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Structural Monitoring of a Large Space Frame

Contrôle structural d'un treillis tridimensionnel de grande dimension

Überwachung eines grossen Raumfachwerks

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SUMMARY
The glass walls and the roofs of the recently completed New York Convention Center are supported by a large space frame. The computer-aided design was highly optimized. Retroprisms for optical surveys and a system for automated sensing of impact, wind, snow, temperature, joint movement, column tilt, and strain at important members have been installed. Software has been developed to check related data for normal structural behavior.

RESUME
Les parois de verre et les toits du Centre de conférence de New York qui vient d'être achevé reposent sur un treillis tridimensionnel de grande dimension. Conçu sur ordinateur, ce treillis a été fortement optimisé. Il comporte des prismes à vision rétrograde pour les études optiques et un système de détection automatique des chocs, du vent, de la neige, de la température, du mouvement des joints, de l'inclinaison des colonnes et des dilatations exercées sur les membres principaux. Un logiciel a été mis au point pour vérifier, à partir de cet ensemble de données, que le comportement de la structure est normal.

ZUSAMMENFASSUNG
Die Glaswände und Dächer des vor kurzem fertiggestellten New York Convention Centers werden von einem grossen Raumfachwerk getragen. Der computerunterstützte Entwurf wurde auf das Höchste optimiert. Retroprismen für optische Messungen und ein System zur automatischen Erfassung von Aufprallen, Wind, Schnee, Temperatur, Fugenbewegungen, Neigung der Pfeiler und Dehnungen der wichtigsten Komponenten wurden installiert. Speziell entwickelte Software überprüft die gemessenen Daten mit denjenigen für ein normales Verhalten der Struktur.

1. INTRODUCTION

1.1 Background

The Jacob K. Javits Convention Center in New York City, designed by I. M. Pei, was first occupied in April 1986. Distinguished by the interplay of large horizontal and vertical planes of black reflective glass, the great hall in this modern "Crystal Palace" vaults from elevation 6 to 23 m, then to 32, 41, and 56 m at the top (see Fig. 1). The space frame roof covers 53 400 m^2, and another 18 600 m^2 of vertical space frame support the glass walls.

Because the details of the space frame are unusual, and because the Center is an exhibition hall and place of public assembly, concerns have been raised for the integrity and safety of the structure. To address these concerns, extensive tests of materials, controlled inspection during erection, full-scale load tests, peer reviews, and independent computer analyses have been performed. To increase confidence in the continued satisfactory performance of the space frame, an ongoing monitoring program has been instituted.

1.2 Description of the Structure

1.2.1 General

The space frame was detailed by the firm PG Structures, subcontractor to the successful bidder for the structural steel, Karl Koch Erectors. Some 75 500 bar elements, each typically a threaded rod within a tube, are joined at about 18 000 hubs to form the space truss. The space truss is generated from square

Fig. 1. Jacob K. Javits Convention Center - East Elevation

grids of 3,05 m elements in two planes, with the nodes of the bottom surface centered under the open areas of the top surface 1,52 m above [2]. Four diagonals and four bars in plane join at each hub. The design process was computer-aided both for selection of members and for analysis of behavior under various conditions of loading.

1.2.2 Special features

The space frame has a number of special features:

-It is divided into several large regions (see Fig. 2) that are continuous in each direction over several spans of 27,43 m; the space frame, 1,52 m in depth, is supported by "diamond trusses" 3,05 m deep by 6,1 m wide at the column strips.

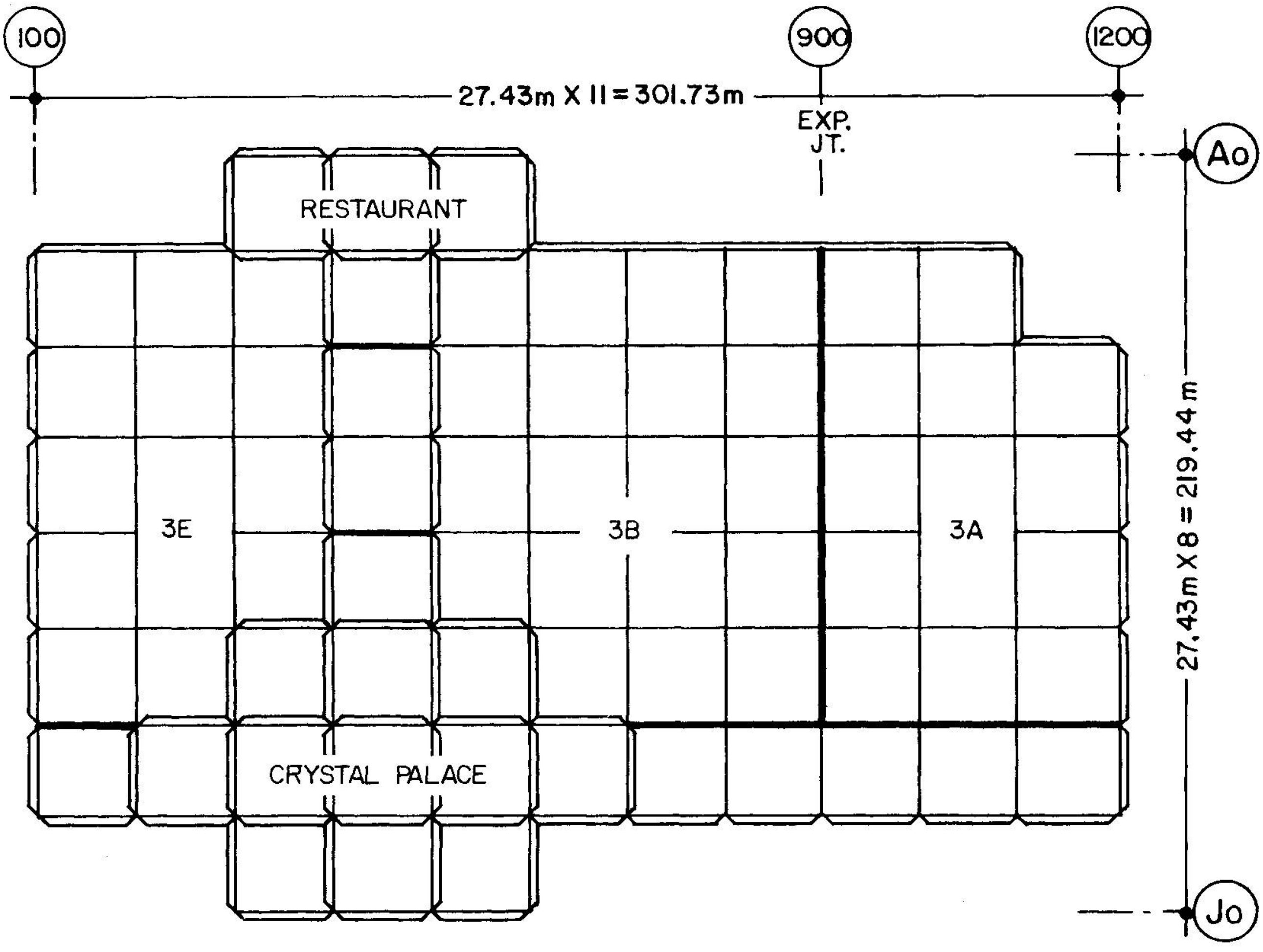

Fig. 2. Key Plan

-High-strength (900 MPa yield) quenched and tempered steels of limited ductility were used for the threaded tension rods. The rods were not upset at the ends; threads were rolled on the body which was the pitch diameter. Since the net area for tension is then less at the thread, yielding is mostly restricted to the unused thread length inside the nuts at the ends of the bars. The factor of safety is 2,0 for yield of the tension members at design load.

-Member sizes are varied so that the structure is "optimized", i.e., with the exception of the smallest, no member is 10 percent larger than it need be, for tension or compression, according to the design methods used. Some light members result, e.g. 13 mm tension rods or tubes 76 mm diameter by 3 mm wall thickness.

-The space frame is composed of separate hub, tube, and threaded-rod elements secured by nuts and washers inside the spherical hubs. Each tube is clamped between two hubs by a single tension-rod connection. In a sense, two threaded connections now depend on the integrity of one nut.

1.2.3 Redundant or alternate load paths
The part of the frame that is only 1,52 m deep is highly redundant: should any member become unavailable to carry load, the load path readily passes to neighboring members without much loss of load capacity. However, those diamond trusses that support exterior spans together with several heavy air-conditioning units, often have a single line of five bare rods, 6 to 8 cm diameter, at the bottom chord in the regions of positive moment. If one of these rods should become unavailable to carry load, only dead load plus some small live load could be carried by the frame.

1.2.4 Dimensional changes
Because regions of the space frame are as large as 137 by 110 m (see Fig. 2), sliding bearings were designed to accommodate changes in dimension due to temperature variation and live loading. Since the section used for tension members is less than half that used for compression members, the tension elements of the space frame will elongate more under load than the compression elements will shorten.

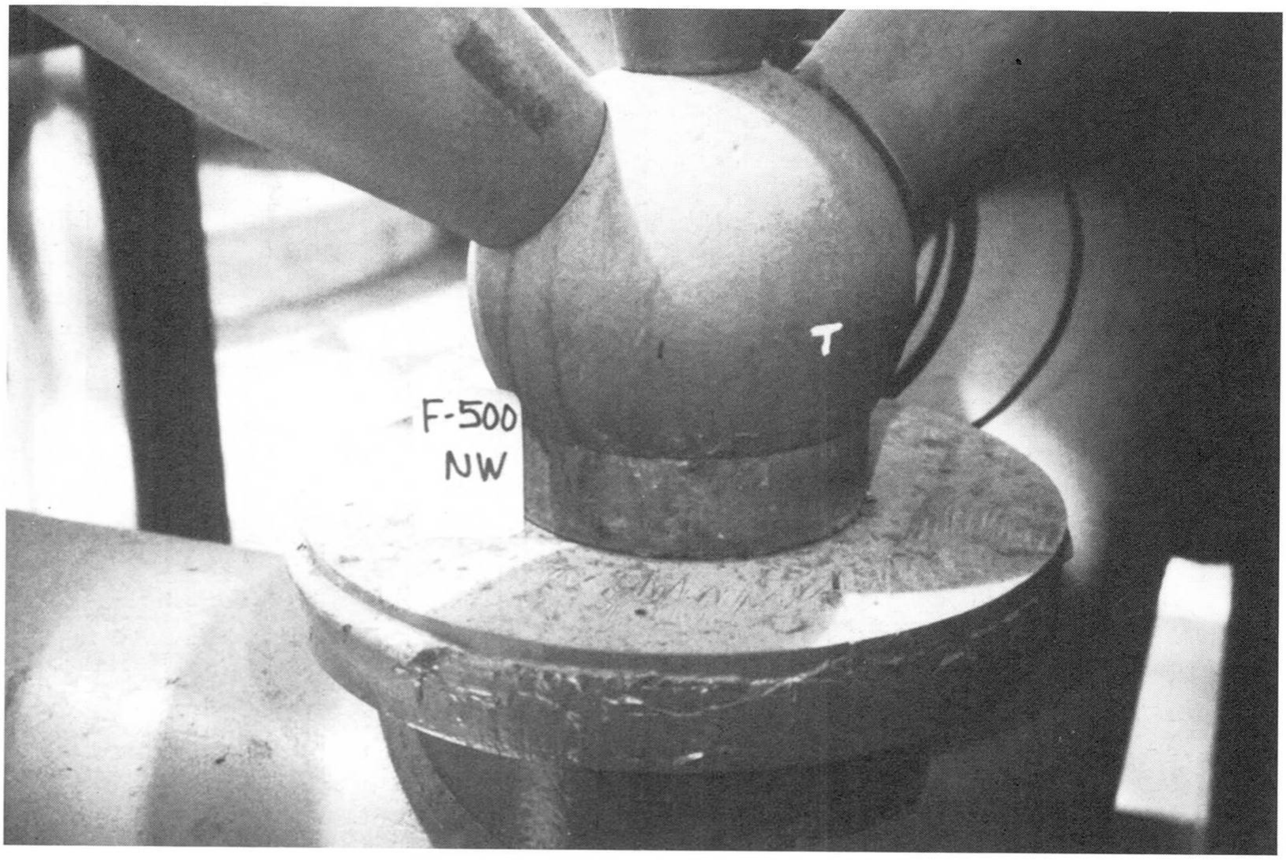

Fig. 3. One of Four Bearing Hubs at Top of "Champagne Column"

1.2.5 Columns and bearings
The horizontal portions of the space frame are supported by the diamond trusses along the column lines. Columns with four-legged towers support the trusses. Each leg terminates in a hub, which bears on the outstretched pipe frame 3 m square at the top of a column assembly (see Fig. 3). The 10 m high columns are

assembled from four pipes of 41 cm dia. filled with concrete and joined by cruciform plate weldments in the center. The shape is said to resemble a long-stemmed champagne glass (see Fig. 4). These assemblies are relatively flexible: the horizontal spring factor at the top is about 10 kN/mm. As the space frame is loaded, either by rising temperature or by gravity loads, the bearings push out from the center toward the edges of the structure. Although designed to slide, some friction occurs. If the friction is too great, loads could build up in the space frame members and in the columns beyond the loads considered in design. While bearings at corners are free to slide in all directions, others are confined to linear motion: this requires all four legs to slide in concert even though they are not rigidly connected to one another. All sliding bearings are unrestrained against uplift.

1.2.6 Rotation of the diamond trusses
Since the diamond trusses in the column strips are continuous over several spans, there will be somewhat more deflection in the exterior spans even when the roof is subjected to uniform load. The unequal deflection will produce a slight rotation of the truss. The four-point bearing at the top of the "champagne column" will then be subject to eccentric load.

Fig. 4. Interior of "Crystal Palace" (looking southwest)

1.3 Concerns

1.3.1 Fire
Fire is a serious hazard in any place of public assembly, particularly in a large exhibit hall. The Convention Center is fully equipped with sprinklers, has a full-time fire brigade on site, and stringent rules for temporary occupancy are imposed. An extensive array of smoke detectors and heat sensors

has been provided to alarm the fire department. Local heating of a high-strength tension bar, even to 400 degrees C., could seriously reduce its strength.

1.3.2 Impact
Impacts are a hazard at the Center because heavy lift equipment and large trucks are constantly used to move exhibits in and out of the show floor areas. A sudden vibration could also result from the fracture of a tension rod in the roof truss. During the recent installation of test equipment in Area 3A, it was observed that a lower chord member of a diamond truss had been struck from below and bent 4 cm out of line.

1.3.3 Concealed damage
Most of the tension rods are concealed within tubes; all connections are typically concealed inside hubs. A flaw in a cast steel hub or in a threaded rod, a missing nut, or ongoing corrosion cannot be directly or conveniently detected.

1.3.4 Design error
Many of the design details, particularly at bearings and other moving joints, but also at other connections, are unprecedented. Experience leads one to expect that some will not behave as intended.

1.3.5 Falling objects
The structure is relatively large, and is in the flight path of two major airports and a nearby heliport. Risk analysis shows that the annual probability of occurrence of an aircraft's hitting the roof is about 1:1 000 000.

1.4 Monitoring Program

To allay concern for "damaged members" -- whether flawed when built into the structure, suffered while in service, or resulting from malfunction of design details [1] -- the State of New York proposed an extensive plan for formal inspections twice a year, once in the winter and again in the summer. Special inspections would be made when an unusual load was encountered. The plan also includes continuous automated sensing by some 150 transducers to characterize the behavior of the space truss under thermal, wind, snow, or impact load.

2. MONITORING BY PERIODIC AND SPECIAL INSPECTIONS

2.1 Exterior Low Roof Deflections

To obtain the response of the space frame to thermal or snow load, and any time-dependent behavior, the deflected shape of the roof will be measured by optical survey. In order to conduct the survey when the exhibit space is occupied, 99 precast concrete monuments 58 x 58 x 14 cm with bronze tablets were set on the roof deck in place of the insulation and ballast layer of the inverted roofing system. Each slab is cemented to a spare piece of EDPM rubber laid on the roofing membrane. Since the slab weighs 100 kg, and the coefficients of friction are about 0.8, the locations can be expected to be reasonably permanent, and will improve the accuracy of benchmark leveling runs. About 350 additional elevations will be taken from points located on concrete slabs that support HVAC units.

2.2 Interior High Roof Drift and Deflection

To obtain both drift and vertical deflections in the glazed high roof areas of the Crystal Palace, Galleria, and Restaurant, 45 pentaprism targets have been situated in the space frame. These retro-prisms allow distance measurements to be made by EDM with about 3 mm accuracy over the typical distance of 50 m or so. A Topcon Geodetic Total Station GTS-3B tacheometer is used to obtain distances to the nearest 2 mm and angles to 1 second of arc. Horizontal control is referenced to 19 survey markers embedded in the floor of the three areas.

2.3 Bearing Movements

Periodic monitoring of bearing-hub movements on the chromed plates atop the "champagne columns" will be facilitated by scratch gages fabricated from stainless spring steel with a hardened stylus at the end to provide a trace on a soft brass tablet, 8 x 8 cm. An approximate record of movement since April 1986 has been provided by means of a coat of paint inadvertently applied over the chromed surface of the bearing plates and by observation of the disruption of recent dust layers.

3. MONITORING WITH AUTOMATED SENSING

3.1 General Description

The system includes some 150 transducers to measure both environmental loadings -- due to snow, wind, solar radiation, and temperature -- and building response to these loads, including strains in roof structural members, lateral building movements, and impacts to the structure, should they occur. Electrical power for excitation, signal conditioning, and analog/digital conversion is provided no more than 20 m distant from each transducer by a distributed system of special data loggers. These are wired in turn to the host computer, nearly a kilometer away from the furthest transducer. The host may be accessed remotely by telephone modem.

3.2 Trial Subsystem

3.2.1 Purpose

The trial subsystem was installed to select sensors and mounting hardware and to provide a real base for the development of data acquisition software. Twenty-seven different sensors were installed in and on the roof structure. Three more were placed in the monitoring office for direct observation and periodic calibrations. Some 2 000 m of cable and three data acquisition units were installed.

3.2.2 Initial studies

-Electrical noise (EMI) from operating HVAC units, lighting, or hand-held radios can interfere with analog signals in transducer leads. Cables with braided shield and with less expensive foil shield were tested at the Convention Center with full-bridge strain gaging and found reasonably noise free.

-Vibrational characteristics of the structure were studied using both accelerometers and velocity transducers. Accelerometer outputs were amplified by a charge amplifier and fed into a Wavetek spectrum analyzer. Natural frequencies of the space truss were about 2.5 Hz; of the individual bar elements, about 29.5

Hz at dead load. The influence of HVAC operation or wind gusts on background vibrations was also recorded.

-Impacts were simulated by dropping a 10 kg steel weight through 0,6 m on bottom chord members of diamond trusses. Impacts were well transmitted about 50 m through the space frame; the log-log plots of distance vs. the unfiltered Power Spectral Density response of the vibration sensors were reasonably linear.

-At first, sensors were placed on bare rod bottom chords of the diamond trusses since these members are the most exposed to impact. It was found that the signal was attenuated if the vibration had to travel past a column and then turn a right angle to arrive at the sensor. Also, even small impacts to the instrumented member caused the sensor to go off scale. Better results were obtained when the sensor was placed on the upper roof structure, just below the roof deck (Elevation 23).

-Since about 25 vibration pick-ups are needed to monitor the space frame that supports the low roof, it is impractical to record and analyze all of the spectral data that could be collected. Instead, a peak-read circuit was developed to monitor each vibration sensor. This circuit is reset after each reading, i.e. once per second.

-The vibration studies were made with a small impact rather than a damaging one, thus it is difficult to set appropriate alarm levels initially. Instead, "soft" alarm thresholds, set low in the beginning, will be raised as experience dictates.

3.3 Measurements and Sensors

3.3.1 Strains in diamond trusses

The bare tension rods, compression chords, and a diagonal compression strut were instrumented as full-bridge load cells using bonded strain gages. These gages are used to indicate live load stress in important structural members. The system determines whether this stress is within allowable limits, and whether it is consistent with the measured loading on the roof. It also determines whether dead load stresses have been released (e.g. fracture of a tension rod in the bottom chord of a diamond truss). Micro-Measurements Series EA strain gages, bonded with AE-10 epoxy, were used for good long-term performance characteristics. Another epoxy adhesive, EPY150 by BLH, was also used. Two tee element gages were used for full-bridge configuration on axially loaded members.

3.3.2 Snow load on roof deck

Strain gages installed on the roof deck and its supports are intended to measure the direct vertical loading (snow load) on the roof. To avoid the problem of arching over a sensor plate, the bending in a top chord that directly supports the roof deck is gaged. HITEC Model HBW-35-125-06-10GP weldable gages in a full-bridge configuration were used for convenience and reliability. Simple load tests were used to calibrate the system.

3.3.3 Temperature

Platinum resistance temperature devices (RTD), Type 100W30 by Omega, were used rather than thermocouples, because RTD's are more compatible with the data loggers used. Temperature is monitored in various locations, including the data logger cabinets, to pick up any significant gradients.

3.3.4 Building side-sway

The roof structure of the building is expected to move laterally in response to wind pressure and temperature fluctuation. Relative building side-sway is measured at expansion joints with Model LRT 150-B linear potentiometers by Waters. The maximum stroke is 150 mm; the maximum positional error is 0,15 mm.

3.3.5 Wind speed and direction
Wind speed and direction are monitored by J-TEC Model VA320 ultrasonic vortex anemometers and wind vanes at the top of 10 m towers located on both the north and south roofs.

3.3.6 Solar radiation
Movements can also be caused by solar radiation that induces temperature changes in the roof deck and curtain walls, which may not be properly measured by the RTD's. Therefore, Hollis MR-5 silicon-cell pyranometers are installed near the anemometer towers to measure total sun and sky radiation.

3.3.7 Bearing movements
Sliding structural bearings located at the column tops should be able to move horizontally to assure that roof structural components are being loaded as the designers intended. Bearing movements are monitored with linear potentiometers to determine whether these movements are actually occurring.

3.3.8 Inclinometers
To resolve lateral movements of the column capital of less than 0,025 mm, tiltmeters that have an accuracy of about 8 arc seconds are installed at 12 columns where bearings seem to be locked. Model QA-1400 servo-accelerometers by Sundstrand are accurate to about 4 arc seconds.

3.3.9 Pressure transducers
The barometric differential on the roof deck is a small but significant part of live load. Setra Model 261-1 pressure sensors range from -0,3 to +0,3 kPa.

3.3.10 Vibration transducers
Impact to important structural members is sensed by Geo Space Model HS-1 vertical velocity transducers. Frequency response is from 4.5 to 200 Hz.

3.3.11 Sensor locations
The deployment of the various sensors is:

Device	3A	3B	3E	High Bay Areas	Total
Strain gaged bare rods	17	15	11	5	48
Strain gaged roof deck	2	3	2	1	8
Strain gaged tubes	3	0	0	0	3
Temperature sensors (RTD's)	7	9	8	7	31
Exp. joint movement (potentiometers)	2	7	5	4	18
Tiltmeters (inclinometers)	4	4	4	0	12
Vibration sensors (velocity type)	7	11	7	4	29
Wind stations (3 sensors ea.)	3	0	3	0	6
Bearing movement potentiometers	2	2	2	0	6
Air pressure transducers	1	1	1	0	3
Power supply voltage	2	2	2	0	6
Totals	50	54	45	21	170

3.4 Data Acquisition System (DAS)

3.4.1 Data Logger: Isolated Measurement Pods (IMP's)
-Data loggers monitor the DC voltage outputs from each sensor. Because of the size of the Center, a distributed system was needed in which data loggers located near the sensors transmit digital signals to a host computer. The Isolated Measurement Pod (IMP), Model 35951B, by the Solartron Divison of Schlumberger is designed to provide both excitation voltage and bridge termination for 10-channels of strain gage signals.

-A 20-channel voltage IMP, Model 35951C, is used where the pulsed 2 VDC supply to strain gages does not provide suitable excitation.
-The IMP's convert the analog voltage signals produced by the sensors to digital signals, which are transmitted over a pair of wires to the computer.
-This is a serial system in which a single pair goes from the computer to the first IMP, from there to the second IMP, and so on. Having only a single line has the disadvantage that should that line be cut, all data from instruments located beyond the cut are temporarily lost. However, the location of the break is easily determined and can be readily repaired provided an exhibition is not in progress.
-Up to 30 IMP's are possible in one net; the system at the Center has 18. All IMP's are scanned once per second, for this system an effective scan rate of some 170 channels per second.

3.4.2 Power supplies
The IMP's are powered from the host location on a protected uninterruptable circuit. Each transducer in turn is powered on an isolated circuit to assure that a short in one line does not have an effect on other lines powered from the same supply. A partial solution is to use only strain gage IMP's, but external +/- 15 VDC supplies are provided for the vibration sensor circuits and other devices.

3.4.3 Network wiring
The communications net supplies DC power to the IMP's and transmits signals both outbound from the host and inbound from the IMP's. Data are transmitted at 163 kilobaud superimposed on the DC power. Each incoming zero bit is divided into four parts: a positive pulse, a negative pulse, and two settling periods. The outgoing zero-bit signals are the reverse: two waits, a positive pulse, and a negative pulse. This accomplishes two purposes: it prevents saturation of the IMP I/O transformers, and it distinguishes between incoming and outgoing data. It does impose fairly high frequency requirements on the transmission line. Current specifications from Solartron for network cable are:

Characteristic impedance	100 ohms +/- 25 ohms
Attenuation at 160 KHz	less than 15 dB/km
Mutual Capacitance	50 pf/m (typ.); 60 pf/m (max.)
Velocity of Propagation	66 percent (typ.)

Alpha No. 9820 is a shielded 2-conductor #16 AWG cable that is said to meet this specification. Attempts to operate the system using other cable that was not impedance matched were unsuccessful.

3.4.4 Host computer
The host computer is a Compaq 386 (IBM-PC AT-compatible) with 1.2 megabyte floppy-disk drive, 130 megabyte hard-disk drive, 1 megabyte of expanded memory (RAM), 80287-8 math co-processor chip, Quadram high resolution monitor and controller card, and an Epson F286 dot-matrix printer.

3.4.5 Software: RTM 3500
The host computer monitors, stores, and prints displays of data collected on the IMP network, using a software package called Real Time Multi-tasking RTM-3500 by Micro Specialty Systems (MSS), Northampton, Pennsylvania to interface with the Schlumberger IMP system. Part of the output format is a spread-sheet that displays the incoming voltage data converted to engineering units on multiple screens. Formulas can be inserted in the spreadsheet to perform conversions and some statistical measures. These can then be used to trigger several types of alarms such as deviation, rate, or limit set-points. The software package is very comprehensive and has proven adaptable to our needs.

3.4.6 Storage of data
An archival data storage rate of once per hour is planned. This will create monthly files of about one megabyte. Data will be stored more frequently if alarm conditions occur. For rapidly changing readings such as vibration or wind, only maximum values will be saved.

3.5 Reports

3.5.1 Software: Shell program
We are currently developing a "shell" or "application" program in Basic [3] that uses the RTM-3500 program in background to gather data, set initial alarms, and save data on disk. The shell program will make data comparisons in real time, allow displays of specific data in graphic and tabular formats, and diagnose alarm conditions for the operator. The program will also analyze historical data (stored on disk) and make possible a variety of presentations, including the automatic generation of monthly reports. As we become more familiar with the data and the relations among the observed behaviors at related sensors, we intend to implement computer programs to interpret the data and produce simplified reports.

3.5.2 Daily
All the reports will be available continuously on the monitors in the Convention Center Control Room and at the engineer's office by modem, including diagnostic reports.

3.5.3 Monthly
Printed monthly reports will summarize the conditions imposed on the space structure and highlight any unusual events.

3.5.4 Emergency
It is expected that, at first, most alarm conditions will be false. Emergency response plans are being formulated.

4. CONCLUDING REMARKS

4.1 Findings to date

4.1.1 Optical Surveys
An optical survey conducted on January 27, 1987, with about 480 Pa snow on the roof found deflections of 3 to 20 mm, less than half that expected,

4.1.2 Damaged Members
The damaged member observed in the lower chord of the diamond truss on Column Line 10 was reportedly damaged by the contractor installing the moveable partition on Line 9 during March 1986. It is remarkable that this damage, although clearly visible from the floor, had not been repeatedly noticed. It is our opinion that the impact which caused the damage would result in an alarm condition on the automated monitoring system. It is fortunate that the damage was located near a point of contraflexure where loss of capacity does not endanger the space frame seriously.

4.1.3 Bearing Movements
Automated monitoring of the bearings has shown less than predicted movements and a tendency to move in jumps. To obtain forces under conditions of no movement, our computer model was modified to lock the bearings instead of using zero

friction as in design. Only one member was overstressed for 10 degrees C. change. This run also provided the effect of temperature changes on roof deck elevations.

4.1.4 Other data collected

-The complete installation was completed in July 1987. Strain, temperature, expansion joint movement, bearing movement, wind and solar radiation data were collected for March 1987 during a trial of the subsystem.

-No snow fell on the roof during March and there are no load related strain gage readings. Useful information was gathered, however, which indicates gage drift and response to other environmental loadings such as wind, temperature, and HVAC system pressure. Drift of gage sensors, at least during the first months of operation, was very low, not more than a few microstrain over the period.

-Temperature changes of 10 degrees C. induce movements at the expansion joints of roughly 10 mm. This amount of movement is about that expected.

-The absolute movement is not vital unless it exceeds the gap provided. So far there is no tendency evident for movement in one direction more than the other, which might indicate ratcheting or walking off supports.

-Total movement of the bearing at Column Go, 1200 was about 1.5 mm which occurred in two jumps. For 6 degrees C., a north-south movement of at least 4 mm was expected.

-An inclinometer with a resolution of less than 10 arc seconds was installed at Column Go, 1200. After transforming the rotation to horizontal movement of the column capital, the response was found to be linear vs. temperature but with considerable noise, which is characteristic of accelerometers used as inclinometers.

-Other data collected provided no anomalies.

5. FURTHER DEVELOPMENT

5.1 Expert System

Logical comparisons of values obtained from sensors that should respond to the same loading will form the basis of an "expert system". As experience develops the patterns of normal behavior for the space frame, we expect to write adaptive software that can reach decisions for alarming at several levels of significance. If non-linear behavior can be resolved, it may be possible to develop the software to include some level of artificial intelligence to assess damage. For the near term, it appears unlikely that the space frame will receive loadings sufficient to provide the "shake-down" conditioning needed for predictable response.

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