



Final Report submitted to the National Institute for Occupational Safety and Health (NIOSH) for the Phase 2 SBIR Project entitled:

*Smart, Safe Scaffolding*  
Grant Number: 1 R44-OH03010-01

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## 0. Overview

VT Sensing, Inc. is pleased to present this Summary of Findings to the National Institute for Occupational Safety and Health for the SBIR award, grant number: 1 R44-OH03010-01, "Smart, Safe Scaffolding". This effort began in October 1995 and officially concluded on September 1997 (analysis of data recorded in a field setting continued until late January 1998). The following text briefly describes the originally proposed effort along with a synopsis of the most significant results.

### Level of Effort Synopsis:

#### Summary

**Beginning Date:** October 1, 1995

**Ending Date:** September 30, 1997

**Reporting Date:** February 7, 1998

#### **Key Personnel Involved on this Project:**

P. Fuhr, Ph.D., Chief Operating Officer and Principal Investigator, 717 hrs

D. Huston, Ph.D., Vice President, 468 hrs

P. Van Laak, M.S., Senior Engineer, 116 hrs

M. Guerrina, Senior Engineer, 2420 hrs

M. Nelson, Engineer, 1740 hrs



## **1. Introduction to the Project - Executive Summary**

The principal task of this project was to investigate whether or not it was possible to detect potentially dangerous changes in load distribution of construction framework. Laboratory measurements were taken in controlled situations, which included weak supports, loose footings, and uplifting of the supports, to ascertain the applicability of instrumented shoring at realistic construction venues.

The next step was to design, fabricate and test an overall system that is capable of providing advanced and early warning capabilities to onsite construction crews working in situations where shoring accidents could happen. The end goal was to have such a sensing and alarm system be used in a large-scale construction site to verify system performance as well as provide a working environment where the alarm warning system could be fully tested and enhanced if necessary. In order to meet these lofty goals, initially a ruggedized system composed of load and tilt sensors, wireless telemetry capabilities, microprocessor based data acquisition and signal processing, and comparative software schemes was designed and fabricated. This system was iteratively tested and modified in multiple laboratory and field settings under ambient conditions ranging from outside mid-winter conditions in Vermont (temperatures ranged from  $-21$  to  $+37^{\circ}\text{F}$ ) to summer conditions in Boston (the maximum was  $+101^{\circ}\text{F}$ ). The culmination of this project was the in-service utilization of the load monitoring system at a 26-story building under construction in Boston. This field effort, which began in early May 1997 and continued until December 1997 (subsequent data analysis continued until mid-February 1998), represented the integration of a load monitoring system into the largest multistory building being constructed in North America with substantial reinforced concrete construction. In addition, a rapid shoring system developed in Europe was used by Beekman and Associates during the construction phase. This PERI system meant that the shoring crews had to learn how to quickly and efficiently install this type of shoring member - which in turn led them to be quite amenable to the utilization of a load monitoring system within the shoring arrangements. Specifically, and as is presented in detail in Section 3 of this Report, instrumented shoring was placed beneath key concrete forms throughout the construction process. Data was taken at short intervals immediately before and after concrete pouring on upper levels. Subsequent data acquisition would occur on a less frequent interval (hourly), with the microcomputer continually examining load distributions obtained from the sensors. The information gathered via this sensor monitoring clearly demonstrates how the load on the shoring changed over time.

To reiterate, the overall project goals were:

(1) to determine if dangerous uneven loading situations could be identified - they can be so identified;(2) develop a load monitoring system that can be readily used in a realistic construction site - this system using wireless telemetry has been developed during this SBIR Phase 2 effort. Details are presented in subsequent sections of this Report.

## **2. Load Monitoring and Construction Site Safety**

In April 1987 the L'Ambiance Plaza in Bridgeport Connecticut collapsed, killing 28 construction workers. This disaster was certainly tragic, but it is even more regrettable due to the fact that it may have been prevented. The collapse of the plaza, which was 60% complete at the time, was blamed on the lack of temporary lateral bracing in the formwork. Unfortunately, this was not an isolated incident. Within the past two months, 2 workers were killed and others were seriously injured when the shoring system being used in a refurbishment of bridge abutments on the SkyWay in Toronto, Ontario, Canada collapsed in May 1994. Speculation as to the cause of the formwork failure is focussing on an improper footing for one key support member. On a broader time scale, over the past 25 years there have been more than 85 collapses of structures under construction that have been directly attributable to formwork failure.

In this SBIR funded research, VT Sensing proposed to develop sensing systems and techniques applicable to the monitoring of construction site shoring and scaffolding. It was anticipated that this sensor network could provide significant information about the load distribution on shoring systems, information that is currently not available. This information could potentially allow dangerous situations to be quickly identified, during as well as after the construction phase, so that corrective action can then be taken. Thus the risk of injury or loss of life at a construction site could be reduced, possibly leading to lower liability insurance costs. Furthermore, this information could also be used to formulate new construction codes that would further enhance construction work safety. Finally, this load distribution data would be stored in a construction site equivalent of the airplane's "black box" flight recorder, thereby providing load distribution and shoring system information which could be retrieved and analyzed following the unlikely occurrence of a major structural failure. Proof of Concept studies have been undertaken followed by exhaustive tests of various simulated and "small-scale modelling" of actual failure mechanisms where multilevel structures have been constructed and subsequently driven to collapse. These studies, which have been reported in a number of technical journals, have revealed that there are certain loading "peculiarities" that precede structural failures. Such "peculiarities" are repeatable and lend themselves to relatively easy identification through simple comparisons of load values and load histories recorded from instrumented shoring members. The task has therefore evolved into one of being able to develop a "smart system", one that is able to sense load distribution variations, compare them to known failure load distribution variations, and make an educated guess as to if the structure is about to fail. The system then sends an alarm signal to the responsible party on the construction site.

## **1.B. Significant Findings**

### **Abbreviated Form:**

We have developed a multiplexed load cell system to sense load distribution changes on shoring systems used at construction sites. Laboratory and field measurements taken at a multistory building under construction showed that this system can quickly identify dangerous situations where the shoring may collapse. Laboratory demonstrations of simulated failure

mechanisms verified that this unique system may even identify "shoring uplift" at its earliest onset - this shoring mechanism was blamed for the recent collapse of a system near Toronto Ontario in which a number of workers were killed and others injured. An alarm system was implemented during the construction site testing. This "alarm" could consistently detect dangerous shoring load distribution changes and relay that information to key personnel via wireless communication. Discussions with numerous construction site managers, company officials and insurance underwriters shows that use of this simple, low cost system may be used to allow dangerous situations to be quickly identified allowing corrective action to be taken. The risk of injury or loss of life at a construction site will be reduced leading to lower liability insurance costs, and lower construction costs. The reduction in construction costs will allow U.S. construction companies to become more competitive, thereby reducing the trade deficit and the national debt while potentially saving lives.

## 2.1. Review of Proposed and Completed Efforts

The following text succinctly states what the Phase II goals and objectives are:

*"The primary goal of Phase II of this research project is to design, build, and test load monitoring and recording instrumentation so that catastrophic failure of construction shoring systems can be anticipated and prevented. This instrumentation will be simple and inexpensive to operate. It will also be of a sufficiently rugged build to survive the extremely harsh environment of a construction site.*

*This project will consist of five main phases. 1. Design and build prototypes systems; 2. Test the prototype units in the field; 3. Design and build production-ready units; 4. Units will be tested in the field and environmental stress tests will be performed; 5. Redesign and rebuild of the production ready units as dictated by the results of the field and environmental tests. Phases 1 and 2 will be completed in year 1. Phases 3, 4 and 5 will be completed in year 2.*

*At the end of year 1, three prototype units will have been constructed. The prototype units will be built mostly from off-the-shelf items that will provide the necessary functional capability to the system. As a result the prototype system will be somewhat larger, and heavier than the ultimate production-ready units. However, the prototype units will provide a basis for the actual construction of smaller more compact units. The second year will first involve the design and construction of the production-ready units. These units will then be tested through a battery of tests to ensure the extended survivability of the units on a working construction site. A partial list of the tests would be as follows: a drop test, heat, humidity, cold, chemical attack, long-term transducer stability and fungus resistance. Based on the results of these tests, modifications will be made to further improve the reliability of the system."*

From many perspectives, it is most prudent to simply examine the original "Progress Timeline" which was presented in the Phase 2 proposal. This timeline depicts the tasks that we have been concentrating our efforts on during the first year of this effort. As shown, it is apparent that there are simultaneous tasks which, most assuredly, are coupled and as such have an effect on each other. A description of each task, described loosely independently follows. At the appropriate points the coupling between these related tasks will be presented. A detailed timeline is shown on the accompanying diagram. Within this diagram it is indicated that while the prototype unit is being developed and fabricated, we would conduct laboratory tests to determine the mechanical fit of the adjustable collar system to standard shoring sizes. In addition, the robustness and power consumption figures for the individual components as well as the assembled unit were determined. Initial ease-of-use tests were conducted within a laboratory setting, as actual shoring systems are loaded via a Tinius-Olson. These tests provided an indication of the load level dynamic range over which the system will accurately perform. The spread spectrum radio telemetry units were tested in a machine shop environment where a significant amount of electromagnetic interference is present (we have found this to be one of the harshest environments for radio electronics to operate). Field testing (Task 2) was carried out at a number of venues, some provided by our subcontracting construction companies, and a fair amount merely on the VT Sensing grounds. Mock shoring systems were fabricated then purposefully loaded to failure to determine the shoring safety system's response to known failure mechanisms. We repeated the laboratory based footing, weak shoring member, and uplift loading tests in the field to determine the operational range over which the sensed signals may be acquired. Being battery based, we compared the anticipated operational (between charging) time with actual performance times. Given the likelihood that certain changes will be suggested based on the field tests of the prototype units, we incorporated the changes into the redesign and fabrication of production ready units (Task 3). We envision that while we may determine certain conditions in our environmental test lab, we will also subject a prototype system to the Vermont winter and see how robust it is when confronted with ice, snow, cold, etc (Task 4). Questions regarding the survivability of the "shoring system failure black box" are incorporated into Task 4 testing and subsequent Task 5 final design and production. If indeed these units are to provide an indication as to why a shoring system has collapsed (the aircraft "black box" analogy), then the units themselves had better be able to withstand the high force impacts that may accompany the falling shoring.

The data to be collected are primarily twofold: one set of data involves the operational performance of the sensing system (e.g., battery lifetime, radio capabilities, alarm light control level fluctuations, immunity to electromagnetic interference, environmental robustness, etc...); the second set of data involves the multiple channel acquired load cell values and a determination of the load distribution being placed across the shoring system. The data to be acquired with respect to the first set, the system performance information, was analyzed to determine if the developed units need modification and/or servicing. In the case of the actual load cell measurements, the second set of data, laboratory and field based testing involved calibration procedures such as linearity determinations e.g., subjecting the sensors to known linearly increasing load values, acquiring the

measured values and subsequently comparing the two to determine actual performance. The load readings was then radio transmitted to a receiver base station where the same tests were repeated, this time determining if the radio link is maintaining sensor signal integrity as well as ascertaining the actual radio telemetry separation (unit to base receiver distance) found on construction sites. Therefore, in essence, the data to be collected are raw load cell readings (which have been suitably filtered and amplified). The analysis of this data is twofold: initially to establish that the sensors are providing actual readings/values, and secondly, compare the load distribution across the instrumented shoring to identify the onset of failure and then activate the alarm if necessary. The fickleness of construction activities makes it virtually impossible to specify at which construction sites we will place instrumented shoring. However, we were most fortunate to be able to have access to multiple large and small scale construction sites on which we could perform various field tests of the overall principles as well as subject the prototype units to realistic operating conditions.

### **2.1.1 Task: "Design and Build Prototypes".**

It was originally estimated that this task would span approximately 9 months, basically commencing upon the Phase 2 start. While such a time estimate may seem overly optimistic, we felt that based on our Phase 1 results, it was indeed realistic. Early into this award, we completed a design for a prototype system capable of measuring loads from several instrumented shoring members. These measurements are combined and analyzed to look for signal variations, where certain styles of signal variations would be indicative of potentially hazardous shifting of loads on the structure itself. As an example, in the case of "Uplift", the signal of each load cell changes quite dramatically as the load is shifted from one support member to the others. Note that as the unbalanced load is increased, the entire structure's load must be handled by the remaining shore members. We simulated this kind of failure mode (which is believed to be the failure mode of a bridge shoring system near Toronto Ontario Canada where 7 workers were killed in a June 1994 collapse) through the test assembly. Once the load press applied a suitable load level, the unequal loading applied through the ball bearing caused uplift to occur as indicated by the measurements.

Please note the distinctive nature of the load cell readings, this particular failure mode lends itself to a relatively straightforward signal processing scheme - one that is used in the system designed for the early warning of shoring collapse

As with any system, it is first and foremost necessary to understand the nature of the signals which will come from the sensors. In our case, the instrumentation used to perform laboratory and field-site measurements consisted of four load cells, a signal amplifier, a data logging device and a microcomputer. The four load cells (Geokon model #3000-300-3.5) are each capable of measuring loads ranging from 0 to 350,000 pounds. Extension electrical cables were constructed to attach the load cells to the signal amplifier. The signal amplifier is a four channel Vishay 2310 strain gage conditioning amplifier. One of the key features is the adjustable calibrated gain. This allows the load cells to be sensitive and stable over a wide range of loads. The signal from the load cell is conditioned and amplified to a voltage between 0 and 5 volts. A Cyborg Loggernaut data taking

device connected the Vishay amplifier to the computer. The Loggernaut is capable of simultaneously recording up to 16 analog channels as well as 8 digital channels. Each analog channel accepts a signal level ranging from 0 to 5 volts, converts it to a digital signal and sends it to the computer. The Loggernaut software and adapter card were installed in a personal computer. The computer had 14 MB of available disk storage on its hard drive which allowed large data files to be stored and subsequently, easily transferred to floppy disk in a compressed format. The computer displays the current voltage readings from four channels on the screen as well as a graph of the trend of past data. While the rate at which data can be logged is variable, for the initial laboratory calibration and testing, data was taken once every second. The data at the construction site was acquired and stored once every five seconds over a 72 hour period. All of the graphs were generated using the Igor graphical programming application (WaveMetrics) on a Macintosh computer. The data files could only be stored on disk in a compressed format. The data files were uncompressed on a UNIX-based computer where the extra information not needed by Igor was removed. These files were then transported to the Macintosh for data analysis.

A number of characteristics and operational procedures were initially performed in a laboratory setting. These efforts ranged from an initial calibration of the load cells and physically configuring a signal conditioning and data acquisition system (and protocols) which would be suitable for operation within the "rough" environs present at a major construction site. During the course of the calibration, we also performed laboratory experiments to demonstrate the use of the developed sensing system to detect the possibility of a weak shoring member being included in an overall shoring system.

**2.1.2. Task: "Calibration"** Before any of the experiments were performed, and to allow absolute versus relative measurements, the load cells required calibration. Calibration was performed by initially loading each of the load cells individually and then setting the gain on the Vishay amplifier. Each load cell was compressed slowly up to a maximum of 20,000 pounds (88,960 N) using a Tinius-Olsen mechanical press. This range was chosen based on the anticipated load levels to be found at the courthouse construction site. The load cell voltage and the electrical output from the Tinius-Olsen's internal sensor were recorded. Once the load reached 20,000 pounds, the gain on the amplifier was set to provide a computer displayed voltage reading of 5 volts (+/- 0.001 V). Any maximum load can be used by merely changing the gain on the amplifier.

**2.1.3. System Design Aspects:** Given the aforementioned data acquisition scheme and the goal for a firm design, we embarked on a dual thrust: we would continue certain design influencing tests using the system previously described while simultaneously designing a significantly smaller sensor preprocessing "station" with telemetry capabilities thereby negating the cumbersome wiring (or tethering) requirements for a realistic system. This second item was deemed to be most crucial singularly due to our experience on actual construction sites where we were attempting to use the tethered data acquisition scheme. The design concept led to the

following realization: each shoring member to be instrumented will be outfitted with a small donut-like metallic attachment. This "sensor head" is positioned between two pieces of interlocking shoring. The sensor head had the load cell positioned such that the shoring member's load is transferred to the load cell, where the load level is measured, and then mechanically transferred onto the lower shoring member.

From an measurement and identification standpoint, there are once again a number of issues that must be addressed in the design and fabrication of a tangible system. The "alarm" feature of this system is, as previously stated, to measure the loads on each instrumented shoring member, extract the load distribution for the shoring members, then compare these values (and/or a time-tagged longitudinal record of the shoring load levels) with preset limits and observable trends to identify the onset of potentially hazardous conditions. Based on these comparative values, an alarm signal is generated. The alarm has two modes: in Mode 1, a simple high brightness Light Emitting Diode (LED) which is housed within the sensor head is illuminated when appropriate; in Mode 2 the LED is illuminated when appropriate and an audible warning signal is sounded. In each case the measurement values along with the onboard processor's determination of a warning status is conveyed via radio methods to a microcomputer (hopefully envisioned) which has been placed in proximity to a construction site official.

**2.1.4. Prototype Design:** Given the potentially rugged environment posed to electronic instrumentation by a construction site, we have paid considerable attention to the development of a robust compact package. The dual-use nature of such an alarm system, that it must provide accurate measurements and serve as the "black box" data logging instrument poses considerable constraints on the choice of components. After investigating a number of methodologies to solving the data acquisition, processing we decided on using a standalone single board computer (SBC) manufactured by Z-World Inc. This SBC, called the Little Giant, has appropriate analog-input channels, enough system memory to execute the required signal processing and comparison.

The system design encompasses a microcontroller, a radio telemetry unit, the actual sensors, and signal processing and interpretation hardware and software to activate an alarm. A key feature of this system is its capability to be untethered from a base computer through the use of radio telemetry. In the developed prototype systems we have relied on using a radio modem unit manufactured by Fluke Corporation. This system, while exceptional in its versatility, is actually too flexible (and therefore too costly) to be included in the final product. We are therefore beginning to use a low-cost code division multiple access Spread Spectrum application specific integrated circuit (ASIC) manufactured by Axonn Corporation. Devices and technologies currently exist which enable the designer to produce CDMA transmitters which are low cost, high performance and compact in size. The AX602 ASIC performs the processes and calculations required for chipping and data modulation, sleep counter and watchdog maintenance, and CRC calculation as well as RF circuit control, voltage multiplication, and low battery detection. When combined with a low cost microcontroller, RF circuitry, and a small number of discrete

components; a full performance direct sequence spread spectrum transmitter operating over the commercial temperature range may be produced for less than \$6.00 in parts cost. It is envisioned that units operating over the full industrial temperature range may be produced for slightly more.

Our current prototype instruments using the Fluke components exhibit a maximum range between sensor head and base computer of approximately 800 feet (this value is our achieved distance in the presence of typical construction site electromagnetic interference and when within the metallic superstructure of a (in this case) old tenement housing. We envisioning being able to extending that range using the AX602 with an improved RF transmitter and embedded antenna.

**2.1.5. Wireless Communications:** Not having to have the sensor heads physically attached (tethered) to the main construction site computer is most important given the logistical nightmares that may arise on a construction site. We have strived to use a radio telemetry system that is robust enough to handle the spurious noise spikes present as large machinery and machines are cycled into and out of service on the site. To that end we have elected to use a "spread spectrum" technique of information transfer. It is prudent to present a brief review of wireless data transmission and then lead into spread spectrum systems.

As an analogy to the use of radio transmission of sensor information consider the case of computer-based local area networks: Originally, microcomputers (for example), were viewed as discrete devices used singularly and frequently required ancillary services such as a printer and a disk drive. By the early to mid-1980's, numerous microcomputers were being configured to share commonly required resources such as a special printer or a large (typically expensive) disk drive. It became necessary for the devices (i.e., computers) to determine if other devices shared the connection to the common resources and hopefully avoid information collisions as each tried to simultaneously use the resource. Such networks were frequently located within one relatively small geographical region such as an office floor in a building and hence was called a "local area network (LAN)." Information and communications protocols have continued to be devised and refined to allow increasingly better access and control of access to the shared resources.

By the late 1980's the much touted revolution in cordless and cellular telephone service seemed to explode with millions of cordless and cellular telephones installed. As with LANs, various communication protocols were developed and refined to allow expanded and enhanced service to more customers.

The merging of LANs and cordless and cellular telephone technologies has been occurring during the past few years. The most familiar instance of this merging is the growing use of "wireless" LANs for computer networks { T. Bunker, "Wireless LANs Cut Cabling Hassles", *Datamation*, Vol. 37, No. 4, 1991} . In such a scheme, the traditional need to have each microcomputer physically wired (or fiberized) together in some network configuration (e.g., token ring or star) has been changed with each microcomputer connected to a transponder/receiver device { V.C.M. Leung, "Diversity Interconnection of Wireless Terminals to Local Area Networks via Radio Bridges", *Electr. Lett.*, Vol. 28, No. 5, 1992} . As with multiple cordless or cellular telephones sharing some common access node, each microcomputer is assigned an individual security code to avoid information collisions or unauthorized use { D.L. Lathrop, "Security

Aspects of Wireless Local Area Networks”, *Comp. and Sec.*, Vol. 11, No. 5, 1992} . Wireless LANs have been installed into major industrial and corporate office complexes with physical distances approaching hundreds of meters.

The use of wireless technologies for data acquisition is thus a logical extension of the bidirectional digital data transmission used for LAN communications. Within the past few months there have been a number of commercially available wireless MODEM devices that have been announced (e.g., the Wireless Logger from John Fluke Mfg. Co.). These devices utilize the 902 to 928 MHz frequency band which the Federal Communications Commission recently authorized for general use.

Spread spectrum is a radio transmission technique used in radio frequency (RF) data communications. Developed originally for military use, spread spectrum technology could ensure secure communications for intelligence, tactical, and command groups and provide nonjammable data links for guidance and delivery systems. The key feature behind the success of spread spectrum in military applications was its high degree of immunity from electrical interference from either natural or man-made sources. Spread spectrum transmission has the ability to send data at rates much higher than standard radio transmissions. These higher data rates approach 10 Mb per second and provide a better foundation for digital data communications than previous transmission formats. The combination of noise immunity and high data rate transmission makes this technology suitable for wireless data communication networks in electrically noisy environments.

In this system's case, radio telemetry interrogation of the load cells and tilt sensors was performed in the laboratory and tested in electromagnetic environments with noise levels significantly higher than those normally experienced on construction sites. The radio telemetry system relied on the sensor(s) providing an analog voltage which was directly amplitude modulated using modified cordless/cellular telephone circuitry. The same radio telemetry system used in the load cell laboratory tests was used with different fiber optic pressure sensors with the results reported in the paper entitled “*Interrogation of Multiple Embedded Fiber Sensors in Civil Structures Using Radio Telemetry*” by P.L. Fuhr, D.R. Huston and T.P. Ambrose, which was published in the *Journal of Smart Materials and Structures*, Vol. 4, No. 4, 1993. A conference proceedings publication of this radio telemetry scheme is “*Radio telemetry interrogation of multiple fiber sensors in civil structures*” by P.L. Fuhr and D.R. Huston in **SPIE Proceedings** Vol. 1797.

As previously stated in the “Prototype..” section of this report, during the course of this project, we have relied upon using a standalone Fluke radio communication unit. In the completed unit we migrated to the highly integratable Axonn Corporation AX602 RF communication component.

#### **2.1.6. Tilt Tests:**

In order to provide an accurate representation of the scale of work involved in fabricating a suitable test-rig for large-scale tilt testing, the following text is an excerpt from a weekly progress report written by VT Sensing mechanical engineer Matthew Nelson:

"The large scale tilt test is almost ready to be performed. Each level of the structure has been built, and the weight basket and safety cables have been constructed, and put up. Pipes were welded onto steel plates for each corner of each level, so that the legs could be placed inside the pipes for setting the structure up. Yesterday we attempted to set up a one story structure, but failed because we could not even make it stable enough to stand up alone without any weight on it. In order to remedy this problem we first tried putting up cross bracing made of bungee cords. The bungee cords did in fact make the structure a little more stable, but not stable enough.

After studying the problem carefully we decided that two things could be done to improve the stability of the structure: 1) Use a larger PVC pipe for the legs of the structure ( we used 1 inch PVC for the first try, should maybe use 1.5 or 2 inch PVC). 2) further modify the brackets that held the ends of the legs so that they could be adjusted and held in a vertical position. ( the one inch PVC had space around it so it could flop around in the bracket) Some 1.5 inch PVC was picked up, this fit fairly closely in the bracket. To further improve the leg brackets, a 1/2 inch pin was welded up the center of the pipe, and three bolts were equally spaced around the top part of the pipe so that they could tighten against the leg and hold it in position. Wooden spacers were also made to fit over the 1/2 inch pin, and also to fit snugly inside the 1.5 inch PVC leg.

Once these modifications were made, the 1.5 inch PVC was cut into 30 inch lengths for the legs. The legs were placed in the brackets mounted on the floor level, a level was used to set the legs as close to vertical as we could get, and the adjusting bolts were tightened. The upper level was then lowered down onto the 1.5 inch PVC legs, and the adjusting bolts on the upper leg brackets were tightened. The level was laid across the upper level to be sure that everything was even, which it was. With our second attempt, we had constructed a fairly stable one story structure. The next step is to apply some weight to the top of the structure and see what happens, and to design some tests that should be done to get useful data from this project." These large scale tests augmented the small-scale tilt tests that verified the most important fact that shoring member tilt angles should be monitored in addition to vertical load levels.

#### **2.1.7. Market Study - Cost of this Unit:**

Instrumented shoring systems probably will be used on construction sites only if they can be shown to increase safety and to have a minimal economic impact or even to have an economic benefit to the contractor. Performing a detailed economic impact analysis for such a system is at present very difficult to the unavailability of pertinent data. However, qualitative judgments about the costs and benefits of such a system can be made.

A very rough estimate of the cost of instrumenting a shoring/scaffolding system can be formed based on our recent experience with embedding fiber optic sensors in a five-story 65,000 sq. ft. \$10,500,000 building. We believe that it would cost approximately \$75,000 to instrument the

shoring with an adequate coverage (20% of all vertical support members) that would prevent many of the overload or premature form removal type of accidents. This would increase the cost of the project by approximately 0.7%.

The cost of such a system can be justified in terms of a reduction in human losses on construction sites. The failure of structural systems during construction often has tragic consequences. The April 1987 collapse of the L'Ambiance Plaza in Bridgeport Connecticut which killed 28 construction workers was not a shoring type construction procedure, but is indicative of the potential scope of construction accidents. Over the past 25 years there have been more than 85 collapses that have been directly attributed to formwork or shoring failures (Hadipriono and H. K. Wang, 1986). Based on these numbers it can be argued that the cost of instrumenting shoring systems is justified, if the instrumented shoring systems significantly reduces the number of collapses and failures.

In addition, there are a number of tangible economic benefits that can possibly be realized through the use of an instrumented shoring system. These include: 1. Increasing the safety of the construction site may lead to a reduction in insurance and injury claims costs; 2. Reducing the number of collapses or partial collapses of shoring systems will reduce the cost of rebuilding and/or replacing the damaged structural components; 3. There are many cases where concrete floor slabs may crack while under construction due to uneven settling and load distribution of shoring and reshoring systems. Such cracks often require the replacement of the slab. The use of instrumented shoring systems may lead to construction practices that prevent such accidents. Presently, there are very few methods at the contractors disposal for preventing such accidents. 4. The use of instrumented shoring systems may enable the contractor to increase the speed and efficiency of the construction process. At present, the decision of when to remove formwork is based on rule-of-thumb design codes that may in some instances be overly conservative. It may be possible to remove the formwork and reshore at an earlier time if the instrumented shoring system indicates that it is safe to do so.

### 3. Project Description: Load Sensing for Improved Construction Site Safety

Over the past 25 years in the U.S. there have been more than 85 collapses of structures under construction that have been directly attributable to formwork failure. Sensing systems and techniques applicable to the monitoring of construction site shoring and scaffolding are designed and implemented with preliminary systems being used in the field and in the laboratory. Such a sensor network can provide significant information about the load distribution on shoring systems - information that is currently not available. This information can allow dangerous situations to be quickly identified so that corrective action can be taken. Thus the risk of injury or loss of life at a construction site can be reduced as well as the associated economic costs. Furthermore, the load data acquired with this system can be used to formulate improved construction codes that enhance construction work safety. Laboratory proof-of-concept experiments as well as actual field site measurements presenting the in-service use and capabilities of an intelligent shoring system are described in this chapter.

#### 3.1. INTRODUCTION

In April 1987 the L'Ambiance Plaza in Bridgeport Connecticut collapsed, killing 28 construction workers. This disaster was certainly tragic, but it is even more regrettable due to the fact that it may have been prevented. The collapse of the plaza, which was 60% complete at the time, was blamed on the lack of temporary lateral bracing in the formwork. Unfortunately, this was not an isolated incident. In May 1994, 2 workers were killed and others were seriously injured when the shoring system being used in a refurbishment of bridge abutments on the SkyWay in Toronto, Ontario, Canada collapsed. Speculation as to the cause of the formwork failure is focussing on an improper footing for one key support member. On a broader time scale, over the past 25 years there have been more than 85 collapses of structures under construction that have been directly attributable to formwork failure<sup>1</sup>.

In general, the primary causes of formwork failures are: 1) excessive loads, 2) premature removal of forms or shores, and 3) inadequate lateral support for the shoring members. If a shoring system does not have sufficient strength and stability to carry the imposed loads, the result can be disastrous. Consequently, determining the load distribution during construction is essential in assessing the safety of the system<sup>2</sup>. A number of attempts have been made at developing computer models intended to evaluate the safety of a formwork structure<sup>3 - 5</sup>. However, an inherent limitation of these programs is that they can not anticipate unusual or extreme circumstances that may occur at the site. Discussions with construction site supervisors reveals that many of the parameters used in the computer models do not accurately represent the reality of shoring support configurations. Furthermore, it is known that construction crews do not always follow the shoring system design. Hence a computer model may not correctly represent the loads and the resulting shoring load distribution present at the actual site<sup>1</sup>.

A viable alternative to computer modeling is the real time measurement of the actual formwork loads. This is accomplished by installing load cells in the shoring system. Load cells are available from a number of vendors, and are relatively inexpensive (in fact, the expense of the devices may be offset by a decrease in the cost of liability insurance). Data from several of the cells can be collected and analyzed by on site. The load information can then be used to alert the work crews to any hazardous situations, and allow sufficient time to correct the problem, and can be logged for load documentation and future shoring design purposes.

A potential use of the logged data would be in the development of wind-resistant shoring design codes. At the present, U.S. Building codes offer little guidance for wind load design<sup>6, 7</sup>. A load cell data system would provide valuable information (such as wind speeds and direction versus the change in loads in the formwork), that can aid in formulating such guidelines.

The work described in this paper investigates whether it was possible to detect (potentially dangerous) changes in load distribution of construction framework. Laboratory measurements have been taken in controlled situations, which included weak supports, soft footings, and uplifting of the supports, to ascertain the applicability of instrumented shoring at realistic construction venues. Extensions of this project into the "real world" have included installation of load cells in the shoring of the following new constructions: (1) a 7 story courthouse in Burlington, Vermont (1995); (2) a maximum security prison in West Virginia (1996); (3) a parking structure in Burlington, Vermont (1996); (4) a 4 story wooden/masonry building being renovated in Burlington, Vermont (1996-1997); and (5) twin 26 story buildings currently under construction in Boston, Massachusetts.

While the prior laboratory and construction site data has provided valuable fundamental and practical information<sup>8,10</sup>, this article will focus on the twin tower activities due to a new type of shoring system used and the overall scale of the project.

### 3.2. EQUIPMENT AND DATA PROCESSING

With the need for load and tilt measurements, each shoring member sensing "platform" consists of a strain gage based load cell, signal amplifiers, and a tilt sensor. In the wired case, this instrumentation is cabled to a data acquisition station which consists of additional signal amplifiers and conditioning circuitry and a Pentium-166 microcomputer with multichannel A/D capabilities. The load cells (Geokon model #3000-300-3.5) are each capable of measuring loads ranging from 0 to 1,557,500 N. Multiconductor shielded electrical cables were constructed to attach the load cells to the signal amplifiers. The signal amplifiers are Vishay 2310 strain gage conditioning amplifiers. One of the key features of the amplifier is the adjustable calibrated gain. This allows the load cells to be sensitive and stable over a wide range of loads. The signal from the load cell is conditioned and amplified to a voltage between 0 and 5 volts. The tilt sensors are from Applied Geomechanics, Inc. and allow for angular measurements ranging from -10 to +10 degrees. An Analog Devices AD590 temperature sensor is also used to measure ambient temperature.

The overall data acquisition rate, in terms of cycling through each load and tilt channel and performing signal conditioning and assessment is approximately 37 complete cycles per second. Specifically, it was determined that at maximum throughput and processing, all channels would be sampled at a 10KHz rate. Subsequent conditioning and interpretation takes approximately 1.3

milliseconds for the tilt sensors and for the load cells approximately 2.2 milliseconds per channel plus an additional 16 milliseconds for load history trend analysis. This gives a complete system response time of approximately 27 milliseconds. We have compared this sensor system response time to actual shoring failure times that we have generated using our test assembly. We have found that the onset of collapse is indeed gradual while the collapse itself is swift. The sensor head components are robust and capable of quick response times. It is our belief that given the nature of most collapses, this system provides very ample room for capture of real world failures.

### 3.2.A. CALIBRATION

Calibration was performed by initially loading each of the load cells individually and then setting the gain on the Vishay amplifier. Each load cell was compressed slowly up to a maximum of 20,000 pounds (88,960 N) using a Tinius-Olsen mechanical press. This range was chosen based on the anticipated load levels to be found at various construction sites. The load cell voltage and the electrical output from the Tinius-Olsen's internal sensor were recorded. Once the load reached 20,000 pounds, the gain on the amplifier was set to provide a computer displayed voltage reading of 5 volts (+/- 0.001 V). Any maximum load can be used by merely changing the gain on the amplifier. Hysteresis associated with each sensor is measured and minimized using computer-based signal conditioning and processing.

### 3.2.B. SENSOR HEAD CONFIGURATION

The design concept led to the following realization: each shoring member to be instrumented will be outfitted with a small donut-like metallic attachment. This "sensor head" is positioned between two pieces of interlocking shoring. The sensor head had the load cell positioned such that the shoring member's load is transferred to the load cell, where the load level is measured, and then mechanically transferred onto the lower shoring member.

From a measurement and identification standpoint, there are once again a number of issues that must be addressed in the design and fabrication of a tangible system. The "alarm" feature of this system is, as previously stated, to measure the loads on each instrumented shoring member, extract the load distribution for the shoring members, then compare these values (and/or a time-tagged longitudinal record of the shoring load levels) with preset limits and observable trends to identify the onset of potentially hazardous conditions. Based on these comparative values, an alarm signal is generated. The alarm has two modes: in Mode 1, a simple high brightness Light Emitting Diode (LED) which is housed within the sensor head is illuminated when appropriate; in Mode 2 the LED is illuminated when appropriate and an audible warning signal is sounded. In each case the measurement values along with the onboard processor's determination of a warning status is conveyed via radio methods to a microcomputer which has been placed in proximity to a construction site official.

### 3.2.C. WIRELESS COMMUNICATION COMPONENTS

The difficulties presented in stretching cables in a construction site environment have led us to use a low-cost code division multiple access Spread Spectrum application specific integrated circuit (ASIC) manufactured by Axonn Corporation. Devices and technologies currently exist which enable the designer to produce CDMA transmitters which are low cost, high performance and compact in size. The AX602 ASIC performs the processes and calculations required for chipping and data modulation, sleep counter and watchdog maintenance, and CRC calculations as well as RF circuit control, voltage multiplication, and low battery detection. When combined with a low

cost microcontroller, RF circuitry, and a small number of discrete components; a full performance direct sequence spread spectrum transmitter operating over the commercial temperature range is used to radio the information from sensor platform to the data acquisition station.

Our current prototype instruments have exhibited a maximum range between sensor platform and base computer of approximately 800 feet (this value is our achieved distance in the presence of typical construction site electromagnetic interference and when within the metallic superstructure of an (in this case) old tenement housing. We envisioning being able to extending that range using the AX602 with an improved RF transmitter and embedded antenna.

### 3.3. LABORATORY WORK

The characteristics of the instrumentation and the operational procedures were initially evaluated in the laboratory. This included initially calibrating the load cells and physically configuring a signal conditioning and data acquisition system (and test protocols) which would be suitable for operation within the rough environment of a typical construction site. During the course of the calibration experiments were conducted that demonstrated the use of the sensing system to detect a weak shoring member in a shoring system. Through these laboratory experiments of simulated potential failure mechanisms for shoring systems, it was determined that the instrumented shoring system is capable of differentiating between "good" and "bad" footing conditions and "strong" and "weak" shoring members through the monitoring and interpretation of the load distribution throughout the shoring. These findings have been previously reported<sup>8-13</sup>.

Of particular importance is uplift occurring on shoring members. If this occurs with shoring on a construction site, the results can be catastrophic. If the shoring members were not connected together with cross-pieces and this occurred, one or more of the shoring members could collapse (as is believed to have happened at a major roadway bridge near Toronto, Ontario in May of 1993 in which a number of workers were injured and killed).

An illustration of up-lift is depicted in Figure 3-1 where a beam is shown resting on supports A, B and C. The beam can be considered as an evenly distributed load (as shown in a). This situation is statically indeterminate because a portion of the total load being supported by A, B and C cannot be calculated from static equilibrium alone. The situation changes when an additional load is applied between two of the supports such as between A and B (as shown in b). While the three supports may still be supporting the load, this fact cannot be verified using statics. As the load increases, the beam deflects (as shown in c), resulting in A and B supporting the entire load. The loads at A and B may now be calculated using statics and the deflection at C can be calculated using beam flexure theory.

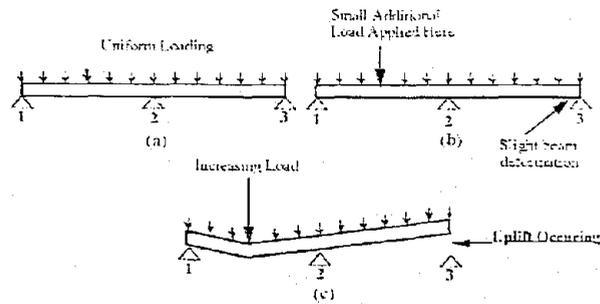


Figure YY. Depiction of shoring "uplift".

Figure 3-1. Uplift occurs as an uneven load causes certain shoring members to assume more of the load while other members may feel little if any load.

The apparatus used for this laboratory experiment is shown in Figure 3-2. Three load cells were placed in a line with a single steel plate resting across the top of the load cells. A ball bearing was placed on the plate between loads cells #1 and #2 so as to produce a unidirectional moment-free point load that acts in the vertical direction. The load was applied with a Tinius-Olsen 267,000 N (60,000 lb.) test frame.

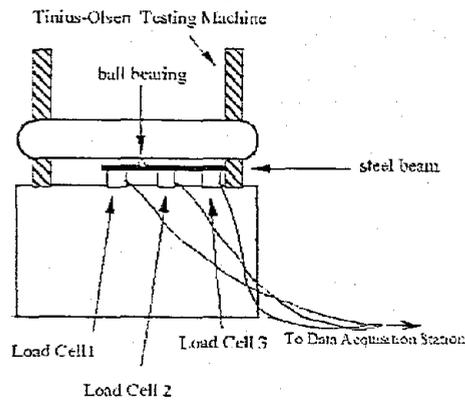


Figure 3-2. Uplift simulation was performed in the laboratory using uneven loading by a press onto steel plates.

As shown in Figure 3-3, as the applied load increased, each load cell experienced an increase in load. Once the load in each load cell reached approximately 37800 N, the load in #3 decreased rapidly to zero. The beam was bent at this point with all of weight supported by #1 and #2. On a construction site, this situation can be particularly dangerous, since the unloaded (uplifted) shoring member may shift and become unstable. After a period of time, the applied load was then decreased, and load cell #3 then again measured an increase as shown in the graph. What is therefore apparent from these measurements is that the instrumented shoring system is capable of detecting uplift. When compared with the previously described experiments, it is apparent that uplift has a distinctly different "load distribution signature" than for weak shoring members or weak footings. This situation may therefore be readily identified by the instrumented shoring system followed by an appropriate notification of the site engineers.

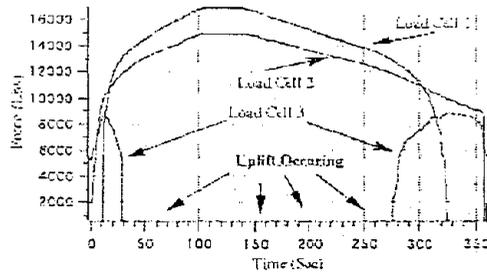


Figure YYY. Uplift load monitoring data.

Figure 3-3. Measurements taken during the simulated uplift failure tests shows how certain load bearing members must sustain higher loads, in the worst case loads that exceed the member's design criteria, while other shoring members have their loads diminish.

The mock shoring tests were designed to verify various collapse mechanisms for single- and multistory structures. In essence they provided a controlled, laboratory environment where excessive loads and vertical and horizontal shearing forces could be applied to structures which possessed instrumented shoring members. In this way load and tilt data could be obtained as the structures were collapsed and subsequently compared with video and photographic records to determine alarm limits. Obtained values were then correlated with previously reported measurements and theoretically obtained values to minimize uncertainty levels in structural failure alarm limits. A representative laboratory collapse setup are shown in Figures 3-4, 3-5 and 3-6. In this configuration vertical loads up to 1000 pounds were lowered via a crane assembly onto various locations along the structure while horizontal shearing loads of up to 600 pounds were applied. Load data as well as tilt measurements in two angles were simultaneously measured using the cabled and wireless measurement systems. A representative graph of this load-to-failure data is presented as Figure 3-7.

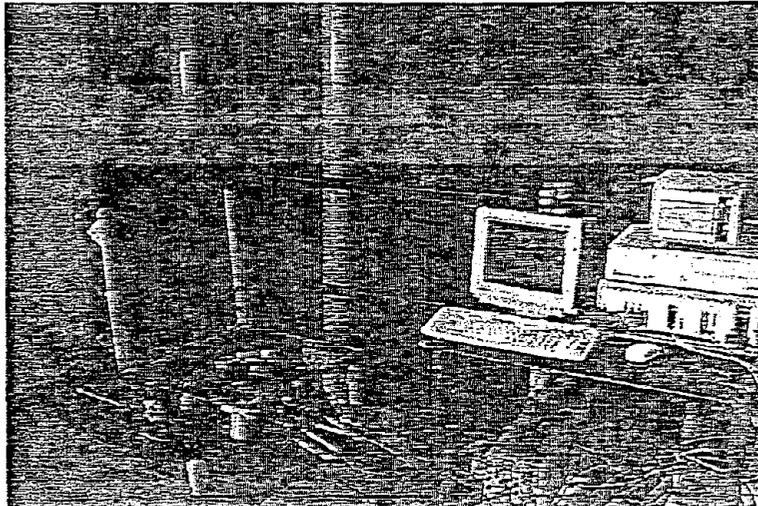


Figure 3-4. Data acquisition system for laboratory based shoring measurements.

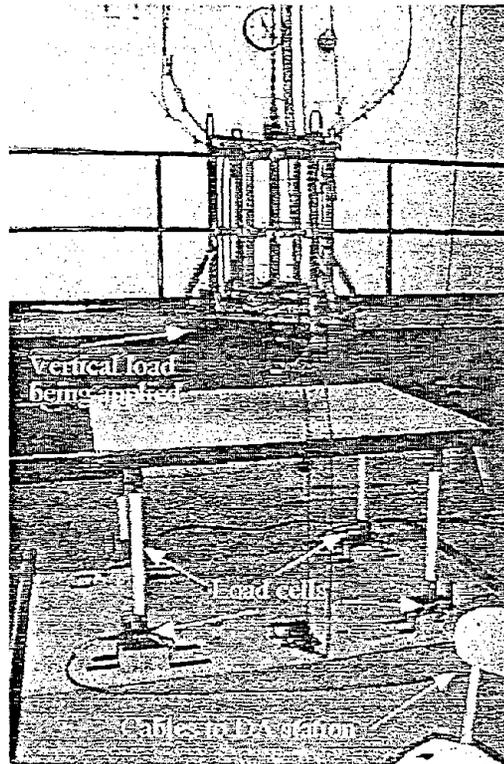


Figure 3-5. The laboratory based load-to-failure measurements used vertical loading while horizontal shearing loads were also applied.

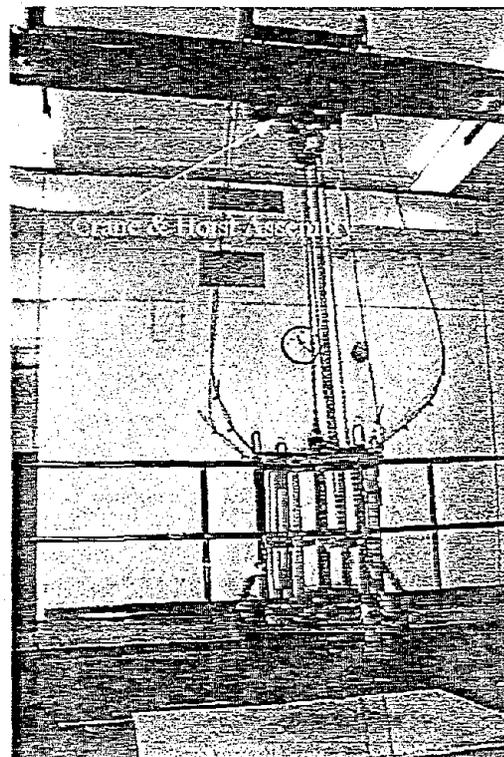


Figure 3-6. This closeup of a single stage shoring system shows the instrumented shoring members as well as the vertical load cage (weighing 365 pounds) being lowered onto the table via a crane.

### 3.4. UPLIFT MONITORING

A final laboratory test simulated a condition referred to as "uplift". In these tests a two-story instrumented structure was designed and built. The structure was subjected to vertical loads which could be placed anywhere on the structure's top as well as variable horizontal side loads meant to simulate shearing loads. Load and tilt measurements were recorded with sensors cabled to the data acquisition microcomputer station. In these load-to-failure tests, the horizontal load level was fixed, in this particular instance a constant 275 pound shearing load was used, while the vertical load varied from zero to 720 pounds. The vertical load was placed off-center purposefully to cause an uplifting condition.

As shown in Figure 3-7, as the vertical load was increased the two-story the measured loads increased until uplift began. At that time the load redistributed itself until certain shoring members began to fail causing an initial tilting of the structure (see Figure 3-8).

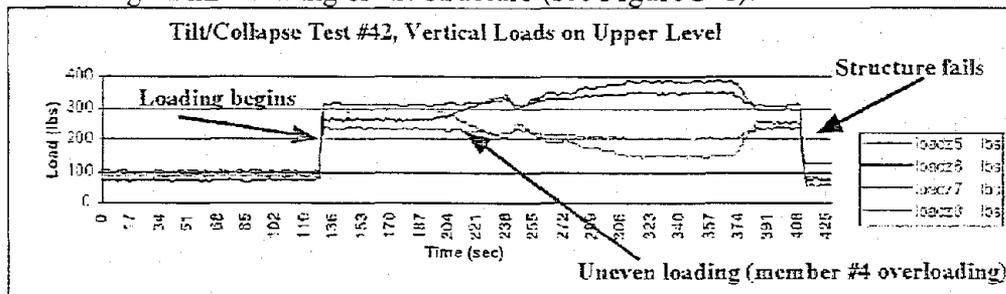


Figure 3-7. This representative graph shows the temporal evolution of the loads and tilts varying as a vertical load increases while the horizontal shearing load of 275 pounds remains constant.

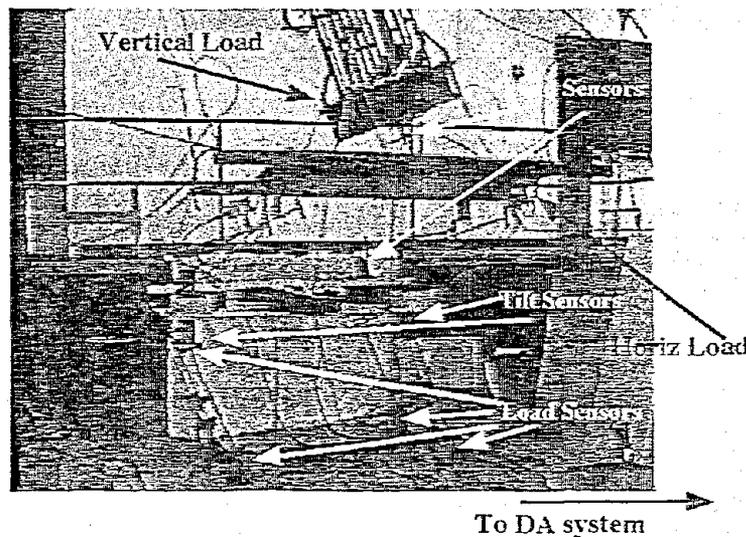


Figure 3-8. As the two-story instrumented structure collapses the loads continue to redistribute themselves unevenly among the shoring members still somewhat capable of supporting loads.

Moments later the entire structure failed, as shown in Figure 3-9.

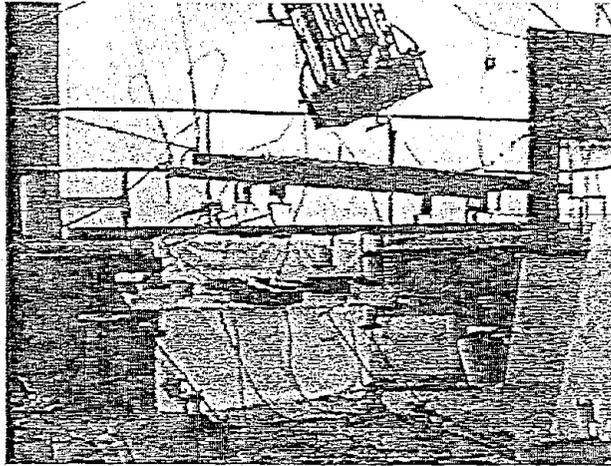


Figure 3-9. Moments later the entire structure fails. In this test condition the vertical loads as well as the structure's "floors" are supported by numerous safety cables to prevent injury to the investigators.

### 3.5. FIELD MEASUREMENTS

As previously mentioned, field measurements have been taken at 5 different sites. However we wish to focus on the current effort twin 26 story apartment towers with associated multilevel parking garages and a 7 story low-rise building in Boston Massachusetts. This project, named the Museum Towers at North Point is owned by Museum Towers LLC, has: Jung/Brannen Associates, Inc serving as the architects; Weidlinger Associates serving as the Structural engineering firm; with construction site logistics being handled by Beekman. Each of the \$50-60M towers is to hold approximately 300 apartments which will rent in the \$1500-2000/month range. This project constitutes the largest concrete-based building construction project underway in the U.S.

For the past few years, particularly in the northeastern section of the U.S., large buildings have been built of steel. However such a steel structure would typically require 14-18 inches of floor separation while a concrete building requires a floor spacing of approximately 8 inches. When constrained to a maximum building height of approximately 230 feet, this means that 26 stories may be placed within the concrete building while on 23 or 24 floors could be placed into a steel structure. It is anticipated that this project's superstructure will be completed by late 1997.

#### 3.5.B. CONSTRUCTION SITE SPECIFICS

As previously stated, this project involves the construction of two 26 story apartment buildings with an associated 7 story attached low rise apartment building and 5 story parking garage. The Boston North Point region is located across from the Boston Museum of Science along the Charles River. Each building uses 8 inch poured concrete slab floors (with rebar reinforcements). A PERI shoring system is used with the shores on the outside portion (away from the internal central tower structure where the elevator shafts will eventually be) being placed on 9 foot by 5 foot center spacings. 8 load cells are used to measure loads from upper decks. This type of shoring requires that the poured upper level be carried by 4 floors of shoring. The concrete strength must reach a minimum of 1500 PSI before the lowest level of shoring members may be removed. The required

fully cured concrete strength is 4000 PSI, a level that has been being achieved within one week - in fact the concrete is continuing to cure up to 6000 PSI strength. A June 18, 1997 photograph of the North Tower is shown in Figure 3-10. A closeup photograph of this building, more clearly showing the PERI shoring members, is shown in Figure 3-11.

North Tower. 10/26 floors poured.

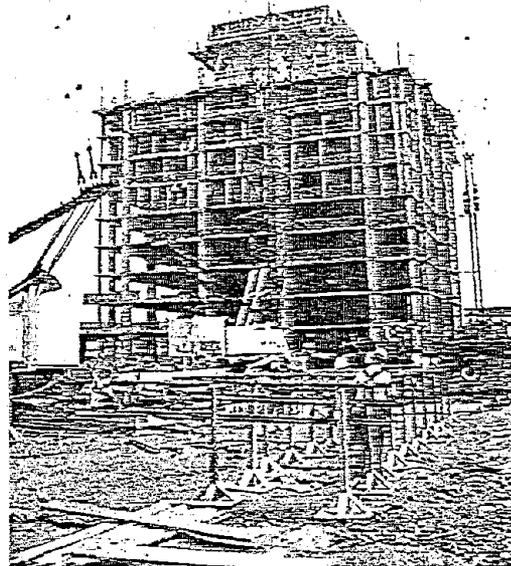


Figure 3-10. View of North Tower on 6/18/97.

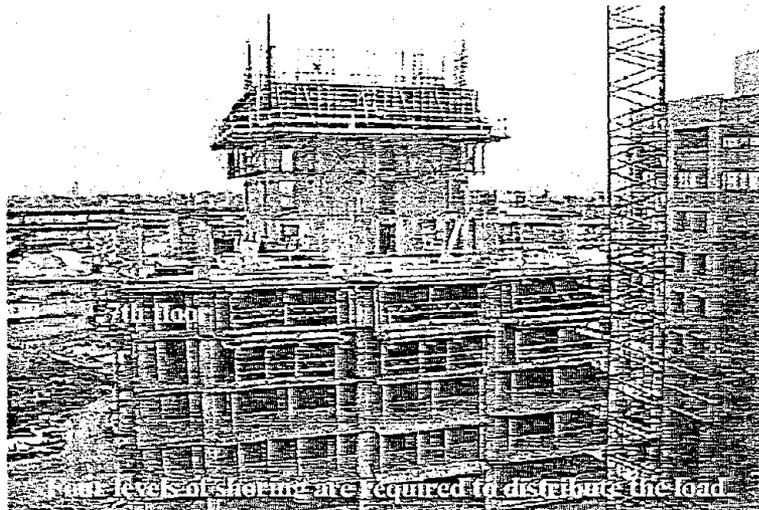


Figure 3-11. This closeup view of the North Tower more clearly shows the four levels of shoring members.

Load cell readings are taken on the 8 cells once per second (slow rate) or 10 times /second (fast rate). Fast recording is typically performed during the pouring cycle so that fast excitation and load variations may be recorded. After approximately 1 hr after the end of the pour (typical pour on this

site lasts for 3 hours - one entire floor at a time), the data recording reverts to the slow rate to look for longer term variations in the load distribution. An instrumented shoring member is shown in Figure 3-12.

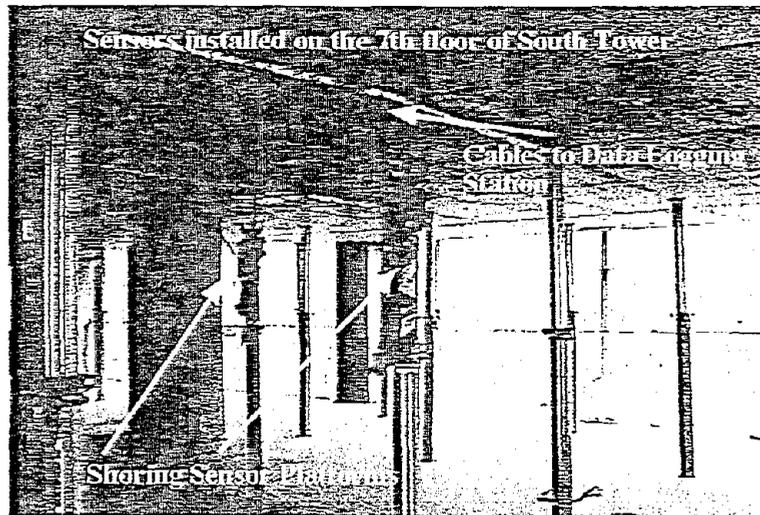


Figure 3-12. This view of an instrumented shoring member is located on the South Tower's 6th floor.

### 3.5.C. LOGISTICS OF FIELD SITE WORK

The successful installation of test equipment and collection of data on an active construction site can be a complicated undertaking. Careful planning, cooperation, and coordination with the site engineer is of paramount importance. The goal was to get as much relevant data as possible without interfering with the construction.

The PERI shoring system used at the Twin Towers construction site requires that four levels of shoring be in place to support the upper floors. New floors are poured every 4 to 5 days. The lowest level of shoring cannot be removed until the concrete immediately above has reached a minimum of 1500 PSI. Testing to see if the concrete has reached this hardness is performed using standard slump and cracking tests. In general it has been found that the concrete reaches 1500 PSI within approximately 3 days - the expected performance criteria is 4000 PSI, which has so far been achieved within approximately 1 week. This concrete has continued to harden and is currently reaching 6000 PSI strengths.

All of this concrete information implies that the lowest level PERI shoring members are being removed every 4-5 days. From our sensing standpoint, this means that we have sensors located on 4 levels with the lowest level varying every 4-5 days. Sensor installation follows the shoring installation. As the onsite construction crews have developed a better understanding of how to optimally install this type of shoring system, they are now able to remove shoring from one floor and reinstall it on another floor within approximately 45 minutes. This requires that we must be in close logistical contact with the shoring crew so that as they are installing the members to be instrumented we are ready for sensor installation. Once the members are in place, the cabling may be correctly placed.

From a logistical standpoint two points are crucial for data collection and responsible activity at

the construction site.

1- Interference with the construction evolution is simply not acceptable. (It is estimated that the labor costs for simply the concrete crew exceeds \$3000/hour)/ Close contact with the site supervisor must be maintained throughout the operation.

2- To facilitate the quick installation and removal of testing equipment, everything was made manually portable. The equipment had to be arranged in a "Turn key" configuration, and the load cell equipped shoring members must be interchangeable with standard PERI shoring posts. All equipment has to be rugged enough to endure rough handling as access to the site was difficult. Conditions on a construction site are not ideal for the implementation of computer driven automated data acquisition, especially during the hot and humid summer months. In anticipation of this, we constructed a portable equipment container to protect the electronic gear from the construction site environment. This container was built using a high density polymer waterproof case. An exhaust fan with a filtered intake port was installed to maintain a suitable temperature inside the box. A false bottom grating was included to keep the equipment out of the water in the unlikely event that the integrity of the box were compromised.

#### 3.5.D. SITE DATA ACQUISITION

Sampling rates were initialized at ten samples per second. Since loading is dynamic during the first moments of the pour, a rapid sampling rate is necessary. Eight load cells and 2 tilt meters are sampled during this fast sampling period. Four hours after the pour the sampling rate was changed to once per second. Data is written onto a WORM optical drive.

Analysis takes two forms: in the first, the data is continually processed and correlated with known trends for shoring system failures. If a known failure trend is identified alarm signals are issued. In the second form, the data is reviewed at daily-to-weekly intervals to examine loading histories and floor-by-floor comparisons of loading situations. Such data review is performed off site.

#### 3.6. WIRELESS DA FOR SMART SHORING

One of the predicaments facing the real-world usage of such a shoring system is grounded in the worksite environment. In a conventional sense, power must be supplied to the load sensors and processing electronics and the data is carried to a microcomputer - data logging station all via cables. The data logging system must be placed in a secure location typically in a more central location within the structure being built while the load sensors are attached to the predetermined shoring members which may be located on different floors potentially a long distance from the data logger. This of course necessitates running heavy and heavily-shielded multiconductor cables around the site (see Figure 3-13). Such cables must be judiciously placed in lower traffic areas with the hope that they will not be broken or tampered with. Our experiences have shown that simply cabling the sensors is a laborious task - one that is compounded by the all too frequent requirements to move the data logging station to a higher floor which causes the cabling to be removed and rerun.

We have developed a battery/solar powered standalone load, tilt and temperature sensing system that directly attaches to the shoring member. The information is then transmitted via a wireless communication link to the data logging station. All cabling needs are removed as are most requirements for almost any moving of the data logging station (in one case the station has remained in the main site trailer). While the electromagnetic environment associated with a construction site is

“noisy” (principally due to welding and large motors operating), our use of a spread spectrum wireless communication channel (please see Sensors December 1996) operating in the 902-926 MHz band minimizes data corruption and loss of signal integrity.

The wireless shoring sensing platform relies on a microcomputer (the Little Giant by Z-World) to perform routine data acquisition and general housekeeping of the platform (battery status etc). On-board processing of the load and tilt information is compared with preset limits which when exceeded causes alarm lights and buzzers to be activated on that particular platform, while, of course, this hazardous condition alarm message is radioed to the data logging system.

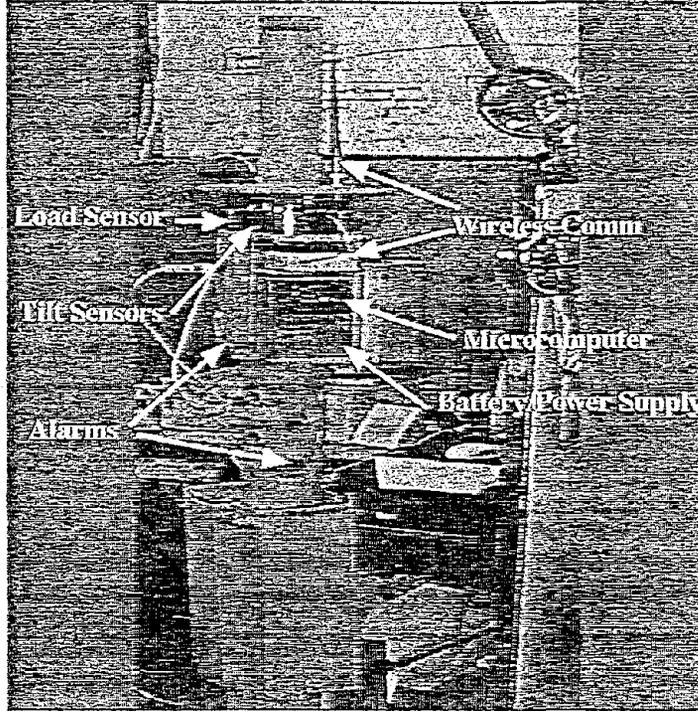


Figure 3-13. The use of wireless communications and batteries for all power needs allows units to be quickly and easily installed throughout the construction site. This unit relies on spread spectrum communications in the 902-926 MHz to achieve good signal fidelity in the presence of large amounts of construction site generated electromagnetic interference.



Figure 3-14. Street level view of the Museum Towers construction project on 9/18/97.

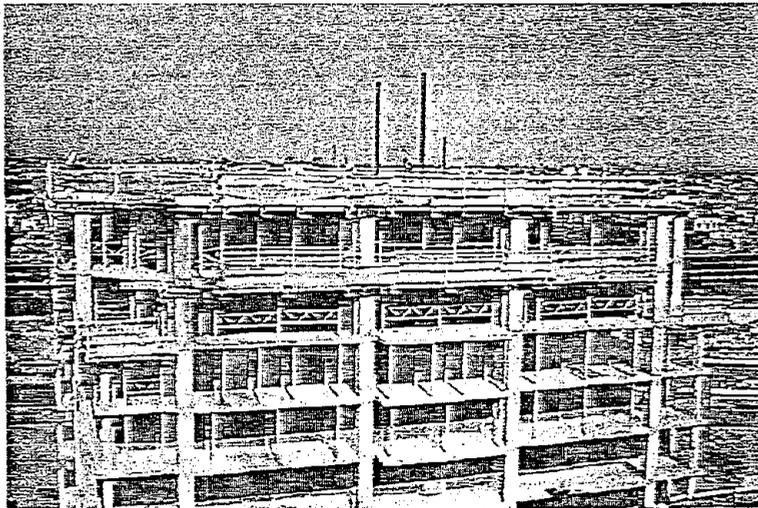


Figure 3-15. View of the North Tower as seen from the top of the South Tower. The four floors of PERI shoring are readily visible.

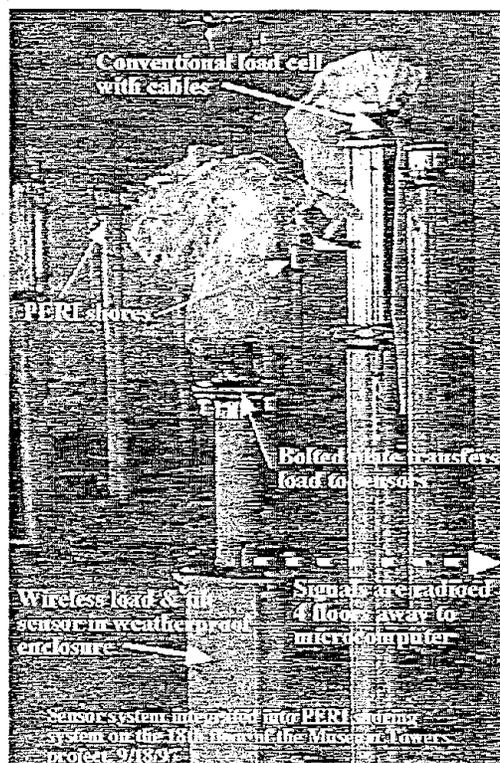


Figure 3-16. View of the wireless load and tilt sensor installed on the 18th floor of the North Tower of the Museum Towers project (9/18/97).

### 3.7. Field Use and Representative Data

Time-tagged data was recorded at this construction site using the wireless tilt and load monitoring system as well as the conventional cabled load cells. In each case, data was recorded at a centrally located microcomputer workstation. Specifically, a Pentium 166 class microcomputer was used to data log the analog readings. The maximum spacing between the conventional load cells and the workstation was 3 floors. Effectively, no matter where the workstation was located the stretching of multiple heavily shielded cables proved at best cumbersome and at worst potentially dangerous to the workers. Alternatively, the wireless battery powered system amply demonstrated its inherent flexibility in being used in a field setting. The unit was easily disassembled from standing PERI shoring members, transported to another location within 4 stories (or approximately 600 feet) of the workstation, and then once again simply put into place on another shoring member. The Little Giant Z-class microprocessor within the wireless unit acquired readings from the tilt and load sensors, performed rudimentary signal processing and then radioed the readings to the workstation. There the information (data) was configured in the manner shown in Figure 3-17 for ease of subsequent processing. The workstation analyzed the data to look for the uplift and support member collapse data trends referred to in section 3.2.

Source File for Conversion: C:\DATALINK\BOSTON2.RAW

Source File Size: 7040

Data Sets Found: 28

Set#	Start Date	Average Tilt (X-axis)	Average Tilt (Y-axis)	Average Load	Battery
0	12:37:55	16	81	1500	120
1	12:38:28	18	80	2255	116
2	01:16:00	11	83	1626	114
26	05:16:00	15	84	1056	107
27	05:56:00	14	86	1069	128

09/19/97

09:46:48

End of Processing

Figure 3-17. The wireless unit's 2-axis tilt readings are integrated with the vertical load readings, battery and time information to provide a more complete picture of the performance of the vertical shoring members.

A representative graph of the wireless unit's readings for vertical load, 2 axis tilt readings, and the battery performance are shown in Figures 3-18, 3-19 and 3-20 as a function of elapsed time.

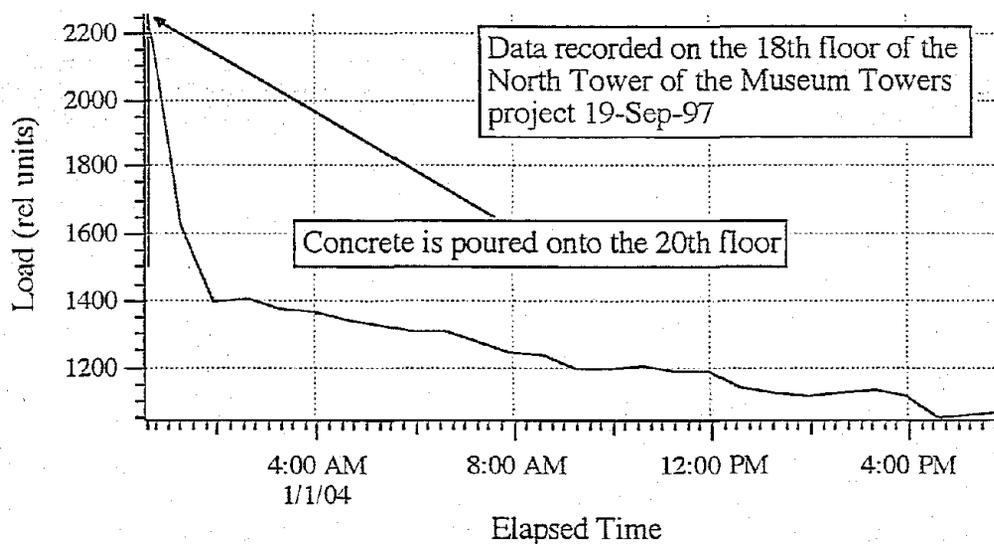


Figure 3-18. The measured load for the PERI shoring member instrumented with the wireless unit is shown before, during and after a large concrete pour occurs.

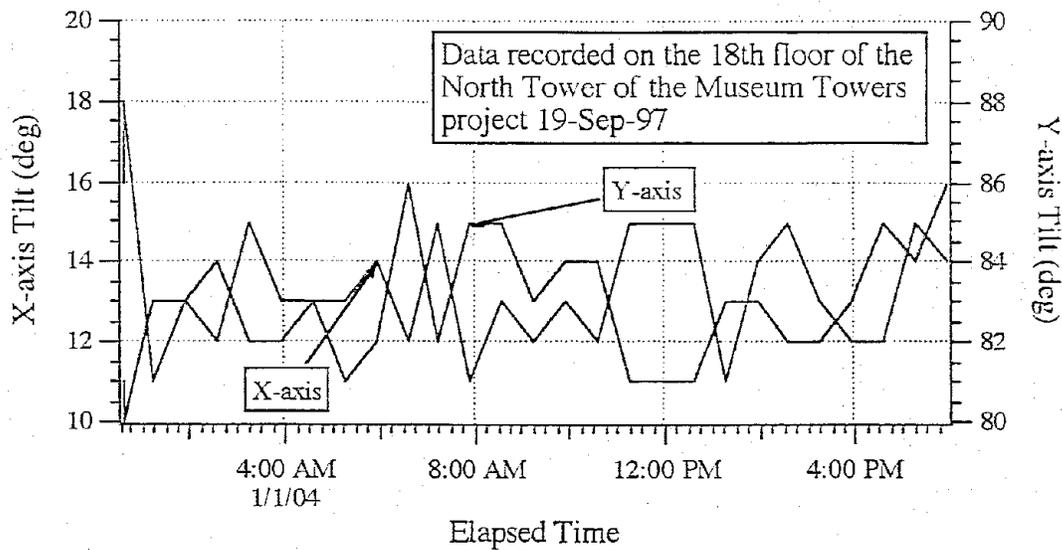


Figure 3-19. The tilt angles in the X- and Y-axes are shown as a function of elapsed time. These measurements were made concurrent with those shown in Figures 3-18 and 3-20.

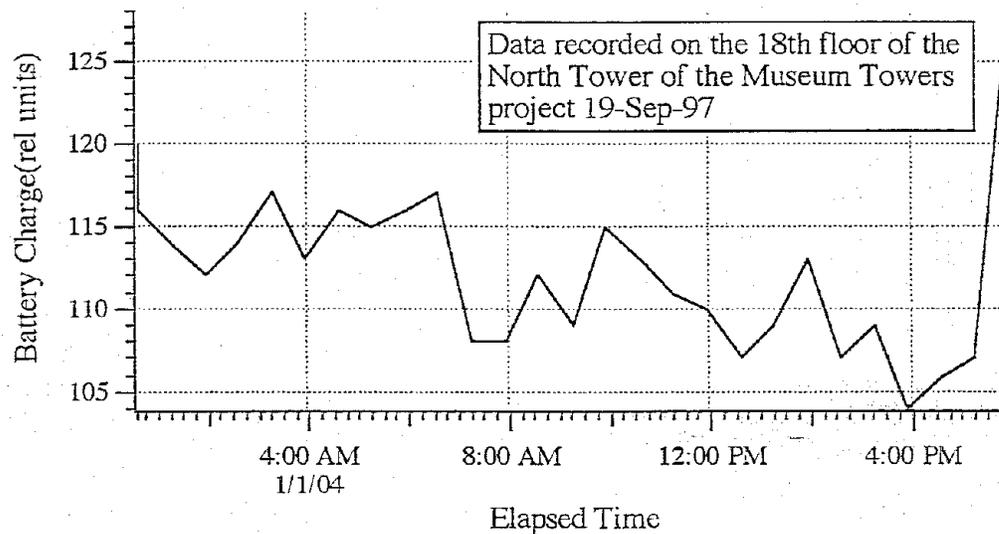


Figure 3-20. The battery performance of the wireless unit is plotted as a function of elapsed time.

### 3.7. SUMMARY

The purpose of this investigation was to develop an instrumented smart shoring system and ascertain its applicability in providing load distribution information for construction site engineers. The smart shoring system was based around the use of 4 conventional load cells plus one unit equipped with a wireless data transfer system placed on various structurally important load-bearing support members of shoring configurations. Initial laboratory calibration measurements were made on these load cells. In a more controlled laboratory environment, the smart shoring system was

stuided to see its performance when presented with three potential failure mechanisms related to shoring systems: 1- weak shoring members; 2- soft fittings; and 3- uplift monitoring. In each case it was observed that such potential failure mechanisms are readily visible upon looking at the load distribution data presented by the instrumented shoring.

From a performance standpoint we feel that these measurements show that in principle instrumented shoring members may be used at actual construction sites to provide load information not previously available. No occurrences of the potentially hazardous shoring failure mechanisms investigated in the laboratory occurred at the site (or in the data). In addition, by using the instrumented shoring load measurements along with extrapolated time constants based on the measured data, it may be possible to determine the state of cure. Such information may be of enormous value to concrete engineers who rely on tried-and-true practices such as cylinder tests to determine the state of the cure cycle. If accurate information regarding the level of cure of the concrete may be predicted via these measurements, or more importantly a prediction of when the concrete will be strong enough to support extra weight, then the project manager (or other cognizant individual) may save considerable costs by knowing when work can continue on to the next level (instead of just waiting), or can avoid potentially hazardous situations by delaying the construction process. and Finally, yes the Musuem Towers are standing and ready for occupancy (Figure 3-21).



Figure 3-21. The completed Musuem Towers (as of February 1998).

### 3.8. REFERENCES

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  9. D.R. Huston, P.L. Fuhr, T.P. Ambrose, E.A. Devino and M.P. Werner, "Construction Load Monitoring Using Instrumented Shoring", Proc. of SPIE Smart Sensing, Processing and Instrumentation, Vol. 2191, Feb 1994., pap #48, pg 408-419, Orlando, FL.
  10. D.R. Huston, P.L. Fuhr and T.P. Ambrose, "Field and Laboratory Measurements of Shoring Loads", Proceedings of the 1996 ASCE Structures Congress, Chicago, IL, April 1996.
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## 4. Overall Project Summary

As has been previously stated, during the course of this project we developed and tested a load monitoring system specifically designed to be used in a realistic construction site atmosphere. Field measurements were performed at the following construction sites: a 6 story courthouse in Burlington Vermont; a maximum security prison near Beckley West Virginia; a single story warehouse in South Burlington Vermont; a parking garage in Burlington Vermont; wooden test structures in Jericho Vermont; and the final building(s) the 26-story Museum Towers in Boston Massachusetts. A view of the completed wireless telemetry system is given in Figure 4.1.

Descriptions of this effort were reported in:

- (1) T.P. Ambrose, D.R. Huston, P.L. Fuhr, E.A. Devino, E.A., and M.P. Werner, "Shoring Systems for Construction Load Monitoring", *Jnl. of Smart Materials and Structures*, No. 3, Vol. 1, March 1994;
- (2) D.R. Huston, P.L. Fuhr, T.P. Ambrose, E.A. Devino and M.P. Werner, "Construction Load Monitoring Using Instrumented Shoring", *Proc. of SPIE Smart Sensing, Processing and Instrumentation*, Vol. 2191, Feb 1994., pap #48, pg 408-419, Orlando, FL;
- (3) D.R. Huston, P.L. Fuhr and T.P. Ambrose, "Field and Laboratory Measurements of Shoring Loads", *Proceedings of the 1996 ASCE Structures Congress*, Chicago, IL, April 1996;
- (4) D.R. Huston, D.V. Rosowsky, P.L. Fuhr, and W.F. Chen, "Construction Shoring Load Measurements", *Proceedings of the American Society of Civil Engineering Structures Congress '95, 13th Structures Congress*, 1995;
- (5) P.L. Fuhr and D.R. Huston, "Load Sensing for Improved Construction Site Safety", to be published in *Sensors Magazine*, June 1998.

### 4.1. Phase 2 Project Goals

This SBIR Phase 2 project consisted of five main tasks:

1. Design and build prototype systems;
2. Test the prototype units in the field;
3. Design and build production-ready units;
4. Field test and environmental stress test the production ready units;
5. Redesign and rebuild of the production ready units as dictated by the results of the field and environmental tests.

As anticipated, Tasks 1 and 2 were completed in year 1. Tasks 3, 4 and 5 were completed in year 2. While somewhat of a repeat of earlier discussion, each Task is described in detail in the following sections.

### 4.2. Task 1 Design and Fabrication of Prototype Systems

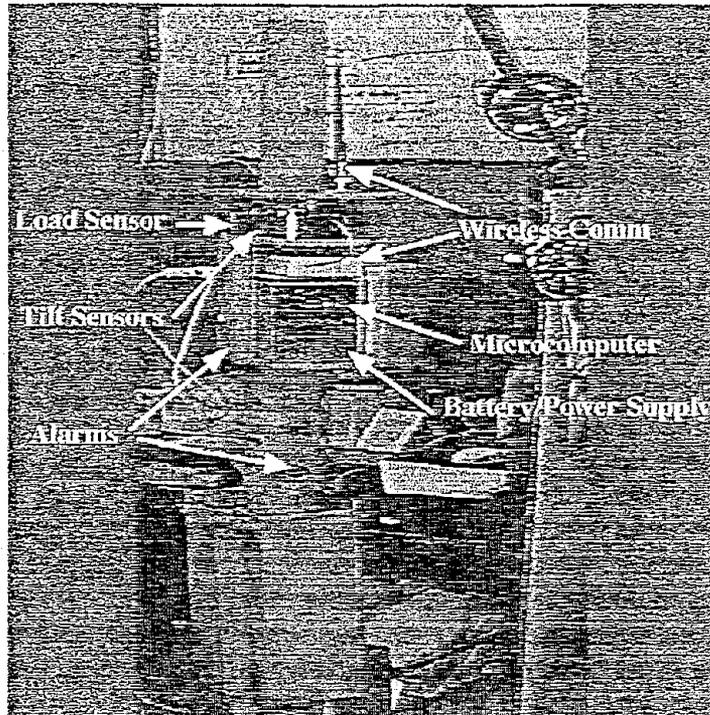


Figure 4.1. The use of wireless communications and batteries for all power needs allows units to be quickly and easily installed throughout the construction site. This unit relies on spread spectrum communications in the 902-926 MHz to achieve good signal fidelity in the presence of large amounts of construction site generated electromagnetic interference.

By the end of year 1, three prototype units were constructed. The prototype units were built mostly from off-the-shelf items that provided the necessary functional capability to the system. As a result the prototype system was somewhat larger, and heavier than the ultimate production-ready units. However, the prototype units did provide a basis for the actual construction of smaller more compact units. During Year 2, the design and construction of the production-ready units was improved. These units were then subjected to a battery of tests to ensure the extended survivability of the units on a working construction site. A partial list of the tests included: a drop test, heat, humidity, cold, chemical attack, long-term transducer stability and fungus resistance. Based on the results of these tests, modifications were made to further improve the reliability of the system. During Year 2, the prototypes were then used in load monitoring of an old circa 1910 building whose lift was removed during the winter of 1997. This provided us with the perfect setting - outside and cold while still relatively harsh from an operational - construction site standpoint. We used this experience to revamp the trickle charging scheme that we were using for the battery-powered operation.

The development of the instrumented shoring system during the two year period involved a series of project milestones to ensure the timely completion of the project. The project milestones involved the development of an increasingly complex and more intelligent system as time progressed. The end result was a system that consists of a series of units which were formed out of interlocking modular collars, as shown in Figure 4.2.1. Each collar will consist of a rubber-coated steel jacket on the outside that is hinged to allow simple installation. An alarm system and visual display, which will be standard equipment on all models, was included. This consists of a simple light and buzzer that will advise anyone in the general vicinity of a potential overload of that particular shoring member. On more expensive models, the base unit is alerted via telemetry as to this hazardous overloading situation. It is envisioned that in future generations, a beeper will then be activated to alert the suitable personnel that a problem exists. Information detailing with which shoring member or members were experiencing the problem will be indicated. This will allow the system to run by itself until there is a problem, thus reducing the need for an individual dedicated to monitor the condition of the instrumented shoring members.

#### **4.2.1. On-Site Base Computer:**

The base unit consists of a PC based computer which is able to receive and store all inputs from the units simultaneously. The base unit also may communicate with sensor head modules to change the alarm levels and detect battery levels. There is potentially an enormous amount of data, depending on the number of instrumented shoring members, to be stored. Therefore, a WORM (Write Once Read Many) system is implemented to solve this dilemma. A WORM system allows more than one gigabyte of memory to be stored permanently on a single 5.25" optical disk, there could be no tampering of data or erasing of disks. This information will be useful if there is a failure, alternatively, studies could be done with the data. In other words, while the sensor head is capable of retaining a limited amount of data, in some sense, the base computer itself serves as the

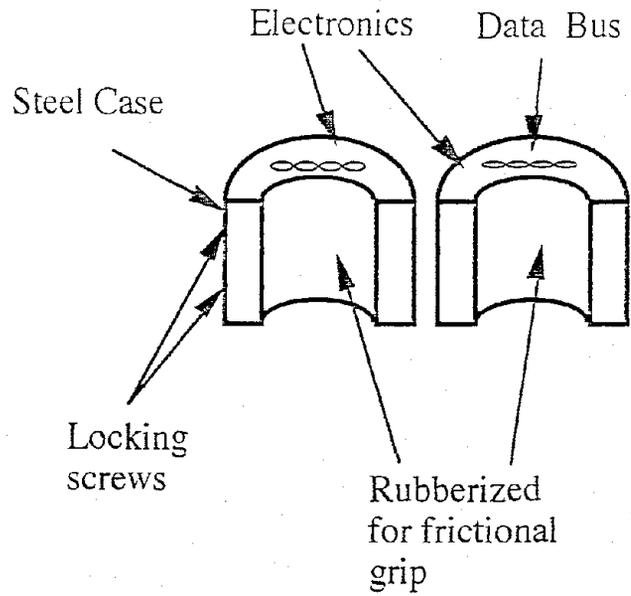


Figure 4.2.1. Individual modular collar

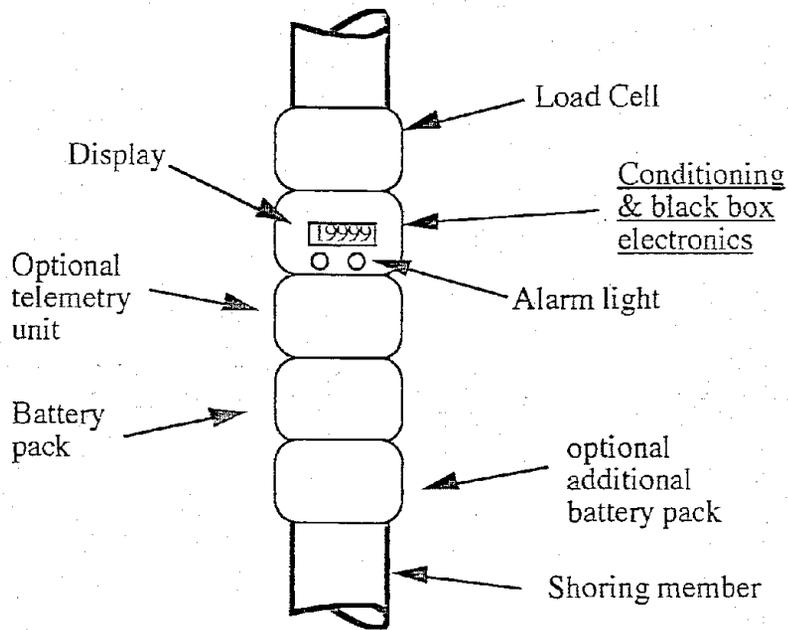


Figure 4.2.2. Major system components

primary "black box" of recorded data - data that could be analyzed in the case of a collapse or partial failure. It is also most noteworthy to mention, that this system has the potential to provide incite as to the dynamics of the curing of concrete in real world situations. This information could be compiled and studied to develop safer and more cost effective means of pouring concrete based on a variety of factors i.e. environmental conditions, volume of the pour, geometric considerations, chemical makeup of the concrete. The bottom line in concrete pouring seems to be "is it cured enough yet?". This statement is indicative of the relative urgency with which the crew would like to move on to the next pour (potentially the deck just above this one) for waiting for the concrete to cure ties up equipment and personnel thereby leading to increased corporate expenses. Any measurements that could provide the cognizant officials with the actual state of concrete cure may be potentially enormously popular.

#### **4.3. Task 2 - Field Tests of Prototype Systems**

The prototype units allowed for rapid evaluation of performance and modification of the unit design based on initial in-field tests. These tests involved a shake down of the units on numerous pours. An examination of typical construction site hazards to equipment was performed to determine how to protect the units from years of constant use. Observations were made as to the implementation of the units to improve their function and operating characteristics. The software and hardware of the base station were developed. The numerous problems that were encountered in this task were systemically examined and led to rapid redesigning for the production-ready units. Site tests were performed at a number of venues ranging from small to very large buildings in cold and hot, but always humid, ambient conditions.

#### **4.4. Task 3 - Design and Fabrication of Production-Ready Systems**

A construction site is an extremely hostile environment for any sort of equipment. Often times equipment is dropped, buried, submerged in a variety of liquids, electrocuted and subjected to extremes of temperature and humidity. These conditions would require that any piece of equipment be virtually bomb-proof. Additional, these units are to act as "black box" recorders in the event of a failure. Therefore, based on the observed and perceived hazards of the construction sites appropriate physical armor was placed around all components of the system (please see Figure 4.1). This steel casing required that all moisture be kept out and withstand chemical attack as well as, physical abuse. Additionally, a rubber sheath encases the units to reduce the shock when they are physically abused. The electronics were examined to ensure linearity, operating temperature insensitivity and low power consumption. The units must be of suitable geometric size and weight to remain useful on the job site. All of these considerations were taken into account when the production-ready units were designed and built. These production-ready units were built and assembled on the component level to ensure that all components were of high quality and fit the geometric constraints. Printed circuit board design and layout software is available to the designers and will be used in the final design. Additionally, a critical evaluation

was performed during this process to ensure ease of manufacturability. This allowed the low cost nature of the systems to be retained.

The final completed prototype unit, as used at the Museum Towers project, is shown in the Figure 4.1.

#### **4.5. Task 4 - Field and Environmental Stress Tests of Production-Ready System**

Each section was thoroughly tested in the lab through a battery of tests to duplicate the conditions on a construction site. Field tests followed the laboratory tests to ensure survivability and continued operation. The damage resistant design of the units was tested by treating the units as standard shoring members. Construction crews use these members on a daily basis and run them through their paces. The environmental integrity of the units was evaluated and the results were examined over a period of several months. No adverse environmental effects were found to diminish the overall system performance.

#### **4.5. Task 5 - Redesign Systems as necessary**

Any shortcomings or problems with the production ready units were corrected during the multiple iterations which this unit underwent throughout its development. A final evaluation of the ease of manufacturability of the units is currently underway.

#### **4.6. Technical References**

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