EFFECTIVENESS OF AN ACOUSTIC CONTINUOUS MONITORING SYSTEM FOR POST-TENSIONED BUILDINGS- AN EVALUATION REPORT

Effectiveness of an Acoustic Continuous Monitoring System for Post-Tensioned Buildings

An Evaluation Report

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An Evaluation Report

Prepared for

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Executive Summary

The effectiveness of an acoustic continuous monitoring system in reporting the time and location of wire ruptures in unbonded post-tensioned tendons of buildings has been evaluated.

When installed in a structure containing unbonded post-tensioned tendons, the monitoring system picks up and records acoustic signals created by the rupture of a tendon wire and by other impact phenomena using an array of accelerometers, a pre-trigger device and an on-site, computer-based data acquisition system. Computer software, incorporating an artificial learning network, analyzes the recorded signals to identify and locate wire rupture events.

The system was evaluated by NRC/IRC in a post-tensioned building by cutting individual tendon wires and by intentionally producing other types of impacts on concrete members. Several months of data obtained from monitoring systems placed in two other buildings were also examined to evaluate the ability of the system to detect spontaneous tendon ruptures.

Based on this investigation, the acoustic monitoring system was considered effective in reporting the time and location of tendon ruptures in the monitored part of an unbonded post-tensioned building. Using the system to monitor the behaviour of a new building or an older building in which the existing condition of the tendons has been established by other techniques, can provide valuable information to assess the structural impact of tendon rupture at any time during the building's life.

It is recommended that the system be further developed to incorporate the capability of reporting the number of rupturing wires producing an acoustic event and to improve the reliability in locating the tendons in which the wire ruptures occurred. This additional information will help improve the accuracy of structural assessments and thus minimize the need for supplementary destructive field investigations.

Résumé

On a évalué l'efficacité d'un système de surveillance sonore continue pour signaler le moment et l'endroit où se produit une rupture de fil dans les câbles de post-contrainte non adhérents de certains bâtiments.

Lorsqu'il est installé dans une structure renfermant des câbles de post-contrainte non adhérents, le système de surveillance capte et enregistre les signaux sonores produits par la rupture d'un fil de câble, et par d'autres types d'impact, au moyen d'une batterie d'accéléromètres, d'un dispositif de préimpulsion et d'un système informatisé d'acquisition de données sur place. Le logiciel utilisé, doté d'un réseau d'apprentissage artificiel, analyse les signaux enregistrés afin de reconnaître et de repérer les ruptures de fil.

L'Institut de recherche en construction du Conseil national de recherches a évalué le système à l'intérieur d'un bâtiment à structure de béton post-contraint en coupant des fils de câble et en produisant intentionnellement d'autres types d'impact sur les pièces de béton. On a également examiné les données obtenues durant plusieurs mois d'essais à l'aide de systèmes de surveillance placés dans deux autres bâtiments afin d'évaluer la capacité du système à détecter les ruptures de câble spontanées.

L'étude a permis de déterminer que le système de surveillance sonore était efficace pour signaler le moment et l'endroit où se produit une rupture de câble dans la partie surveillée d'un bâtiment en béton post-contraint à câbles non adhérents. En utilisant le système pour surveiller le comportement d'un bâtiment neuf ou d'un bâtiment âgé dont on a déjà déterminé l'état des câbles au moyen d'autres techniques, on peut obtenir d'utiles renseignements pour évaluer l'effet d'une rupture des câbles sur la structure à n'importe quel moment durant la vie utile d'un bâtiment.

On recommande que le système soit amélioré afin d'y intégrer la possibilité de signaler le nombre de fils qui se rompent et qui produisent un son, et d'améliorer sa fiabilité à localiser les câbles dans lesquels se rompent les fils. Cette information additionnelle contribuera à améliorer la précision des évaluations de structures et réduira ainsi au minimum la nécessité de procéder à des examens destructeurs additionnels sur le terrain.

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1. Introduction

Evaluation of post-tensioned (PT) buildings poses a challenge to professional engineers. The tendons are hidden from view and external evidence of their corrosion is seldom apparent. Therefore, non-destructive techniques that can determine the in-situ condition of tendons are essential.

To assess the structural impact of tendon damage requires techniques that can determine the in-situ condition of tendons. However, to make rational decisions on whether to repair or rebuild, and to schedule and budget for repairs, techniques that determine the rate of deterioration are also required. In this respect, a technique that can detect and locate the rupture of individual tendon wires can be very useful.

The effectiveness of such a technique was evaluated by the Institute for Research in Construction (IRC) of the National Research Council (NRC) under a contract with the Canada Mortgage and Housing Corporation (CMHC) and a letter of agreement with the proponent. This report contains the method and findings of this evaluation.

2. Evaluation Protocol

A protocol, which was agreed to and signed by the proponent, was developed by NRC/IRC to evaluate an acoustic continuous monitoring system. The complete protocol is given in Appendix I with the most relevant portions being restated below.

2.1 Objective of Evaluation

The evaluation was carried out to determine if the acoustic continuous monitoring system could detect and locate the rupture of a tendon, or of one or more of its wires, and record and report such events continually over a period of time with reasonable accuracy.

2.2 Evaluation Criteria

The effectiveness of the technique depends on its accuracy in detecting and locating tendon ruptures. For structural safety reasons, the technique should not miss reporting actual tendon ruptures, but on the other hand, it should not raise false alarms by reporting spurious events, such as floor impacts from heavy falling objects. Interpretation of captured events should not rely mainly on operator judgment. Proper identification of ruptured tendons is important to avoid replacement of intact tendons during building repairs. If the technique can also report the number of wires of a multi-wire tendon, which ruptured during an event, the structural impact of failures could be assessed more accurately.

The following criteria were used to judge the effectiveness of the technique:

A. Simplicity

a. Type, number, weight and size of field equipment
b. Field power requirements
c. Ease of installation
d. Ease in interpreting field data
e. Destructiveness to the building under investigation
f. Disruptiveness to building functions and occupants

B. Accuracy and Reliability

a. Closeness of measured or estimated parameters to actual conditions
b. Reproducibility of measurements
c. Ability to ignore or filter spurious signals
d. Sensitivity of the system to other sources of noise and vibration
e. Dependence on operator or interpreter
f. Ruggedness of equipment
g. Frequency of calibration

C. Sensitivity and Range

a. Threshold sensitivity in detecting wire breaks
b. Resolution of coordinates for locating a wire or tendon break
c. Minimum time interval between two discernible wire breaks

2.3 Method of Evaluation

The technique was evaluated by carrying out the following tasks:

1. Review of information obtained from the proponent on the working principle, equipment, field procedure, analysis and interpretation of field data, manner of reporting results, limitations of the technique known to the proponent, and range of cost for using the technique
2. Observation of field operation at a number of sites where the system has been installed on a commercial basis
3. Field testing of the technique in a building to determine its capabilities and limitations in detecting and identifying artificially induced tendon/wire ruptures and other acoustic events
4. Verification of spontaneous tendon/wire breaks reported by the technique in a number of buildings being commercially monitored by the technique.

3. Description of Acoustic Continuous Monitoring System

The following information was gathered from written materials submitted by the proponent, interviews with proponent personnel and field observations of the technique by NRC/IRC personnel.

3.1 Working Principle

Rupture of a stressed tendon releases substantial energy creating an acoustic wave that is transmitted into a concrete structure in all directions. Using the monitoring system, this acoustic signal is picked up by an array of sensors that are attached to the surface of the concrete member and recorded whenever its strength exceeds a preset and adjustable threshold. As the system also picks up other structural-borne acoustic signals which are comparable in amplitude to tendon ruptures, all recorded events are processed and analyzed by a proprietary computer program using an "artificial learning network" (ALN) to identify actual tendon ruptures and to locate the ruptures within the member.

3.2 Equipment

Piezoelectric *accelerometers* are used for sensing the vibration in the concrete member created by the rupture of a tendon wire. They are connected to a *pre-trigger device*, the output from which is fed into a *data acquisition system* controlled by an *on-site computer*.

To minimize the recording of most trivial events, the *pre-trigger* device, configured to accept only signals possessing certain characteristics, determines which signals are recorded and which are ignored. Information collected by the on-site computer is periodically downloaded to a *central computer* via *phone lines* for processing and screening by a *computer program* that identifies and locates tendon ruptures.

3.3 Field Installation

The accelerometers are attached to the surface of the concrete member (generally the slab soffit) with a strong adhesive. Typically, one accelerometer is used for every 100 sq. m of slab area although the presence of unusually short tendons or discontinuities (expansion joints etc.) in the monitored portion of the slab may require a higher density of accelerometers. The connecting cables are routed along the slab surface to where the recording equipment (pre-trigger device and data acquisition system) is installed. A telephone link is established between the on-site computer and the central computer.

The slab is divided into zones, the number and size depending on the total area to be monitored and on the presence of acoustical barriers, such as expansion joints. A special multiplexing technique is used to reduce equipment costs by minimizing the number of channels required in the data acquisition system to monitor the slab.

Following installation, the system is tested and the threshold in the pre-trigger device set at an appropriate level for the site. This can be done by producing impacts of known characteristics on the slab, although the proponent prefers to do it by cutting a few wires from one or more tendons if site conditions permit. Normally, the threshold level is set at about 50% of the smallest release of energy from actual wire cuts.

3.4 Data Acquisition

When a sensor (accelerometer) signal produced by an acoustic wave exceeds the threshold level of the pre-trigger device, the data acquisition system is activated and waveforms from all slab sensors recorded for a period of about 150 milliseconds. The system remains busy for a short time interval to record and write the collected information into a computer file. If more events occur during this busy interval, they are not recorded. To minimize the chances of missing additional wire or tendon ruptures, the operator can set the busy period to as low as two seconds.

Data collected by the on-site computer is periodically transmitted to the central computer, the frequency of transmission depending on the amount of data collected.

3.5 Data Processing and Analysis

Each recorded event is analyzed by a proprietary computer program to determine whether the event is a wire or tendon rupture. In this process, the characteristics of the recorded event are compared to those of previously verified ruptures in the same and/or other buildings. A final manual screening/verification of all recorded events is usually conducted by an experienced operator.

The source of each event is placed within the zone registering the strongest sensor signal. The location of the event within that zone is then determined from the times of arrival of the acoustic wave at all sensors situated within that zone. If the recorded event is interpreted as a wire or tendon rupture, the orientation of the tendon sustaining the rupture is also determined by analyzing the times of arrival and signal strengths of the other sensors.

A scale drawing is prepared for the sensor layout from measured distances of the sensors relative to each other and to a fixed reference point, generally one of the sensors. The stated accuracy of sensor positions in this layout is ±300 mm. Another drawing is prepared with the sensor layout superimposed on the structural layout of the member so as to show the source locations of events recorded by the system and the orientations of tendons suspected of sustaining wire ruptures.

3.6 Report

A log of all events recorded by the on-site system is prepared showing their times of occurrence in year/month/day and hr:min:sec, and their location coordinates in centimeters from the reference sensor. Events identified as ruptures are marked as such. The location and orientation of ruptured tendons are also shown on a plan of the member.

3.7 Cost of Using Monitoring System

The cost of monitoring post-tensioned buildings by the acoustic continuous monitoring system depends principally on the area of the slab to be monitored, accessibility of the slab soffit, and the required frequency of monitoring reports. The proponent estimated in the spring of 1997 that the cost of installation could vary from \$5 to \$10 per m^2 and that for monitoring from \$0.60 to \$0.90 per m^2 per year.

4. Field Tests

4.1 General

To determine the monitoring system's capabilities and limitations in a reasonably short period of time, the technique was tested under controlled conditions using artificially induced events, such as cutting tendon wires, striking the structure with hammers and dropping heavy weights onto floors. Because the ultimate proof of the technique's effectiveness lies in the verification of technique-reported ruptures in tendons, a building in Calgary was and still is being monitored by the technique.

4.2 System Installation at Test Site

To evaluate the monitoring system under controlled conditions, the system was installed by the proponent at the request of NRC/IRC in a second post-tensioned building in Calgary. About 1800 m^2 of the ground floor slab over an underground parking garage beneath the building, henceforth called Building A, was selected for monitoring. Slab tendons were of the pushed-through type and nominally 15 mm in diameter. They were uniformly distributed in the N-S direction and banded over columns in the E-W direction in most of the designated area.

The proponent divided the designated area into three zones and instrumented these zones with a total of 55 accelerometers. This is about three times the normal density of sensors reported earlier by the proponent in describing the technique. The proponent explained that the structural layout was unusual as many tendons in the area were only 6.4 m long and the slab was segmented by several expansion joints that acted as acoustical barriers.

Following installation of the system, the proponent demonstrated its operation to NRC/IRC personnel by testing the system after setting the threshold level for the pre-trigger. Six wires of a single tendon were cut (the 7th wire snapped on its own). The cuts were observed to activate the monitoring system as sensor signals were recorded on the data acquisition system.

4.3 Unusual Acoustic Environment of Test Site

Continuous monitoring at the test site began in September 1995 soon after the monitoring system was installed. Within a few days, field work for another technique under NRC/IRC evaluation began on the same slab. This work included chipping concrete from the slab to install inspection recesses and expose tendon anchors. The chipping action triggered the acoustic monitoring system continually causing it to record a huge amount of irrelevant data which needed to be examined by the proponent. The recordings also filled up the storage disk and thus forced the system to shut down several times. The proponent was therefore authorized to turn the system off between 7:30 AM and 5:30 PM every weekday until this other work ended.

Because of this problem, the proponent developed a pre-trigger device which would activate the recording system only if an event occurred after a pre-set and adjustable time interval from the last recorded event. If an event occurred within this interval, the device would not only ignore the event but also reset the interval timer to zero. Thus, after the system had recorded the first chipping hammer event, the highly repetitive hammer actions were not recorded again unless a pause in chipping occurred which was longer than the pre-set interval. This change proved to be extremely helpful in minimizing the amount of data collected at the site as chipping was performed sporadically on the floor slab until May 1996. Unfortunately, if a tendon or wire ruptured during the chipping process, it would have been missed by the acoustic monitoring system.

4.4 Tendon Cutting Tests

The technique's ability to detect and locate the rupture of individual tendon wires was tested by deliberately cutting tendon wires. As 30 tendons were to be cut and extracted from the same slab area for the evaluation of the other technique, some of these cuts were used to test the acoustic monitoring system. This overlap in activities helped reduce the evaluation costs for both techniques. The proponent was not present at the site during any of the tendon cutting tests.

As concrete chipping was also scheduled to occur on the days selected for the tendon cutting tests, NRC/IRC took the following steps to avoid collecting data triggered by the chipping operation: 1) turned amplifier input level on the pre-trigger device to zero position prior to the start of chipping, 2) turned amplifier level back to normal before conducting the cutting tests, and 3) prohibited chipping during the cutting tests. As the monitoring system was never turned off—only the input level on the pre-trigger device turned to the minimum setting—no start-up entry was written into the data acquisition system to assist the operator determine the times of the cutting tests.

A log of tendon cutting activities is given in Table 1. Twelve tendons were cut for the tests. All seven wires were cut in 10 of these tendons and one or two wires in the remaining two. The exact time of each wire snap was recorded for six of the severed tendons. One wire was cut for each test but occasionally more than one snapped as a result of the cut. Most of the tendons were cut with a noisy hand-held grinder, some rather quickly such as tendon 109W. The other three wire cuts in each of two tendons were conducted by NRC/IRC using a quieter high-speed cutting tool.

4.5 Impact Tests

Seven impact tests were conducted to test the system's ability to distinguish acoustic signals produced by objects striking the slab from those produced by wire ruptures. A 2-kg sledge hammer and a 5-kg instrumented hammer were used for these tests. A log and a brief description of the tests are given in Table 2. Impact Tests 2 and 3 were deliberately conducted on the same day as some of the cutting tests. In each of the impact tests, numerous impacts were produced at intervals similar to those arising from wire cuts. The intent was to make a series of impacts appear as tendon cuts to determine whether the reporting of wire ruptures was influenced by circumstantial evidence.

5. Field Test Observations

5.1 Manner of Reporting Wire Snaps

In the first monitoring report submitted by the proponent to NRC/IRC, (sample pages are given in Appendix II), many events in the log of recorded events were marked as 'likely snaps' or 'probable cuts' with a probability of 0.5 of being a wire snap. As this was considered equivocal for the purpose of judging the effectiveness of the technique in detecting wire snaps, the proponent was asked for clarification before system-reported events were compared with NRC/IRC test records. In response, the proponent requested that all reported 'likely snaps' be interpreted as snaps (ruptures) and also decided not to qualify events diagnosed as snaps with any probability in subsequent reports. The authors interpreted the submitted monitoring reports accordingly.

System-reported wire snaps were examined to find if they matched NRC/IRC records of wire cuts in both time and location. For an accurate comparison, the system-reported times were corrected by deducting a synchronization error of 50 seconds with respect to the NRC/IRC clock.

5.2 Accuracy of Event Detection

Of the 12 tendons cut, seven appear to have been detected as at least one wire snap was reported by the acoustic continuous monitoring system. Time plots of actual and system-reported events associated with these tendon cuts are shown in Fig. 1. In four of the tendons (Nos. 27E, 109E, 112E and 125S) for which the exact time of each wire snap was noted, some snaps were detected by the monitoring system. The reported wire snaps match very well in time with actual snaps for tendons 112E and 125S, but not so well for 27E and 109E. In three of the tendons (7W, 108W and 109W) for which exact times of wire snaps were not recorded, five wire snaps were reported by the monitoring system for tendon 7W, two for 108W and only one for 109W. Interestingly, these three tendons were cut with the noisy hand-held grinder.

The other five tendon cuts were not detected by the acoustic continuous monitoring system. In three of these tendons, the cuts were made with the grinder and in the remaining two with the high-speed miniature cutting tool. The monitoring system was reported OFF by the proponent during the time when two of these tendons were cut even though it was scheduled to be ON.

The first two of the four impacts of Impact Test 2 were reported as wire snaps (Fig. 1). Impact Tests 1, 3, 4 and 6 were not reported as wire snaps. During the remaining impact tests, i.e. Tests 5 and 7, the system was reported to be OFF even though it was again scheduled to be ON.

5.3 Accuracy of Event Location

In proponent reports, the location of an event is given by its X-Y coordinates in a Cartesian system whose origin is located at one of the sensors and whose axes are oriented either parallel or perpendicular to the tendons (Fig. 2). It was generally observed that for all events associated with the cutting of a single tendon both the X and Y coordinates of each wire cut varied with the Y coordinate varying more than the X. Delta x (Δx) shown in Fig. 2 was found to range between 0.03 m and 0.87 m and Δy between 0.55 m and 2.59 m.

5.4 Proponent's Explanation of Observations

Following the comparison of system-reported wire snaps and test events, the authors sent their observations as well as the log of events (time and location of each wire snap) to the proponent for comments. The proponent felt that the noisy grinder was responsible for the apparent failure of the monitoring system to detect a number of the wire cuts or to capture the exact time of the cuts. Grinder noise in some instances appears to have triggered the system into a recording mode, forcing it to miss the wire snaps that followed moments later. Records of recorded events previously screened out by the ALN (artificial learning network) as spurious were forwarded by the proponent to NRC/IRC for review. After comparing these records with the log of events, the authors became convinced that grinder noise had indeed caused the system to miss and/or wrongly mark the times of many of the wire cuts.

For the two undetected wire cuts in tendon 31W, which were made by NRC/IRC using a high-speed miniature cutting tool, the proponent reported that the computer file containing those events had been damaged and thus was inaccessible by the central computer for analysis.

As for the system being OFF on two occasions when it was scheduled to be ON, the proponent explained that the system had to be turned off several times to download large amounts of data collected from events generated primarily by the on-site chipping activities of the other contractor. But on one occasion, the acoustic monitoring system was turned off to fix a hardware problem with the on-site system.

The larger scatter in the y-coordinate (direction of slab tendons) for events that were generated by the cutting of several wires at a single location on a tendon, was explained as follows. The program on the central computer determines the point where the stress wave caused by a wire rupture rebounds and enters the slab and not the point where the stress wave is generated. As this rebound can occur anywhere over an appreciable length of the tendon, differences between actual and reported locations along a tendon can be expected.

6. Verification from On-Going Monitoring

Building A, the test site selected for the field evaluation of the system, has been undergoing continuous system monitoring since September 1995. Five spontaneous (naturally occurring) wire breaks, three 'probable' and two 'possible', were reported by the proponent as of March 1997. Shortly thereafter, verification of the reported ruptures was conducted by the proponent using the screwdriver test in the presence of a representative of a Review Panel member. All breaks were confirmed by finding broken tendon wires within 750 mm of the reported locations.

Several other buildings in Canada and the United States are currently being monitored by the acoustic continuous monitoring system on a commercial basis. Two among this set of buildings are Building B, being monitored since February 1994, and Building C since September 1995. The proponent recently verified a number of ruptures reported by the monitoring systems in the two buildings.

From the area being monitored in Building B, the system reported 12 wire ruptures as of November 1996. Ten of these were confirmed by the proponent using the screwdriver test and subsequently by visual inspection of extracted tendons. The eleventh was found on the designated tendon but 5 m from the reported location and the twelfth was a spurious event. Twelve ruptures were also reported by the monitoring system as of May 1996 in Building C. Nine of these were confirmed by the proponent using the screwdriver test. However, the remaining three could not be verified because of difficulty in accessing the reported locations of the wire breaks from the slab soffit.

7. Discussion

7.1 Accuracy

Based on the system's detection of a significant number of deliberate wire cuts, the explanation provided by the proponent for the system's failure to detect the remaining cuts, and the soundness of the technique's working principles, the authors were satisfied that the acoustic continuous monitoring system would detect and locate the vast majority of spontaneous wire ruptures. As two hammer impacts were falsely reported as wire ruptures, it was felt that the system would also identify, from time to time, spurious events as wire ruptures. However, at least four other impact tests were not reported as wire ruptures indicating that the program on the central computer can, for the most part, differentiate the energy patterns produced in the slab by hammer impacts from those induced by wire ruptures. Consequently, the authors believe that the likelihood of false reporting will be small. The confirmation of most of the reported wire ruptures in Buildings B and C would appear to corroborate this belief.

The scatter obtained in pinpointing the location of a wire rupture along a tendon (y co-ordinate in Fig. 2) does not detract from the system's effectiveness as the exact location of a rupture on a tendon is not particularly important. However, variability in the x co-ordinate direction (Fig. 2) is important as this co-ordinate identifies the tendon having sustained a wire loss. High resolution in this co-ordinate is needed, therefore, to ensure the replacement of only damaged tendons. The technique's observed resolution appears adequate to identify the source of an event in distributed tendons (well-spaced tendons) but it is too coarse for a set of banded tendons (closely-spaced tendons). Supplementary field investigations, such as the screwdriver test, may therefore be necessary, on occasion, to identify the damaged tendon from among a few suspect tendons.

7.2 Reliability

The custom-made accelerometers were rugged and of adequate sensitivity. They were not prone to malfunction as they did not contain a built-in amplifier requiring a continuous source of electrical power. The other on-site components were also well suited to their environment as no serious breakdown of any system hardware occurred at the test site (Building A) during the evaluation period (fall 1995 to spring 1997).

The frequency of downloading field data to the central computer can be easily adjusted to minimize the potential for loosing data stored on the on-site computer. The software program that analyses recorded events and identifies and locates wire ruptures has evolved during the course of this 18-month evaluation, improving its accuracy significantly. This was achieved by enhancing the criteria used to discern wire ruptures from other events and by continued training of the ALN using the large number of confirmed wire ruptures from several building sites. The proponent appears to be sufficiently resourceful to fix any software 'bug' that may appear in future.

7.3 Simplicity

The on-site equipment of the acoustic continuous monitoring system is electronic, and hence fairly complicated to lay people. However, the system is simple enough to be installed and used effectively by trained personnel. While a working system can be assembled from components purchased off the shelf, the proponent designed and fabricated some of them to improve performance and save cost.

Installation of the on-site system is essentially non-destructive as no chipping or removal of concrete is required. The accelerometers, which are fabricated by the proponent, are easily attached to a concrete surface using a strong adhesive. A minor short-term disruption to building functions and occupant activities may occur during installation of accelerometers and interconnecting cables on the ceiling of occupied floor areas. Monitoring is passive and silent causing no inconvenience to occupants or interference with normal building functions. Energy requirements are nominal as only the computer-based data acquisition system requires line power.

Manual processing and interpretation of field data are possible and practicable for a small number of captured events at a single building site. For analysis and interpretation in real-life applications, however, automation is indispensable. The proprietary computer program, which is fast, sophisticated and user-friendly, takes care of this tedious but complex process.

7.4 Detection of Multiple Wire Ruptures

The acoustic monitoring system does not attempt (as of spring 1997) to determine the number of wires ruptured during any event. While most wire snaps in real life probably occur one at a time, multiple wire breaks are not uncommon. As the lost capacity of a tendon is directly proportional to the number of wires ruptured, information collected by the monitoring system would be more useful if it could also reliably report the number of wires ruptured in an event. The authors believe this is feasible and the proponent is currently working to achieve this capability.

8. Conclusions

The acoustic continuous monitoring system is based on sound scientific principles. The equipment is reliable, sophisticated and rugged. The computer software, used only by the operator, is user-friendly and relatively self-explanatory. The system when tested was found capable of detecting wire ruptures in unbonded post-tensioned tendons and reporting when and where a rupture occurred. While the system is unlikely to miss capturing wire ruptures, it may sometimes report spurious events as wire ruptures. The likelihood of such false reporting appears to be small.

The acoustic continuous monitoring system appears to be an effective monitoring tool for buildings with unbonded post-tensioned tendons. The following benefits could be derived from using the system:

1. If installed in a new building soon after construction, the system could provide the information required for the evaluation of the residual structural capacity of post-tensioned members and for the repair of these members at any time during the life of the building.
2. In existing buildings containing previously broken tendons, system monitoring for several months could help identify problem zones where inspection of tendons should be concentrated.
3. By helping to identify problem zones, the monitoring system could also assist in determining the underlying causes of the problem for timely intervention.
4. The monitoring system makes replacement of detected broken tendons easier as little probing is required to locate them.
5. By reporting the times of occurrence of ruptures, the monitoring system could help determine the rate of deterioration of post-tensioned members and thus help in scheduling and budgeting repair work. Knowing the rate of deterioration may help the building owner decide on whether to repair or rebuild the structure.

9. Recommendations

The acoustic continuous monitoring system at present does not attempt to determine the number of wires ruptured during an event. Multiple-wire breaks occurring simultaneously in a tendon are not uncommon. It is therefore recommended that this capability be developed, if possible, so as to help engineers more accurately assess lost structural capacity and thus minimize supplementary destructive field investigations to obtain this information.

It is also recommended that the resolution of the location co-ordinate that pinpoints the tendon sustaining a wire rupture be improved so as to reduce the probing that may be required to identify it from amongst a group of closely spaced tendons.

TABLES AND FIGURES

Table 1 Log of Tendon Cutting Activities for Evaluation of Acoustic Continuous Monitoring System

DATE & TIME[1]	ACTIVITY	COMMENTS
Sep 13, 1995		
10:30 to 11:00	All wires of tendon 2W cut at garage entrance	By on-site contractor[2]; no record of exact times
11:28:00	System amplifier turned DOWN	
13:43:30	System amplifier turned UP	
13:45 to14:05	All wires of tendon 7W cut at garage entrance	By on-site contractor; no record of exact times
14:07:25	System amplifier turned DOWN	
15:27:00	System amplifier turned UP	
15:34:25	1st wire cut of tendon 31W at 1 m N of recess	By NRC[3]
15:37:05	2nd wire cut of above	
15:42:28	System amplifier turned DOWN	
16:15:20	System amplifier turned UP	
	Cutting tendon 109E at recess	By on-site contractor under NRC supervision
16:18:08	1st wire	
16:19:16	2nd wire	
16:21:16	3rd wire	
16:22:12	4th wire	
16:31:15	5th wire (no more snaps were heard)	
16:45:30	1st wire of tendon 96E cut at recess	By NRC
16:51:55	System amplifier turned DOWN	
Sep 14, 1995		
7:52:06	System amplifier turned UP	
8:46:33	System amplifier turned DOWN	
8:50:17	System amplifier turned UP	
	Cutting tendon 125S at recess	By on-site contractor under NRC supervision
8:56:20	1st wire	
8:57:10	2nd wire	
8:57:37	3rd wire	
8:58:25	4th wire	
8:58:52	5th wire	
9:00:12	6th wire	
9:01:00	7th wire	
9:04:00	System amplifier turned DOWN	
13:29:50	System amplifier turned UP	

Table 1 (cont.) **Log of Tendon Cutting Activities for Evaluation of Acoustic Continuous Monitoring System**

DATE & TIME[1]	ACTIVITY	COMMENTS
	Cutting tendon 27W at recess	By on-site contractor under NRC supervision
13:35:00	1st wire	
13:35:50	2nd wire	
13:36:30	3rd wire	
13:37:08	4th wire	
13:39:48	5th wire	
13:39:59	6th wire	
13:40:05	7th wire	
13:46:40	System amplifier turned DOWN	
17:55:38	System amplifier turned UP	
Sep 15, 1995		
9:23 to 9:26	All wires of tendon 109W cut at recess	By on-site contractor; no exact times
9:27 to 9:32	All wires of tendon 108W cut	By on-site contractor; no exact times
9:35 to 9:43	All wires of tendon 27E cut	By on-site contractor; no exact times
9:48:50	System amplifier turned DOWN	
16:25:19	System amplifier turned UP	
	Cutting tendon 112W at recess	By on-site contractor under NRC supervision
16:36:35	1st and 2nd wires	
16:38:25	3rd, 4th and 5th wires	
16:46:50	6th wire	
16:47:33	7th wire	
	Cutting tendon 112E at recess	By on-site contractor under NRC supervision
16:48:22	1st wire	
16:48:49	2nd and 3rd wires	
16:50:00	4th wire	
16:50:30	5th wire	
16:51:08	6th and 7th wires	

Notes:

1. Time of hearing the wire snap
2. All cuts by on-site contractor, under NRC supervision or not, were made by a grinder
3. Cuts by NRC were made by a high-speed tool

Table 2 Time Log of Impact Tests

DATE & TIME	ACTIVITY	COMMENTS
Sep 15, 1995		
16:28:20	Test 1 – Hit column 3-F at 400 mm above garage floor	By NRC
	Test 2 - Hitting slab soffit at tendon 111 1 m from Line G	By NRC
17:02:11	1st hit	
17:04:06	2nd hit	
17:04:56	3rd hit	
17:05:25	4th hit	
Sep 16, 1995		
	Test 3 - Dropped instr. hammer on G. floor near Col. 4-G	By NRC
9:02:40	1st drop at 1 m west and 0.6 m south	
9:05:23	2nd drop at 1 m west and 0.75 m south	
9:07:22	3rd drop at 1 m west and 1.0 m south	
Mar 26, 1996		
14:16	Test 4 - Hit slab soffit near S-E corner of garage	Independent Consultant
Apr 9, 1996		
	Test 5 - Hitting slab soffit twice near S-W corner of garage	Independent Consultant
17:52	1st hit at 0.5 m east of West wall	
18:05	2nd hit at 0.7 m east of West wall	
Apr 16, 1996		
12:23	Test 6 - Hit slab soffit near Column 11-F	Independent Consultant
Apr 24, 1996		
18:22	Test 7 - Hit slab soffit near Column 4-E	Independent Consultant

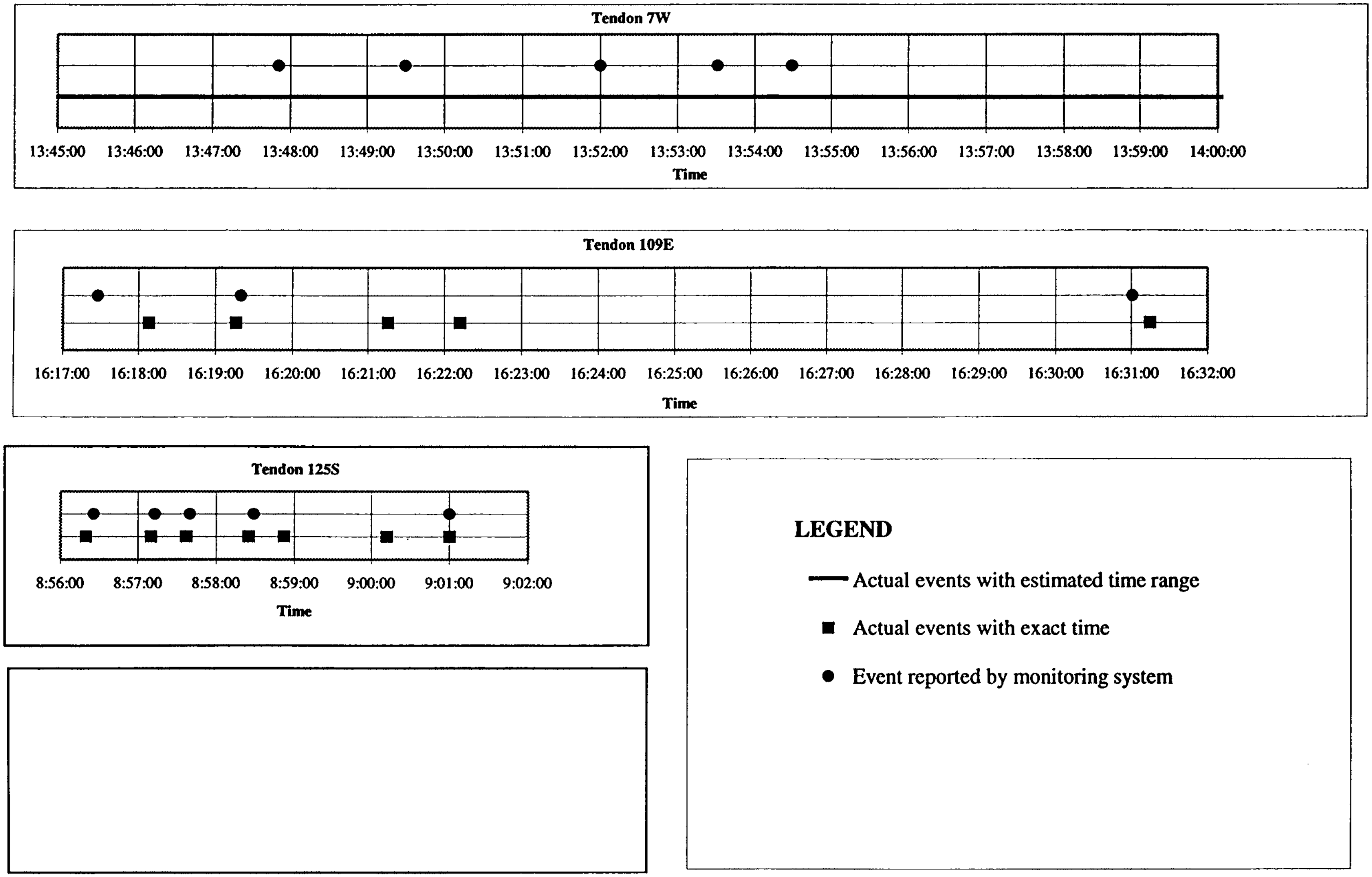
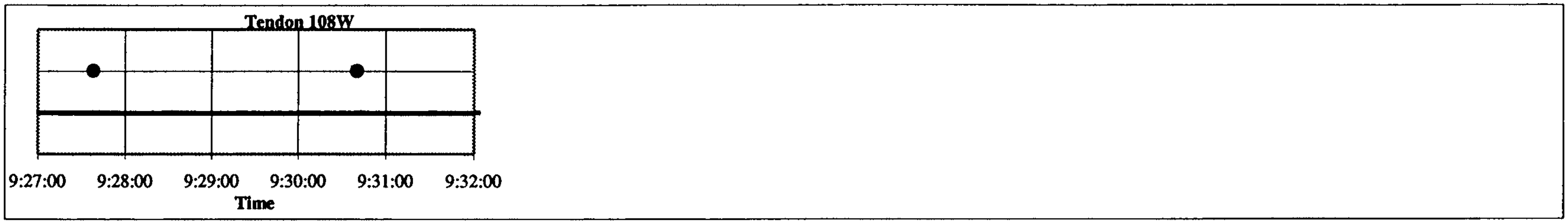
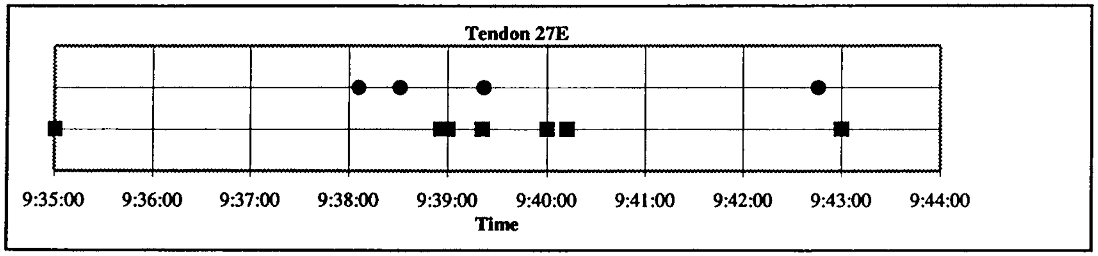
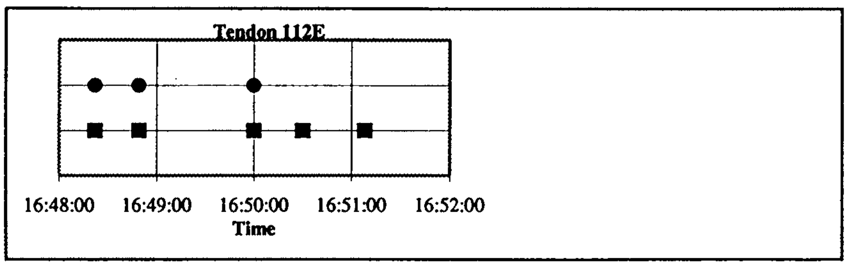
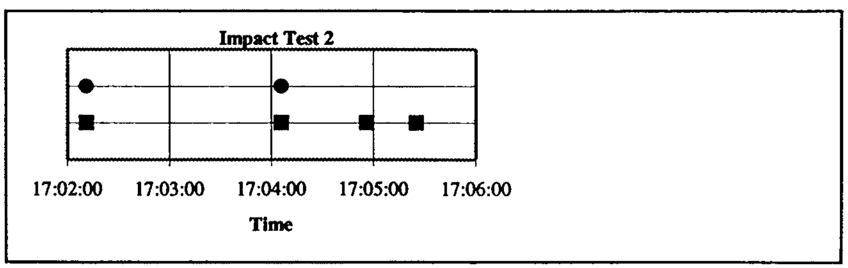


Figure 1 Time Plots of Actual Events and Events Reported by the Acoustic Continuous Monitoring System









LEGEND

— Actual events with estimated time range

■ Actual events with exact time

● Event reported by monitoring system

Figure 1 (cont.) Time Plots of Actual Events and Events Reported by the Acoustic Continuous Monitoring System

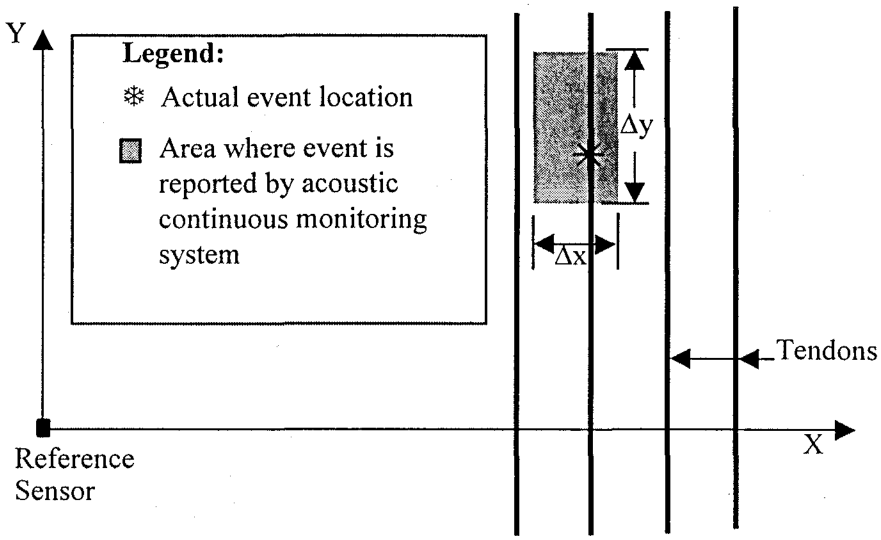


Figure 2 Event Location by Acoustic Continuous Monitoring System

Appendix I

NRC/IRC PROTOCOL
FOR THE EVALUATION OF
AN ACOUSTIC CONTINUOUS MONITORING SYSTEM

1. Introduction

NRC/IRC has been recently requested by the Canada Mortgage and Housing Corporation (CMHC) to evaluate some of the promising techniques of evaluating and repairing post-tensioned building components. The acoustic continuous monitoring system, owned by the proponent, is one of the evaluation techniques to be evaluated.

This document, prepared by NRC/IRC, is intended to form the basis of an agreement between NRC/IRC and the proponent for the former to carry out the evaluation. The document defines the criteria and method for the evaluation of the monitoring system as well as the responsibilities of the proponent and of NRC/IRC in carrying out the evaluation.

2. Objective

The objective of the present evaluation of the acoustic continuous monitoring system is to determine its cost-effectiveness as a tool for the non-destructive monitoring of unbonded post-tensioned tendons in building slabs by detecting and locating the breakage of whole tendons or individual wires which form the tendons.

3. Features under Evaluation

The monitoring system will be evaluated for its capability to detect and locate the breakage of one or more wires of a tendon or of a whole tendon as it occurs in a real-life building.

4. Evaluation Criteria

The following criteria will be applied to evaluate the capabilities and limitations of the acoustic continuous monitoring system:

A. *Simplicity*
   a. Type, number, weight and size of field equipment
   b. Field power requirements
   c. Ease of installation
   d. Ease in interpreting field data
   e. Destructiveness to building under investigation
   f. Disruptiveness to building functions and occupants

B. *Accuracy and Reliability*
   a. Closeness of measured or estimated parameters to actual conditions
   b. Repeatability and reproducibility of measurements
   c. Ability to ignore or filter spurious signals
   d. Sensitivity of the system to other sources of noise and vibration
   e. Dependence on operator or interpreter
   f. Ruggedness of equipment
   g. Frequency of calibration

C. *Sensitivity and Range*
   a. Threshold sensitivity in capturing wire breaks
   b. Resolution of co-ordinates for locating a wire or tendon break

c. Minimum time interval between two discernible wire breaks

5. Method of Evaluation

NRC/IRC will carry out the evaluation of the acoustic continuous monitoring system by

a. conducting interviews of the proponent's personnel and/or studying written materials obtained from the proponent,
b. verifying the system's findings of artificially generated wire/tendon ruptures, and
c. verifying the system's findings of broken wires/tendons from the monitoring of a real-life building.

A panel of consulting engineers conversant with repair of post-tensioned buildings will be invited to provide comments on the NRC/IRC evaluation protocol and on the results of the evaluation. The names of the consulting engineers in this panel are given in Section 9.

5.1 Interviews and Written Submissions

NRC/IRC will interview proponent personnel and/or study the proponent's written materials to obtain information on the following:

a. Working principle of the system
b. Method and manner in which the field data are acquired, interpreted and translated into reported findings
c. Limitations of the system
d. Range of cost of the system for use in real-life monitoring

5.2 Field Evaluation

Field evaluation of the acoustic continuous monitoring system will be carried out in Building A, located in Calgary, Alberta. An area of up to 3000 m^2 in a garage floor of the building will be monitored for six months to a year by the system.

After the system is installed, wires in some tendons and/or whole tendons will be intentionally broken and various sounds generated to test the system's capabilities and limitations.

The breakage of wires or tendons reported by the monitoring system will be verified by conducting visual and/or other examinations deemed appropriate by NRC/IRC on the tendons removed from the slab.

6. Proponent Responsibilities

The proponent will carry out the following tasks at no cost to NRC/IRC, assuming all risks and liabilities for injury to their personnel and damage to their equipment and to the building:

1. Perform all field work to install the acoustic continuous monitoring system and to carry out the monitoring of an area up to 3000 m^2 in size by the system.
2. Explain the data acquisition process to, respond to questions from, and facilitate observation by NRC/IRC personnel during the field testing.
3. Submit a report to NRC/IRC that will include, for each tendon diagnosed to have sustained a breakage,

   i) time when the breakage occurred, and

ii) identification of the tendon and location of the breakage measured from a clearly established reference point.

4. Provide NRC/IRC personnel, through interviews, how the field data was interpreted and translated into the reported findings.

The proponent is not obligated to divulge any information to NRC/IRC that they consider proprietary or that has the potential to compromise their competitiveness. However, lack of certain information may limit the ability of NRC/IRC personnel to properly evaluate certain capabilities of the system. NRC/IRC will identify such instances, if any, in its report.

7. NRC/IRC Responsibilities

NRC/IRC will perform the following tasks at no cost to the proponent:

1. Identify the area of the slab to be monitored by the system.
2. Verify the findings of the monitoring system by performing visual inspection, and/or other examination as deemed appropriate by NRC/IRC, of tendons removed from the slab.
3. Provide the proponent a copy of the excerpts of the NRC/IRC report to CMHC that pertains to the evaluation of the acoustic continuous monitoring system.

8. NRC/IRC Rights

NRC/IRC has the right to disclose its evaluation of the acoustic continuous monitoring system to CMHC and to the members of the panel of consultants given in Section 9.

NRC/IRC will also have the right to publish its evaluation in scientific research journals and magazines. The acoustic continuous monitoring system will not be identified specifically but only in generic name in such publications.

9. Panel of Consultants

The following consulting engineers will be invited to provide their comments on the present NRC/IRC protocol for the evaluation of the acoustic continuous monitoring system and on the findings of the evaluation:

Mr. Norm Webster	Read Jones Christoffersen Ltd., Calgary, Alberta
Mr. David Woodall	Campbell Woodall and Associates, Calgary, Alberta
Mr. Anast Demitt	Adem Engineering, Calgary, Alberta

More members from the consultant community may be added to the panel in the future.

10. Time Schedule

The anticipated time slots during which the interviews and the field investigation will be carried out are given below:

1. Pre-field-testing interview(s)	June 8 to 15, 1995
2. Field testing	June 13 to 25, 1995
3. Post-field-testing interview(s)	September 1 to December 31, 1995

NRC/IRC will notify the proponent of more specific dates as soon as details of the field conditions are known.

Appendix II

SAMPLE PAGES FROM
THE ACOUSTIC CONTINUOUS MONITORING SYSTEM
REPORT

Note:

The following pages have been photocopied from the acoustic continuous monitoring system report after changing the name of the building to Building A.

Event Report for

Building A Parkade, Calgary, AB

from Sep/12/95 11:47:00 to Sep/28/95 12:46:07

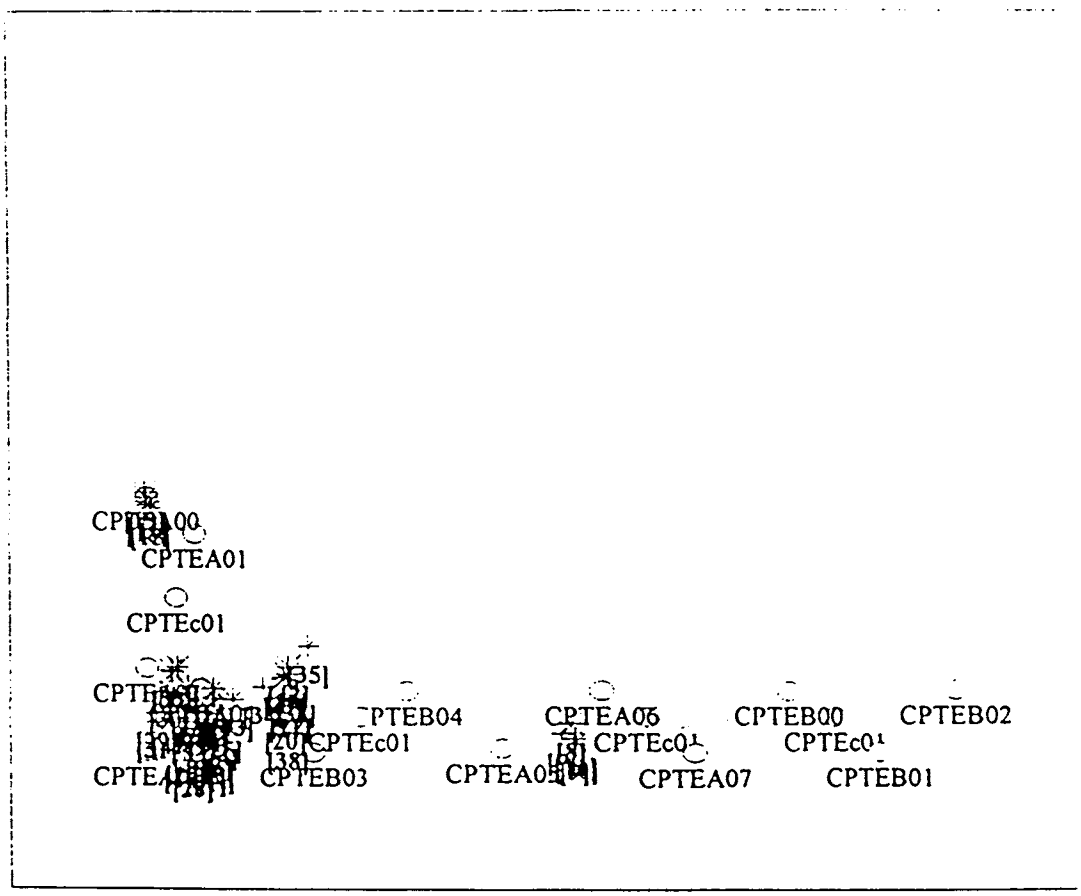
Up Time: 271.06 hours (70%)

Total Events: 66

Printing Time: Oct/07/95 16:46:22

Building A Zone 1

Oct/07/95 16:46:22



[1] Sep/12/95 11:48:58	Known Wire Cut (1.000)	(0.69, -1.01) CPTEA04
[2] Sep/12/95 12:02:11	Known Wire Cut (1.000)	(0.71, -1.55) CPTEA04
[3] Sep/12/95 12:07:35	Known Wire Cut (1.000)	(0.99, -3.15) CPTEA04
[4] Sep/12/95 12:11:01	Known Wire Cut (1.000)	(1.43, -2.54) CPTEA04
[5] Sep/12/95 12:13:49	Known Wire Cut (1.000)	(0.88, -0.62) CPTEA04
[6] Sep/12/95 12:18:10	Known Wire Cut (1.000)	(1.14, -3.21) CPTEA04
[7] Sep/12/95 14:39:12	Known Wire Cut (1.000)	(3.53, 0.92) CPTEA05
[8] Sep/12/95 14:42:10	Known Wire Cut (1.000)	(-1.87, -2.02) CPTEA06
[9] Sep/12/95 14:42:59	Known Wire Cut (1.000)	(4.31, 0.31) CPTEA05
[10] Sep/12/95 14:44:03	Known Wire Cut (1.000)	(-1.55, -3.22) CPTEA06
[11] Sep/12/95 14:49:25	Known Wire Cut (1.000)	(-1.62, -3.02) CPTEA06
[12] Sep/13/95 16:18:18	Probable Cut (0.500)	(2.51, 0.36) CPTEA03
[13] Sep/13/95 16:20:10	Probable Cut (0.500)	(-0.68, -0.75) CPTEA04
[14] Sep/13/95 16:31:51	Probable Cut (0.500)	(-0.73, -1.38) CPTEA04
[15] Sep/14/95 08:57:16	Probable Cut (0.500)	(0.27, -0.76) CPTEA00
[16] Sep/14/95 08:58:03	Probable Cut (0.500)	(0.23, -0.40) CPTEA00
[17] Sep/14/95 08:58:30	Probable Cut (0.500)	(-0.01, -0.10) CPTEA00
[18] Sep/14/95 08:59:19	Probable Cut (0.500)	(-0.01, -0.58) CPTEA00
[19] Sep/14/95 09:01:50	Probable Cut (0.500)	(-0.12, 0.23) CPTEA00
[20] Sep/15/95 09:04:04	Probable Cut (0.500)	(-1.81, 2.45) CPTEB03
[21] Sep/15/95 09:04:51	Probable Cut (0.500)	(-1.53, 3.19) CPTEB03
[22] Sep/15/95 09:06:10	Probable Cut (0.500)	(-1.37, 3.39) CPTEB03
[23] Sep/15/95 09:23:47	Probable Cut (0.500)	(-0.40, -1.51) CPTEA04
[24] Sep/15/95 09:26:46	Probable Cut (0.500)	(-0.23, -1.18) CPTEA04
[25] Sep/15/95 09:28:28	Probable Cut (0.500)	(1.26, -2.07) CPTEA04
[26] Sep/15/95 09:31:30	Probable Cut (0.500)	(0.77, 0.00) CPTEA04
[27] Sep/15/95 09:32:01	Probable Cut (0.500)	(0.42, -1.92) CPTEA04
[28] Sep/15/95 09:32:56	Probable Cut (0.500)	(2.94, -0.55) CPTEA03
[29] Sep/15/95 16:49:12	Probable Cut (0.500)	(0.58, 2.41) CPTEA03
[30] Sep/15/95 16:49:39	Probable Cut (0.500)	(-2.10, -0.17) CPTEA04
[31] Sep/15/95 16:50:50	Probable Cut (0.500)	(0.55, 1.86) CPTEA03

[32] Sep/15/95 17:03:01	Probable Cut (0.500)	(1.64, -0.25) CPTEA02
[33] Sep/15/95 17:04:56	Probable Cut (0.500)	(1.54, -0.15) CPTEA02
[34] Sep/22/95 15:30:27	Probable Cut (0.500)	(3.92, 0.09) CPTEA04
[35] Sep/22/95 16:11:04	Probable Cut (0.500)	(-0.34, 6.63) CPTEB03
[36] Sep/22/95 16:11:25	Probable Cut (0.500)	(-1.16, 4.17) CPTEB03
[37] Sep/22/95 16:16:15	Probable Cut (0.500)	(5.24, 0.73) CPTEA04
[38] Sep/22/95 16:16:50	Probable Cut (0.500)	(-1.66, 1.24) CPTEB03
[39] Sep/22/95 16:17:24	Probable Cut (0.500)	(5.44, 0.92) CPTEA04
[40] Sep/22/95 16:18:07	Probable Cut (0.500)	(5.46, 0.89) CPTEA04
[41] Sep/22/95 16:18:33	Probable Cut (0.500)	(5.20, 0.61) CPTEA04
[42] Sep/22/95 16:21:54	Probable Cut (0.500)	(5.53, 1.37) CPTEA04
[43] Sep/25/95 14:26:55	Probable Cut (0.500)	(2.00, -0.68) CPTEA04
[44] Sep/25/95 14:33:28	Probable Cut (0.500)	(4.28, -0.01) CPTEA03
[45] Sep/25/95 15:07:19	Probable Cut (0.500)	(1.99, 0.06) CPTEA02
[46] Sep/25/95 15:51:29	Probable Cut (0.500)	(2.37, -0.01) CPTEA03
[47] Sep/25/95 15:52:30	Probable Cut (0.500)	(1.61, 2.08) CPTEA03
[48] Sep/25/95 15:52:58	Probable Cut (0.500)	(2.92, 0.67) CPTEA03
[49] Sep/26/95 09:24:17	Probable Cut (0.500)	(-0.82, 0.17) CPTEA04
[50] Sep/26/95 11:53:07	Probable Cut (0.500)	(0.69, -3.55) CPTEA04
[51] Sep/26/95 11:57:34	Probable Cut (0.500)	(3.72, -0.20) CPTEA03