis Technique

Developed during the late 1960's at NASA for the purposes of estimating damping from random vibration measurements to track deterioration in aircraft wings, the Random Decrement analysis technique provides a convenient approach to extracting the desired response component. Details of the technique are found in Ref [2], and an overview of the application to the measured responses acquired during burn tests is presented below.

The Random Decrement is a time domain averaging technique that extracts the free vibration component of the measured response. A threshold level is selected and applied across the entire response, and a segment (of predetermined length) is extracted each time the threshold is crossed. A typical application of the analysis technique would produce a single Random Decrement Signature, or RDS, by averaging all of the segments extracted from the entire response. If however, a collapse index is to be based on a time varying sequence of signatures, an alternate averaging scheme is required. While a variety of averaging schemes can be used to obtain a time varying sequence of signatures over the entire response, the following approach was used.

After extracting all segments across the entire response, the first RDS in the time varying sequence is obtained by averaging segments 1 through 50. A typical segment of length 0.5 secs is shown in Figure 41. The next RDS in the sequence is obtained by averaging segments 2 through 51, and so on. In this manner, each RDS results from the moving average of 50 segments. A typical RDS is shown in Figure 42.

The power of the technique lies in the fact that as the number of averages increases, the random portion of the response should eventually average to zero. Since the sign of the initial velocity condition alternates between positive and negative, the initial velocity portion of the free response should also average to zero (assuming a random velocity distribution). If a sufficient number of averages are available, the RDS should only contain that portion of the response associated with the free vibration due to the initial displacement condition or threshold. The resulting signatures will exhibit a decay envelope that can be described by $e^{-\zeta\omega_n t}$. A methodology exists that allows the envelope parameter $\zeta\omega_n$ to be estimated from the magnitude of the analytical function associated with the RDS. The method and a theoretical application are described next.

For each RDS, an analytic function can be defined as

$$RDS_a(\tau) = RDS(\tau) + jHT(RDS(\tau))$$

where $RDS_a(\tau)$ is the analytic function of $RDS(\tau)$ and $HT(RDS(\tau))$ is the Hilbert Transform of $RDS(\tau)$. τ is the time variable in the signature. Written is this form, the analytic function is complex and can be re-written as

$$RDS_a(\tau) = |RDS_a| e^{-j\theta(\tau)}$$

where $|RDS_a(\tau)|$ and $\theta(\tau) = \tan^{-1} \dfrac{HT(RDS(\tau))}{RDS(\tau)}$ are the magnitude and phase of the analytic function. Since the Hilbert Transform is obtained by taking the Fourier Transform of $RDS(\tau)$ and shifting all negative frequencies by 90 degs and all positive frequencies by –90 degs and then taking the inverse Fourier Transform, the magnitude of the signature remains unaffected by the Hilbert Transform. The decay envelope can still be represented by $e^{-\zeta\omega_n t}$ and the product $\zeta\omega_n$ can be obtained as

$$\zeta\omega_n = \frac{d}{d\tau}\left(-\ln|RDS_a(\tau)|\right) .$$

The above result suggests that the product of the system parameters ζ and ω_n is determined from the slope of the envelope of the analytic function.

To demonstrate the above relationship, assume a RDS of the form

$$RDS(\tau) = e^{-0.0628\tau} \sin(6.2829\tau + \theta)$$

where the system parameters $\zeta = 0.01$ and $\omega_n = 2\pi \, {}^{r}\!/_{s}$. The RDS is plotted as the top trace in Figure 43 and the natural log of the magnitude of the corresponding analytic function is plotted as the bottom trace. The absolute value of the slope of the magnitude is the estimate of the product $\zeta\omega_n$ and is obtained by linear curve fit to be 0.0618, which is 1.6 % less than the actual value of 0.0628.

The Random Decrement analysis technique and the analytic function based methodology for estimating the product $\zeta\omega_n$ have been applied to the measured responses from the steel frame burn test. A collapse index based on the values of $\zeta\omega_n$ estimated from a time varying sequence of signatures during burn is shown in Figure 44. Index values prior to 200 secs do not exist for this test since the first segment to exceed the threshold level did not occur until after 200 secs.

The trend in the index appears to track changes in $\zeta\omega_n$ during burn that are consistent with expected results. For instance, if each system parameter and hence their product remains fairly unchanged in the presence of “low-level” damage, then any index based on $\zeta\omega_n$ could be expected to vary slowly as collapse occurs. This is clearly indicated in the index behavior approaching 400 secs. The oscillation in index value after 400 secs requires additional study; however, the saturated response transients (i.e. clipped peak responses) may affect the index behavior during this time. Still, the index shows a definite declining trend in $\zeta\omega_n$ as collapse occurs. Collapse coincides with a sudden drop in index that occurs after 500 secs and correlates well with the index based on response magnitude and with the large transients in the measured responses as collapse occurred. Predictive capability of the index remains to be evaluated, but indices that can exhibit slowly varying behavior could prove useful in monitoring changing conditions in burning structures.

5.0 Outcomes and Implications

A number of significant outcomes have been identified as a result of the research effort described above. The most significant outcomes are associated with

1. the conduct of full-scale burn tests on wood and steel frame structures that verified the existence of fire-induced behavior in burning structures, and with
2. the development of test procedures and instrumentation and the ability to acquire high quality vibration responses in a burning structure, and with
3. the conduct of tests on wood and steel frame structures in which responses were acquired that captured structural behavior at ignition, during burn and during a major collapse event, and with
4. the development and evaluation of collapse indices based on response magnitude, response statistics and system identification parameters that detect changing conditions in wood and steel frame structures and that appear to provide early warning of impending collapse.

The implications of these outcomes, and of the research program in general, especially in the aftermath and context of the collapse of the WTC Twin Towers and of WTC 7 appear to be many. While it is premature to claim that a full assessment of the proposed field and analysis techniques to predict collapse in a burning structure has been made, the concept of being able to track changes in fire-induced structural responses leading to collapse appears to have merit.

If additional field tests can be performed that produce responses of the type described in the analyses of the collapse indices above, and if trends in the indices continue to suggest an ability to relate fire-induced vibrations to changes in structural condition, then a number of significant contributions to the fire research community may result. Sensors could be designed and developed specifically for monitoring behavior in the event of a structural fire. Real-time collapse indices based on these recordings would provide firefighters with information not currently available and that could lead to improved safety during operations, mitigating injury or even loss of life. The basic concept of fire-induced vibration monitoring demonstrated by the current effort is believed to be suitable for tall structures, or any structure, that exhibits structural behavior during burn.

6.0 Recommendations for Future Work

Although a number of outcomes and findings have resulted from the current effort, improved field test procedures and a better understanding of sensor requirements are needed. The development of wireless sensors with adequate sensitivity would enhance field-testing and perhaps reduce instrumentation costs. The sensor used in the field tests described here provided excellent data quality but at high cost (in excess of $1000 per unit). Although the sensor used was able to capture low-level random behavior, evidence of clipped transient peaks in some records near collapse suggest that a lower sensitivity may be needed to measure larger transient peak amplitudes.

Additional field burn tests on structures are required. The database of fire-induced responses must be expanded in order to better understand the dynamic behavior of burning structures and to enhance confidence in the proposed techniques. More work is also needed in the analysis and development of indices for predicting impending collapse. In particular, additional studies related to the application of random decrement analysis to fire-induced responses should be performed. Effects of filtering measured responses, of saturated or clipped transient peaks, and of averaging schemes on the random decrement signatures require further study.

7.0 Summary and Conclusions

Field test procedures and instrumentation have been developed for the monitoring of fire-induced vibration responses in burning structures. A series of field tests in which wood and steel frame structures were burned has been completed. For each test, measurements of structural response prior to ignition, at ignition and during burn were acquired using highly sensitive accelerometers mounted to the structure. Structural responses of wood frame and steel frame structures that experienced roof collapse during burn have also been acquired.

Collapse indices have been developed based on response magnitude, response statistics, and on system identification parameters derived from measured fire-induced vibration responses. The indices were evaluated for trends that indicate changing conditions during burn. Indications of collapse in a wood frame and steel frame structure can be seen prior to actual collapse.

Findings from this study may provide firefighters with information not currently available that could inform operations during a structural fire. Sensor development is underway that could lead to wireless devices capable of being used by firefighters to monitor changing conditions in a burning structure. In addition, sensors may also be installed in existing structures to transmit information in the event of a fire. Finally, fire-induced responses may also be used to determine estimates of ignition start time and location with the structure. This capability may prove useful for fire and arson investigators.

8.0 References

1. Farrar, C.R. and Doebling, S.W., "An Overview of Modal-Based Damage Identification Methods," in Proc. of DAMAS Conference, Sheffield, UK, June 1997.
2. Asmussen, J. C., “Modal analysis based on the random decrement technique - application to civil engineering structures,” Ph.D Thesis, Aalborg University Library, 1997.

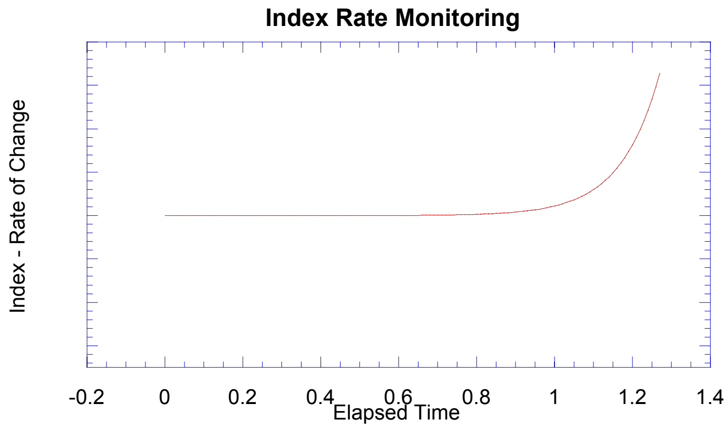
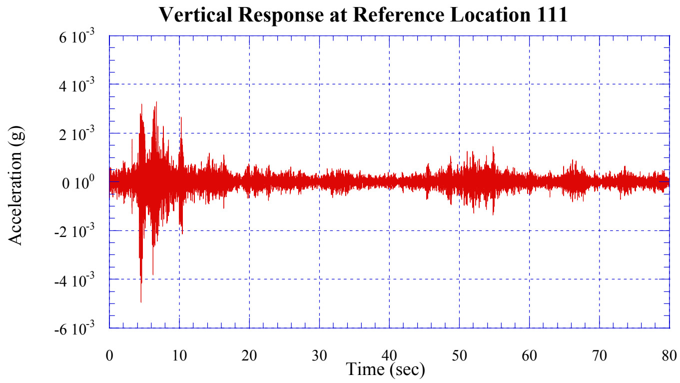


Figure 1 – Proposed Index behavior for predicting impending collapse based on acoustic emissions measured from a burning structure.

Figure 2 – One of four two-room wood frame structures burned to collapse during training exercises conducted by the Phoenix Fire Department and NIST.

The structure was outfitted with typical furnishings and walls were covered using drywall or wood paneling. Although somewhat difficult to see from the bottom pictures, a vertical strand of thermocouple wiring is shown in the bedroom and front room of the structure.

Figure 3 – Phoenix Fire Department burn test of one of the four structures.
The top picture shows the mannequins and HVAC on the roof early in the burn, and the bottom picture was taken after roof collapse and prior to firefighting operations.



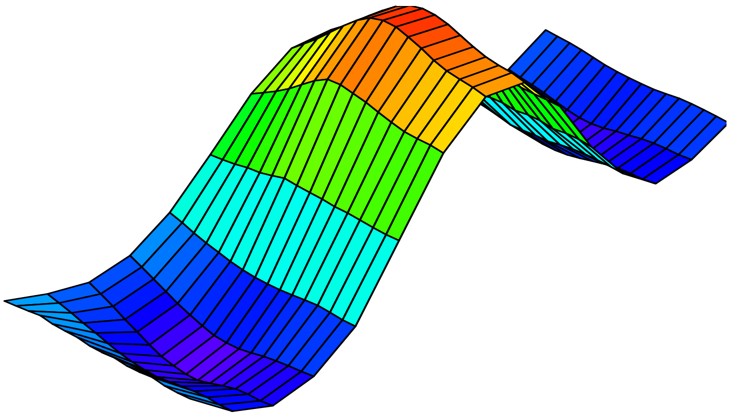


Figure 4 – Seymour Ave. bridge located near Cincinnati, Ohio (top) and a typical measurement (middle) taken during an ambient test.
The measurement is acceleration acquired on the bridge deck and the transient spikes seen in the first 10 secs of the response are associated with traffic passing under the bridge. No traffic was allowed on the bridge during the tests. The remaining portion of the measurement is characterized as being random and low-level (milli-g's). The bottom figure is the fundamental vibration response shape of the bridge obtained from the ambient response measurements.

Figure 5 – Servo-balance accelerometer shown in an aluminum mounting block.
The instrument is a highly sensitive unit that is typically flown on aircraft guidance and control units. Rigid body accelerations (that correspond to 0 Hz) are acquired using the accelerometer and this proves to be a useful characteristic for the vibration monitoring of burning structures. (see Appendix I for specifications).

Figure 6 – Research assistant shown cutting the thermal insulation blanket used to protect the accelerometer during burn tests.
(see Appendix II for specifications).

Figure 7 – Installation sequence of an accelerometer in preparation of a burn test. The top figure shows the sensor mounted on the exterior brick surface with the thermal blanket nailed to the surface and the mounting block bolted to the brick. The sensor is then covered with a layer of thermal blanket (middle, left) that is again nailed at the mounting location (middle, right). Finally, aluminum foil is placed over the mounting location and sealed along the edges using aluminum duct tape. A tight seal aids in preventing smoke and water damage to the sensor.

Figure 8 – Completed sensor installation in preparation of a burn test.
Aluminum foil is used to protect the sensor's cable, and where possible, the cable can be buried adjacent the structure for additional protection.

Figure 9 – Measurment center.
Shown is the signal conditioning box that contains 10 channels of conditioning (see block diagram below). Sensor cables are routed from the measurement locations on the structure to the box and then transferred to the computer controlled A/D (laptop system shown).

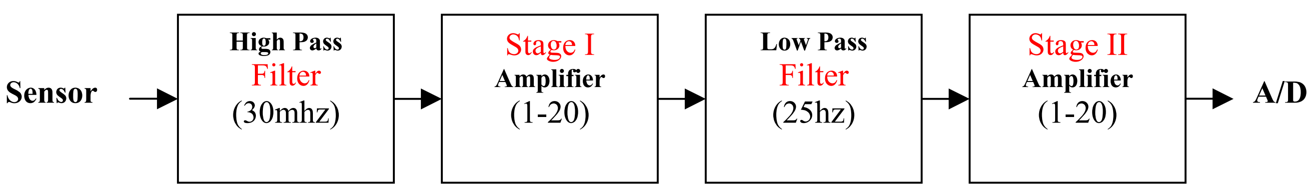


Figure 10 – Typical signal conditioning block diagram.
The sensor output is filtered to remove unwanted drift not associated with structural behavior and is then amplified, filtered again, and amplified prior to being digitized by the analog-to-digitial (A/D) converter.

Table 1 - Field tests conducted to evaluate field test procedures for monitoring and predicting collapse in burning structures.

Of the tests conducted, responses associated with roof collapse were acquired on a burning wood frame structure during the Kinston tests and on a burning steel frame structure during the Smoketown Mall tests.

Structure Type	***Location, Date***	***Description***	*Number*
Wood truss and brick	Phoenix, Arizona – March 2001	Large warehouse	1
Wood frame	Kinston, North Carolina - July-August 2001	Single family homes	3
Lightweight steel open-web truss and concrete block	Woodbridge, Virginia – May 2002	Strip mall stores (Smoketown Mall)	3

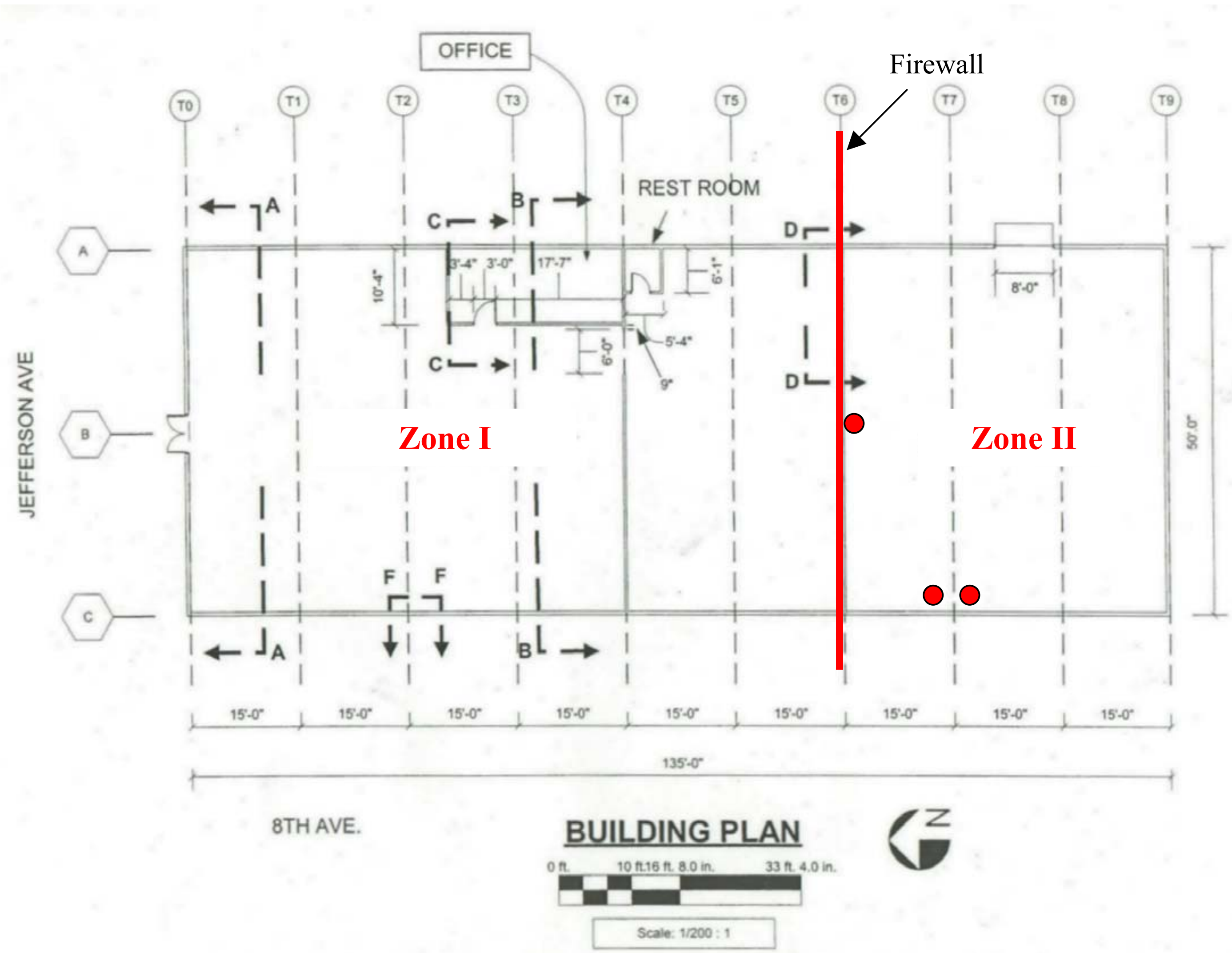
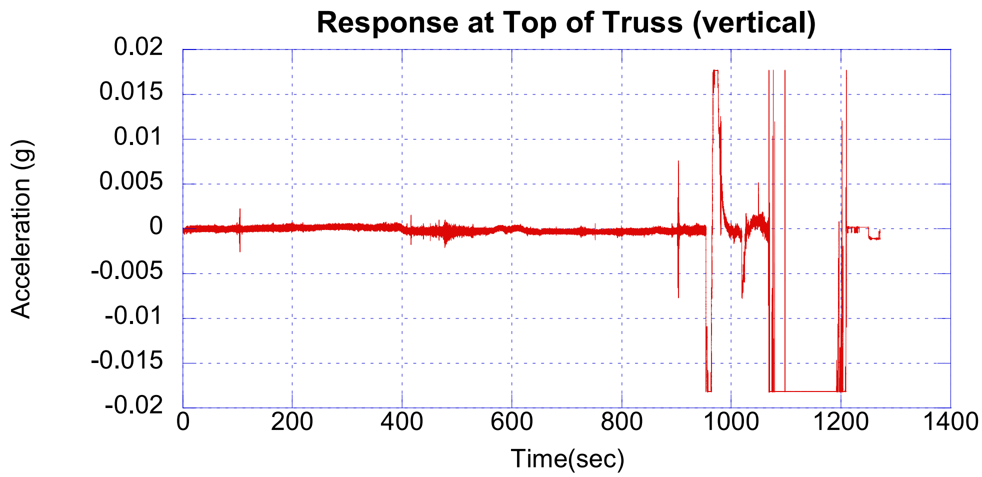
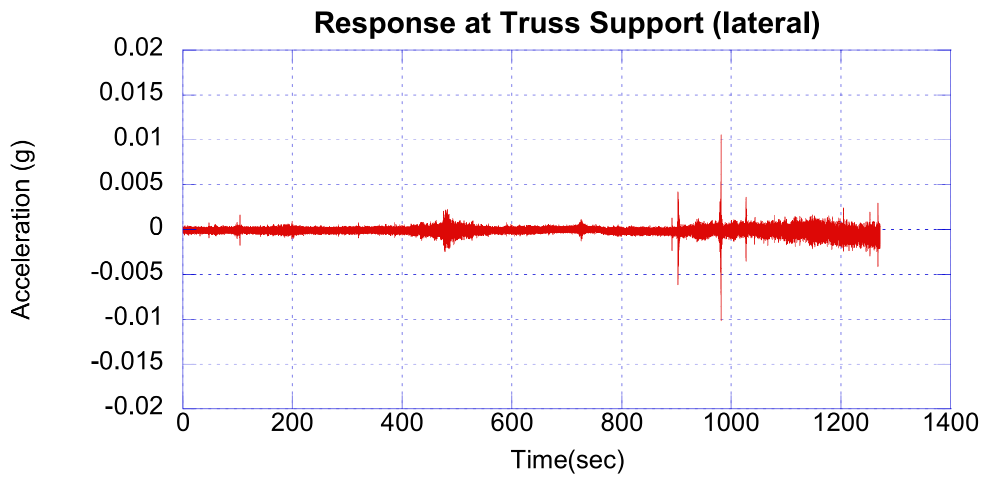


Figure 11 – Building plan of the Phoenix warehouse.
During the first burn, fire was ignited in Zone I and was allowed to burn until roof collapse but was prevented from entering Zone II. Fire-induced responses were acquired at locations in Zone II denoted by the solid red dots. A second burn test was conducted by igniting a fire in Zone II, however, no additional measurements were acquired during this test.

Figure 12 – Phoenix warehouse burn test.
The top photo was taken during preparations and shows the firewall built (extending beyond roofline) to allow two separate burn zones in the warehouse. The bottom photo was taken shortly after ignition.



Response at Top of Truss (vertical)
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
Acceleration (g)
0
200
400
600
800
1000
1200
1400
Time(sec)



Response at Truss Support (lateral)
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
Acceleration (g)
0
200
400
600
800
1000
1200
1400
Time(sec)