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SENSORS AND MEASUREMENT TECHNIQUES FOR ASSESSING STRUCTURAL PERFORMANCE

Edited by:
Richard D. Marshall

PROCEEDINGS OF AN INTERNATIONAL WORKSHOP

U.S. DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
National Engineering Laboratory
Center for Building Technology
Gaithersburg, MD 20899

Sponsored by:
National Institute of Standards and Technology
National Science Foundation

Co-Sponsored by:
Panel on Wind and Seismic Effects, UJNR
ASCE Performance of Structures Research Council

Held at the National Institute of Standards and Technology
Gaithersburg, Maryland
September 8 - 9, 1988

U.S. DEPARTMENT OF COMMERCE
Robert A. Mosbacher, Secretary
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ABSTRACT

This report identifies research and development efforts needed to advance the state-of-the-art in instrumentation and measurement techniques for assessing structural performance. Four topic areas consisting of 1) seismic effects, 2) wind effects, 3) effects due to occupancy, traffic, snow and other loads, and 4) sensor technology were addressed by respective task groups during a two-day meeting of international experts. The forty-eight specific recommendations presented in the report are intended to serve as a research agenda for use by universities, research establishments and funding agencies.

Keywords: bridges; buildings; instrumentation; loads; research; sensors; structural engineering; structural response.

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PROCEEDINGS

INTERNATIONAL WORKSHOP

ON

SENSORS AND MEASUREMENT TECHNIQUES

FOR ASSESSING STRUCTURAL PERFORMANCE

INTRODUCTION

A two-day meeting of international experts was convened at the National Institute of Standards and Technology to review the state-of-the-art in structural response measurements, related sensors and measurement techniques. Workshop participants included representatives of the private sector, universities, instrument manufacturers and government agencies. Based on the needs identified in the course of the task group deliberations, a research agenda consisting of forty-eight specific recommendations was prepared for the use of research establishments and funding agencies.

BACKGROUND

To better understand structural behavior and to validate models of structural loading and response, there is a continuing need for reliable field measurements. Field measurements, particularly those obtained over extended time periods, also provide important information on which to base assessments of the condition and performance of engineered structures. Because such measurements require almost constant monitoring and frequent equipment servicing and calibration, they tend to be costly. In some cases field studies have produced test data of questionable accuracy, thus complicating and confusing the process of model validation. In other cases the malfunctioning of monitoring equipment has resulted in the loss of valuable data associated with rare events such as strong ground motions or extreme winds.

New materials and improved technology are having a dramatic impact on the reliability and versatility of measurement devices. Instrumentation systems incorporating self-diagnostics and "smart" sensors are making possible more reliable and more efficient field measurements. Low cost and reliable microprocessors, combined with non-volatile memory systems, are making it possible to collect, process and store data in either continuous or intermittent modes for periods of several years.

This background provided the motivation for organizing a workshop at which international experts could exchange ideas and research findings, discuss needed research efforts, and formulate a research agenda for use by laboratories and funding agencies. The workshop was jointly sponsored by the National Institute of Standards and Technology (NIST) and the National Science Foundation (NSF). Cosponsors were the Panel on Wind and Seismic Effects (U.S.-Japan Cooperative Program in Natural Resources) and the Performance of Structures Research Council (American Society of Civil Engineers).

TECHNICAL PROGRAM

The technical program consisted of a plenary session followed by four concurrent task group working sessions. Theme lectures were presented in the plenary session and these lectures established the charge to each of the four task groups for the remainder of the workshop. The theme lectures addressed the following topics:

SEISMIC EFFECTS
WIND EFFECTS
EFFECTS DUE TO OCCUPANCY, TRAFFIC, SNOW & OTHER LOADS
SENSOR TECHNOLOGY

The major issues addressed by the task groups and their recommendations for a research agenda were presented at the closing session of the workshop. Each specific recommendation was accompanied by a statement of the problem or need and the general approach to be taken.

SEISMIC SENSORS AND MEASUREMENT TECHNIQUES FOR ASSESSING STRUCTURAL PERFORMANCE

Ahmed M. Abdel-Ghaffar* and Sami F. Masri*

ABSTRACT

Guidelines for the strong-motion instrumentation of civil engineering structures are presented. Instrumentation objectives and criteria for selecting structures for strong-motion instrumentation are introduced. Importance of recording various quantities of motion, the three-dimensionality of the structure, the soil-structure interaction, the temporal and spatial variation of input-ground motions are emphasized. Finally, the role of system identification techniques in the interpretation of the recorded structural response and accordingly in improving the state of knowledge of structural behavior during strong earthquakes is discussed.

INTRODUCTION

Increased demands on structural performance, improved mathematical models and the tools to verify these models often require the design effort to be supplemented with a comprehensive instrumentation program. Also, regulations often require the measurement, collection and analysis of data to evaluate system or structural performance under different loading conditions.

It is extremely important to have "complete" instrumented civil engineering structures to indicate the nature of the response to strong earthquakes. The term "complete" instrumented structure means instrumentation that is capable of providing a completely adequate definition of input ground motion as well as structural response. The input motion can be measured by strong-motion accelerographs, often mounted in buildings, on dam abutments, bridge superstructures and foundations or at an appropriate site in the immediate vicinity of the structure that is not obviously influenced in a major way by local geologic structural features, as indicated by Bolt and Hudson (1975). The instruments to measure structural response can usually be mounted at different locations (at least two) on the structure, avoiding special superstructures which may introduce localized dynamic behavior.

The data recovered from instrumented structures subjected to earthquakes can be valuable in improving the state of knowledge of structural behavior, engineering

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design and construction practice. Furthermore, the acquisition of such data is essential to evaluate the potential earthquake hazard of existing similar structures and also to evaluate the safety of particular structures after strong earthquake-induced ground shaking has occurred.

Strong motion sensors and records are valuable tools for researchers, practicing engineers as well as for public safety. For example, ground motion or free-field records can provide vital information for: (i) interpreting earthquake damage, (ii) determining earthquake mechanisms or fault-source parameters, and (iii) determining the influence of local site conditions on earthquake ground motion.

Furthermore, structural response data recovered from sensors can provide vital information for: (i) evaluation of the effect of structural and nonstructural elements on the response, (ii) investigation of soil-structure interaction, and (iii) development of mathematical models. Such strong motion data can be used only if sensors are deployed and records are collected, processed and disseminated.

STRONG-MOTION RECORDS

Earthquake strong ground motion is vibratory ground shaking that can cause damage to man-made structures and is recorded near the location where an earthquake has occurred. The actual level of ground motions above which motions are "strong" is not well defined. Typically, ground motions with a peak acceleration greater than 0.05 g are of interest to earthquake engineers, and those greater than 0.2 g are currently considered potentially damaging.

A strong-motion record is defined as the record of ground or structural motion caused by relatively large earthquakes (usually magnitude $M_L \geq 3.5$). This strong motion, recorded as a function of time, may be recorded as:

1. A light trace on a film, or
2. A line on a strip of paper, or
3. An analog or digital signal on magnetic tape.

This motion is recorded as an electrically or mechanically generated signal which is proportional to the instrument-base-motion within some acceptable error.

Generally, strong-motion records are recorded on accelerographs which can be analog or digital. In the analog instrument they are recorded on light-sensitive film or paper, or on magnetic tape, and in the digital instrument they are recorded in digital form on magnetic tape. Both instrument types are powered by batteries, are triggered into operation by the strong motion itself (commonly 0.01 g in the vertical direction in the U.S.) and are available either as self-contained triaxial instruments or remote-accelerometer control-recording instruments. In the self-contained variety, all major components (accelerometers, recorder, and trigger) are housed in one container, whereas in the remote-recording type (the type recommended for installation on dams, bridges, and large civil structures), these elements can be physically separated but are interconnected by low-voltage data cable.

INSTRUMENTATION OBJECTIVES AND LOCATIONS

In general, all structural strong-motion instrumentation programs should have the same purpose: to obtain data that will improve the state of knowledge of structural behavior during strong earthquakes. The amount of strong-motion instrumentation that should be installed on a structure is dependent, of course, on the intended use of the data. From the earthquake engineering and structural dynamics point of view, the proper location of permanent instrumentation to record strong ground motion on and in the immediate vicinity of structures is an important question. Proper placement will yield information about the response of the structure, the nature of different modes of vibration and the coupling of these modes. Information indicating the effects of soil-structure interaction and, possibly, the damping of the structure as well as the phase differences in the motions of the horizontally extended foundations may also be obtained. The following are general suggestions for the selection of appropriate locations of the instrumentation; it should be noted that these suggestions assume an ideal set of circumstances and, thus, do not consider any economic limitations.

1. Three-Dimensionality of Structural Response: For example a set of three orthogonal instruments should be located on any given cross section of the structure between the top-or mid-point (point of symmetry) and the point of support or abutment. All of the instruments should be situated so as to record vertical motions, horizontal motions in the longitudinal direction of the structure, and horizontal motions perpendicular to the structure. These records would help to identify the different modes of vibration. Another set should be located on the top or mid-point section to record, exclusively, symmetric vibrational modes. A third set should be situated on another location of the structure to obtain a better spatial configuration of the modes of vibration. If the structure has several members, such as towers and cables in the case of a cable-supported bridge, additional sets of instruments should be located in positions similar to the above-mentioned locations in order to get a clear picture of the global structural response.

   Figure 1 shows an example of a well-instrumented earth dam in a highly active seismic zone, namely the Long Valley earth dam in the Mammoth Lake area of Northern California (Abdel-Ghaffar, 1986). The spread of sensors on the crest and downstream face of the dam is an excellent configuration to capture the 3-D mode shapes of the dam vibration. Figure 2 shows a comprehensive scheme for a modern cable-supported (stayed) bridge. Again, the sensors are well spread and located in different positions to provide adequate information on the complex three-dimensional response of the structure.

2. Spatial and Temporal Variation of Ground Motion Inputs: Two additional sets of instruments should be used, one located at each intermediate foundation (such as piers in the case of a bridge structure, Figure 2) in order to correlate the ground motions at the two sites and to evaluate any phase differences. These placements are particularly important in bridges having very long spans, such as cable-supported bridges. Finally, three-dimensional instruments should be located, also, at each of the end supports or abutments. From these locations information may be obtained to evaluate the effect of the differential motion of the supports on the movements and interaction of spans (in the case of bridges), and thus on the structural response.

3. Soil-Structure Interaction: To study the soil-structure interaction, at least one set of instruments should be located on each of the banks, or the site surrounding the foundation, in line with the piers of the bridge, for example, and below each end of the bridge deck.

4. Finally, free-field ground motions should be obtained by at least a set of instruments to be located in the near vicinity of the structure (see Figures 1 and 2).

As a final note on the instrumentation objectives, it is worth emphasizing that most structural strong-motion instrumentation programs are anticipated to have one of the following primary goals: The acquisition of data to improve engineering design and construction practice; the acquisition of data to evaluate the potential earthquake hazard of existing similar structures; or the acquisition of data to evaluate the safety of particular structures after strong earthquake-induced ground shaking has occurred. Structures instrumented under programs having safety evaluation as their primary goal generally require substantially less instrumentation than those instrumented under programs having one of the other two above-mentioned goals. Ideally, a strong-motion instrumentation scheme should be designed to incorporate the following structural objectives:

1. Force-Level Determination: Such instruments should provide data that can be used to calculate maximum internal stresses and strains at any desired location and to study or predict possible failure modes.

2. Mathematical Model Identification: The instruments should be designed in accordance with the identification or verification of a mathematical model of the structure and should provide data that can be used to evaluate the assumptions made in the formulation of any mathematical model used in the design and/or analysis stage. This allows for the possibility of improving state-of-the-art techniques for modeling structural behavior during earthquake excitation. In addition, mathematical models formulated through the analysis of strong-motion records can be used to study possible failure modes as well as to predict significant structural distortions of similar structures during future earthquakes.

3. Mathematical Model Verification: The verification of a mathematical model is normally of greater interest than the determination of force

levels for a particular structure during a particular earthquake, primarily because the results of a mathematical model study may have wider application.

The area of mathematical model identification or verification under strong ground shaking that may induce nonlinear behavior of the structure requires special attention to sensors and measurement techniques if accurate results are needed. Among the considerations that influence the choice of instrumentation systems for the class of problems under consideration are:

1. The type of direct measurements to be recorded. Due to nonlinear effects, acceleration measurements may not be sufficient by themselves to yield accurate measurements of structural displacements and deformations.

2. The number of sensors to be used within a distributed structure. The order of high-fidelity mathematical models is heavily influenced by the total number of available measurement channels. In situations involving nonparametric mathematical models (which are quite useful for nonlinear systems) the order of the identified model (i.e., degrees of freedom) is equal to the total number of sensors recorded simultaneously.

3. The location of the sensors within the structure is an important factor that can have a significant influence on the quality of the identification results. The optimum location(s) of the instrumentation is determined on the basis of the expected deformation patterns of interest and on the types of instruments being used.

4. Synchronization of multi-channel recording systems is essential if accurate mathematical models are needed. This is also crucial if wave propagation effects are to be accurately measured in distributed structures.

RECOMMENDED INSTRUMENTATION SCHEMES

The factors that should be considered in the design of instrumentation schemes are:

1. The objective of the instrumentation program which should yield satisfactory data
2. The expected behavior of the structure, including potential failure mechanisms
3. The quantities of motion that are to be measured
4. The (reduced) mathematical model that is to be developed to represent the dominant structural behavior.

The selection of the type and locations of a strong-motion instrumentation scheme for seismic monitoring of civil engineering structures is based upon several factors as follows:

1. The type of information which the instrumentation is intended to yield,
2. The expected structural performance, and
3. The response quantities that are to be recorded.

In general, absolute accelerations are, so far, the most convenient and desirable quantities of structural or ground motion to record. Although in recent years the need for strain-displacement as well as rotational-motion measurements is on the increase, there is not yet an available comprehensive set of records.

A. Input Ground Motion

The free-field sensors should be situated to obtain records of ground motion that are not influenced by (i.e., do not include) structural response. Because of the intended use of free-field recordings, it is important that such instrumentation be installed near the structure on similar foundation or soil conditions, but that it not be located immediately adjacent to the structure. The criterion utilized for buildings in California, which specifies that sites intended to be free-field should be at a distance from the instrumented structure equal to one and one-half times the estimated wavelength of a shear wave (at the surface) having a period equal to the fundamental period of the instrumented structure, should apply to general civil engineering structures. The free-field instrumentation should provide important information on the direction of seismic-wave form arrivals, on wave phase lags, and on the overall three-dimensional response of the ground surface in the vicinity of the structure.

B. Soil-Structure Interaction

Ground-level instrumentation should be installed to provide information on the extent to which soil-structure interaction has occurred at the site; that is, the extent to which the structure mass and stiffness have influenced the motion recorded at the base of the structure support(s). Even in cases where foundation conditions suggest that it is highly unlikely that soil-structure interaction might occur, at least one free-field site should be instrumented in order to validate such an assumption.

The amount of instrumentation to be installed at the base of each support where soil-structure interaction is expected is dependent on the expected mode of soil-structure interaction. Normally, soil-structure interaction can be expected to occur in the form of horizontal translations or rotations about a horizontal axis. In those instances where horizontal translations of the structure support base are expected, one accelerometer is required for each principal direction of interest (normally the longitudinal and/or transverse directions). In those instances where rotations about a horizontal axis are expected, either a rotation sensing accelerometer or a pair of vertical accelerometers is required for each principal direction of interest.

C. Spatial Variation of Input Ground Motion

The following three basic ground motion conditions are expected to exist at the site: (1) the ground motion is expected to be identical (or nearly so) beneath each support; (2) the ground motion is not expected to be identical beneath each support even though the foundation materials are considered to be rigid relative to the structure; and (3) the ground motion is not expected to be identical to the support motion because the foundation material is not rigid relative to the structure.

Condition (1) exists if the entire structure is situated on firm, relatively homogeneous foundation material and if the structural horizontal length (or length of spans of interest in the case of bridges) is less than a critical distance, Lc_r, (Rojahn and Raggett, 1981) given by:

$$L_{cr}(n) = T_n * c * 6^o/360^o$$

where

$L_{cr}(n)$ = recommended maximum spacing between instruments located at the base of structural supports for each dominant mode of response, n,

T_n = natural period of dominant mode of response, n, and

c = apparent or actual horizontal propagation velocity of the dominant seismic-wave forms (c = 3,000 m/s for S-body waves, normally the dominant wave forms at locations close to the source region of shallow earthquakes; c= 2,700 m/s (approximately) for surface waves which may be dominant at larger distances).

The critical distance is primarily dependent on the following two factors: (1) apparent or actual horizontal propagation velocity of the ground motion; and (2) the fundamental or lowest natural frequencies of the structure (or span of interest in case of bridges). These factors provide estimates of the maximum phase lag that can be expected to occur between acceleration histories recorded at various points on the structure. Such phase lags are considered to be significant in force determination and mathematical modelling studies if they exceed 6^o (Rojahn and Raggett, 1981) which would result in wave amplitude errors as large at 10 percent at any time.

In the case when the foundation material is firm or the foundation conditions vary significantly from one end of the structure to the other, but the horizontal dimension of the structure is longer than L_{cr} for one or more dominant modes of response, condition (2) is considered to exist. In this case, instrumentation should be installed at the base of two or more structure supports (in case of a discretely supported structure) or of two or more locations on the foundation of continuously supported structures (such as dams). The number and arrangement of sensors to be installed at each support base to be instrumented is dependent on the direction(s) of the expected dominant mode(s) of response. In those instances where condition (3) is expected to exist, that is, in those instances where the foundation material is flexible (relative to the structure), instrumentation should be installed at the base of each support at which that condition exists and at the base of one or more additional supports, depending on L_{cr} for dominant modes of response and the length of structure (or span of interest).

Figures 3 and 4 illustrate the basic elements affecting the design of strong motion instrumentation as well as the response quantities to be measured for long-span structures. These basic elements are also applicable for any major civil engineering structure.

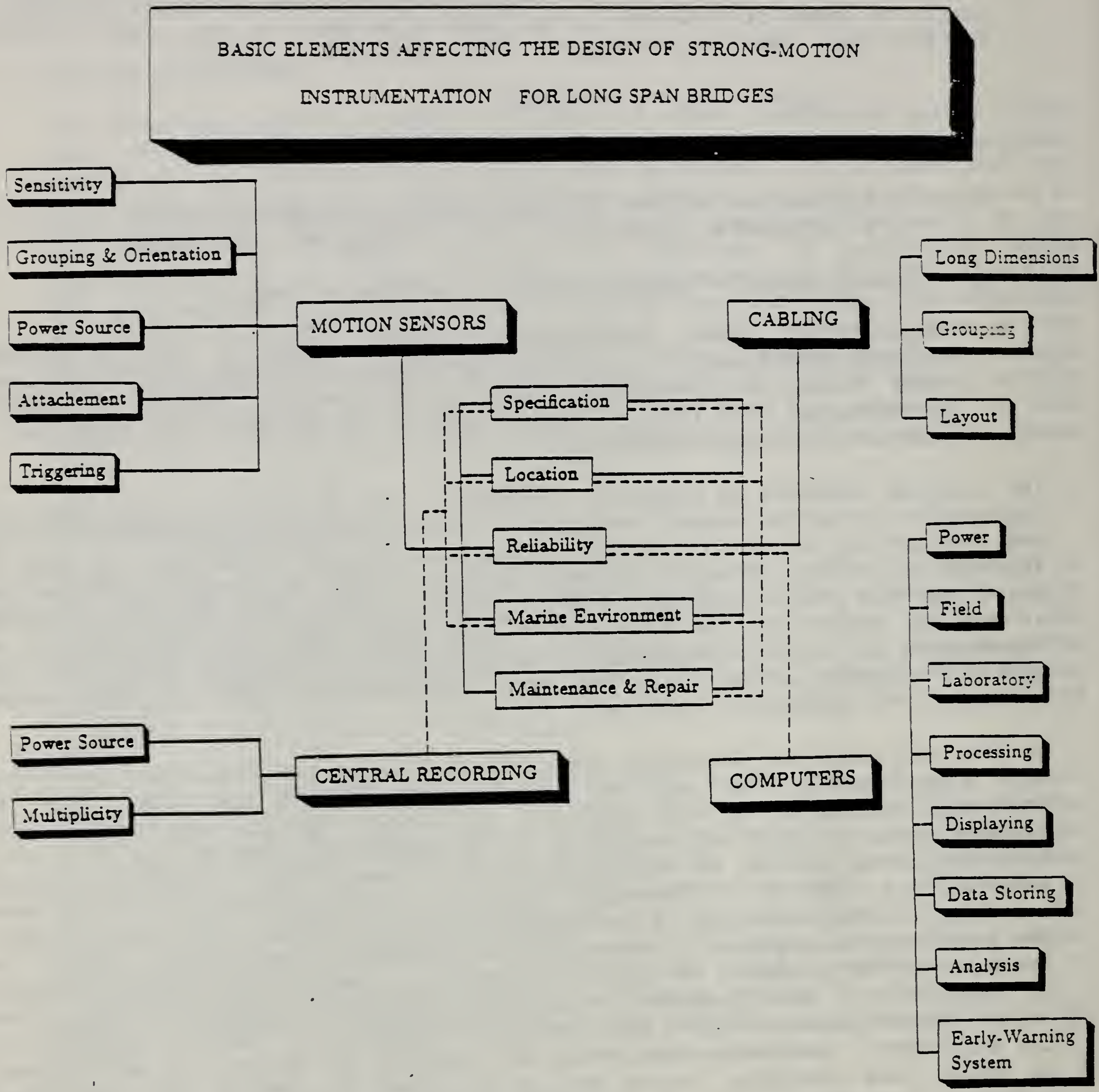

Figure 3. Basic elements affecting the design of strong motion instrumentation for long-span bridges.

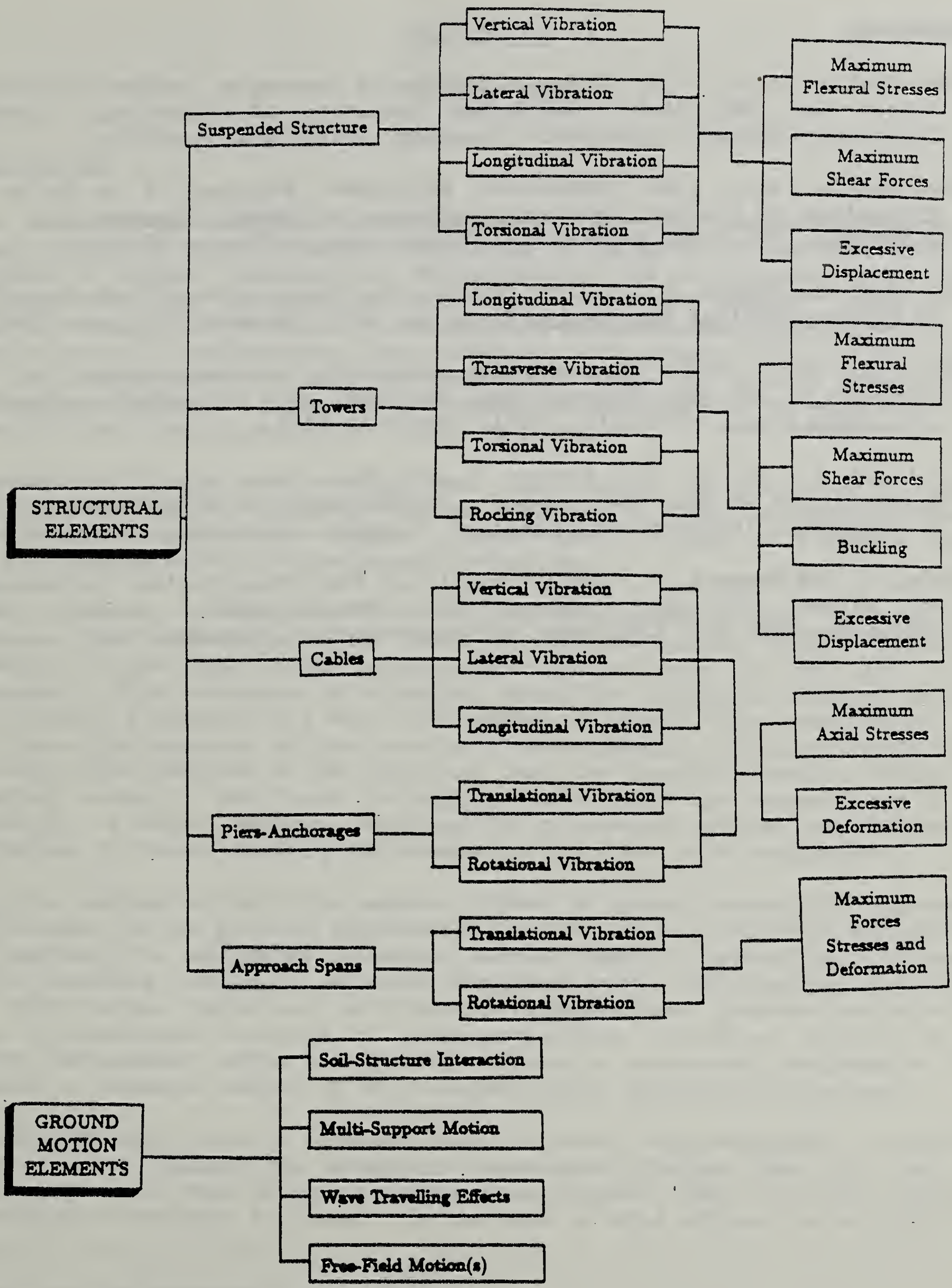

Figure 4. Basic earthquake induced structural response and ground motion quantities to be measured on long-span bridges.

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WIND EFFECTS

W. A. Dalgliesh*

INTRODUCTION

Wind and earthquake effects on structures have much in common: extreme events occur rarely and vary in severity according to geographic location; structural response is dynamic; deformations, displacements, and accelerations may occur in any direction, but the main concern is for horizontal motion. Consequently, some instrumentation developed for monitoring seismic effects can serve for wind effects as well. Sharing tools and techniques will promote better understanding and interchangeability of data and expertise. There may also be opportunities for shared programs. In addition, further development and economies of scale should follow from expanding the number of users.

Because data acquisition systems and displacement or acceleration sensors developed for seismic programs may be adapted for wind, in setting research priorities we should focus instead on such specific needs as pressure sensors and building permeability measurement techniques.

Wind action on a structure differs from earthquake effects in that wind pressures are distributed over every bit of its surface area. Earthquake effects, on the other hand, usually are applied only at the base of the structure. Wind pressures on cladding, being the difference between external and internal pressures, are more complicated to measure than base motion. Not only does the pressure on the outside of the cladding fluctuate continuously, and vary with location on the structure, but the internal pressure (within the cladding assembly, and inside buildings) varies with the permeability of the cladding. A major research challenge is to develop sensors and measurement techniques to relate cladding performance to the input wind conditions.

Wind, in combination with the buoyancy effect of indoor/outdoor air temperature differences and the pressure differences caused by the air-handling equipment of the building, is implicated in another serious aspect of structural performance of the building envelope. Moisture deposited within the cladding assembly by air infiltration (rain) and exfiltration (condensation) promotes corrosion and loss of structural capacity of vital components. Moreover, quality of the indoor environment, while not directly related to structural performance, also depends on adequate control of air transport under differential pressures.

To identify high-priority research needs in sensor and measurement technology, we must first examine the structural assessment programs that will use that technology. If those programs cannot find support, there is little point in developing technology for them. In the case of wind effects on buildings, an

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assessment program has a greater chance of being funded if it provides information on the durability or serviceability of the building enclosure at the same time as exploring structural performance.

With these recommendations in mind, let us now consider briefly the important features of wind effects on structures, and some implications for the acquisition of data.

IMPORTANT FEATURES OF WIND EFFECT MEASUREMENTS

Variability in Space

Structures deflect wind around themselves, causing positive pressures on windward-facing walls, and negative pressures on most other surfaces. These pressures are non-uniform, with particularly large gradients near windward edges. Eddies shed from upwind structures increase the spatial variability of the flow approaching downwind structures.

The input forces for calculating structural response of the whole structure, or components of it, are sometimes found by integrating the differential pressures over the relevant surface areas. Many pressure sensors are needed to account properly for spatial variations in surface pressure.

Wind forces on a structure are modified by the geometries and positions of structures immediately upstream, as well as the general terrain roughness. This means that wind direction is another important variable. In addition, wind velocity and turbulence vary with height above ground. It is generally impractical to install enough wind sensors in the right locations to define the oncoming wind completely.

Variability in Time

Pressures at any point on a structure vary continuously with time, as well as from point to point on its surfaces. The most rapid fluctuations have rise times of a fraction of a second. Although design based simply on the magnitude of the peak gust pressure or suction is still common, the wind resistance of some materials depends also on duration of exposure to high stress. Rapid pressure fluctuations should be sampled at least 30 times per second; window-sized gusts may last from 1 to 10 seconds, and building-sized gusts, up to 1 minute.

The next largest time scale of importance is the duration of the storm, which can vary from a few minutes (passage of a tornado) to a few hours (passage of a hurricane or winter cyclone). Where data storage is limited, the latter parts of long storms may be lost, depending on how the data acquisition system is programmed.

On a climatic scale, the basic unit of time is usually the year. To generate design data for structures with useful lifetimes of 30 to 50 years, records at least this long are desirable; however, there are strategies for extrapolating from much shorter data series. It is generally impractical to monitor a structure over its whole lifetime to determine its response to the design load.

Data Acquisition Strategy

No matter how long you wait, or how many sensors you can afford, some critical events or details will be missed. Thus, field data must be combined with a wind tunnel study and other information to fill in the inevitable gaps. Local meteorological records may be useful.

Data systems usually run unattended for long periods; reliability and provision for redundant measurements of key parameters are highly important. Data should be checked, processed, and archived (monthly) according to plan. Malfunctions must be caught early, and recording tactics optimized as events accumulate. Automatic zero-drift and calibration signal recording are required at regular intervals (at least daily). Full calibration using physical inputs traceable to standard values, (at least half-yearly) give the results credibility.

In addition to basic statistical summaries of all sensors (assumed connected to a central microprocessor), special records can be taken of pre-defined events. For example, record every sample of every channel for a predetermined period whenever a threshold wind speed is exceeded.

This concludes general comments on the nature of wind effect measurements. To assist the task group in listing and ranking specific needs for research on sensors and measurement technology, suggestions are offered in the context of research objectives arising from field projects in Canada (Dalgliesh, 1982; Ganguli and Dalgliesh, 1988).

RESEARCH OBJECTIVES AND SENSOR/MEASUREMENT TECHNOLOGY NEEDS

Definition of Input Wind Conditions

Wind speed and direction at key locations on site, air temperature and barometric pressure, are essential. Each field site presents its own problems with respect to siting instruments, but there is an opportunity to select, and to improve upon, speed and direction sensors. In addition to being rugged and easy to maintain, they should have a flat, linear response to fluctuations from D.C. to 10 Hz. Direction is difficult to record as a single signal; sometimes sine and cosine are recorded, and another option is to record up to 540 degrees azimuth. There is scope for improvement here.

Temperature and barometric pressure are required to convert from speed to pressure. An auto-ranging micro-barometer with resolution down to 5 Pa should be developed for use within buildings to register wind-induced fluctuations in the internal pressure.

Measurement of Structural Response

Excessive tip displacement and rotation about the vertical axis of a tower supporting microwave antennae, interfere with transmission. Displacement is also a good measure of overall structural response. Special-purpose instrumentation has been developed for following the tip displacement of a building, relative to its base (Dalgliesh, 1982). The fundamental requirement is to have a reference against which to measure motion. One method is to direct a laser beam vertically up an existing shaft, such as an elevator. Photo-cell detectors mounted on the moveable carriage of an X-Y plotter have been used to send error signals to the drive motors of the carriage, to keep the detector array locked on the beam. Air temperature variations introduce spurious fluctuations in the beam, which must be filtered out, and great care must be taken to ensure that the foundation under the laser does not rock, causing amplified displacements at the top.

Horizontal acceleration measurement provides a cheaper, more direct measure of perceptible motion. At least three sensors are required per level to include the effects of torsion. Accelerometers are also used for determining building frequencies, damping, and mode shapes. Frequencies and damping can be amplitude-dependent (Dalgliesh et al, 1983). A stable datum can also be a problem for accelerometer measurements, in that any tilting of the instrument is indistinguishable from acceleration. Perhaps some space-age spin-off in the form of a gyroscopic platform might be considered to isolate accelerometers from local rotations of structures on which they are mounted.

Strains in structural members of a high rise office tower have been measured by foil gauges, which have been surprisingly reliable and stable over several years of monitoring (Dalgliesh, 1982). If combined with the necessary circuitry, strain gauges might form part of packages to work with various parts of the structure as load cells for continuous and permanent monitoring of performance.

Validation of Wind Tunnel Design Data for Tall Building

The basic measurements for detailed assessment of how well wind tunnel design data reflects the behaviour of real buildings are differential surface pressures--located to match critical readings from the wind tunnel. Records are taken of the arithmetic mean, standard deviation, minimum, and maximum for each 5 or 10 minute interval (Dalgliesh, 1982). Various statistical comparisons and tests are possible. A sample rate of 30/s should be sufficient to define peak gusts in most situations. Analog filters with low pass at 10 Hz will control aliasing. It is important to guard against blockage of the tubing to pressure taps. A solenoid and valve must be incorporated with pressure sensors to provide zero readings at the end of each sampling interval. Surprisingly, there do not seem to be commercially available units that have all of the required features, so an opportunity for research is presented.

Every field experiment requires a dynamic pressure reference as a measure of the strength of the input wind, usually derived from wind speed at a location clear of interference from the building or any neighbouring structures. For comparison with wind tunnel results, a static pressure reference is also needed; in the wind tunnel this is usually taken from a pressure tap mounted flush on a side wall of the tunnel, or else from the static ports of a pitot tube, but there is no easy analogy to be found in the field situation. If the reference sides of all surface pressure transducers are connected to the same internal location, a best-fit value for the internal pressure due to wind effect can be derived. At least one micro-barometer should be used to track the effects of wind on the internal pressure directly. As mentioned elsewhere, some research on instrumentation and measurement techniques, including data reduction to remove barometric pressure trends, will be required.

The measurement and analysis of wind effects on internal pressure is very important for cladding design, the control of moisture in the wall, and the functioning of the building enclosure to prevent rain penetration. In the cold season of northern climates, excessive exfiltration in a poorly functioning wall may result in dangerous formations of icicles on high-rise buildings.

Structural Performance of Cladding

Through-the-wall pressure gradients are important for the design of two-stage walls in which the outer layer is vented to outside as a rain screen. Multiple taps in each instrumented, compartmented panel check its performance. Data are also used to build better analytical models and develop wind tunnel techniques to study local effects. Improvements would be welcome in methods for deployment of pressure cells, or tapping points for spatially integrating readings of gusts over individual compartment panels.

Once the pressures are apportioned to the various layers of the wall, there remains the problem of how to express the load on the rainscreen as some fraction of the total load across the wall; the maxima are usually out of phase, to such an extent that they may even be acting momentarily in opposite directions (Ganguli and Dalgliesh, 1988).

One of the unsolved problems for cladding design is the assessment of missile hazards--roof gravel and other loose construction materials that are implicated in a significant proportion of glass failures during windstorms. Some thought should be given to developing a survey technique for missile sources upwind of a structure at risk, evaluating wind speeds required to cause projectiles to become airborne.

Roof uplift accounts for a major part of wind damage. Designers must ensure that the air barrier can transfer wind load through a valid load path to the foundation. There is a need for a weather-proof method for placing a low-profile sensor on top of, and within roofing systems to find out which layers are actually resisting the wind induced suctions, particularly in regions of rapid fluctuations and spatial variation, near corners.
These examples, coming mostly from research on buildings, do not represent a complete list of possible research topics. It will be up to the task group, over the next two days, to debate the merits of an expanded list, and to provide guidance on those items perceived to be of particular importance. The following remarks may strengthen our resolve to present recommendations that will result in action.

RESEARCH FOR SENSORS AND MEASUREMENT TECHNIQUES

Making recommendations for high priority research should be more than an academic exercise. We must keep in mind the needs of the end users who must be persuaded to fund the field research. After field researchers make structural performance assessments, we should expect certain design or construction practices to be either confirmed or changed. Structural performance assessment should be interpreted broadly. Serviceability and durability are also important to end users, and often the same data serve to assess safety, serviceability and durability. Even some non-structural functions, such as the control of rain penetration and air leakage, require wind data for proper design and evaluation.

Where possible, the recommendations should encourage the use of common tools and standard techniques. Sensors, signal conditioning and pre-processing, transmission, storage, analysis, and archiving of data will become cheaper, more reliable, and more widely understood and accepted in proportion to the number of users and applications found for them. Any new research priorities should concentrate on those parts of problems for which there are no off-the-shelf solutions. This reduces to a minimum the new technology that must be developed, proved, and learned. A modular approach to problem solving should be encouraged.

As with any project where accountability is required, there should be intermediate objectives, with checkpoints where progress is monitored, and if necessary, tactics for proceeding to a solution revised. Finally, sensor/measurement technique projects are not ends in themselves; they stand a better chance of timely completion if their deadlines are driven by actual structural assessment projects.

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EFFECTS DUE TO OCCUPANCY, TRAFFIC, SNOW & OTHER LOADS

Robert A. Crist*

INTRODUCTION

It is a pleasure and honor to be invited as a speaker for this International Workshop on Sensors and Measurement Techniques for Assessing Structural Performance. I have been assigned the dubious honor of addressing the subject of the workshop with respect to occupancy, traffic, snow and other loads. If one were to refer to the American National Standards Institute A-58 Standard for Minimum Design Loads for Buildings and Other Structures, you would find the majority of the Standard is made up of requirements for seismic and wind effects and the remainder for occupancy and snow loads. Traffic and other load effects are not referred to so this allows me some flexibility in addressing how we may approach the problem of performance of structures relating to the load area that I have been assigned.

TYPES OF LOADS

We should understand the definitions of the various loads that I am addressing before considering the response of structures to these loads. Snow loads are obvious and are covered under building codes and in detail in the ANSI A-58 Standard. Similarly, occupancy loads, which are those vertical loads superimposed upon the structure such as human weight, furniture, partitions, etc. also are well covered by building codes and by ANSI A-58. Traffic can be considered in a generic sense. It may be vehicular, human or, in some unusual cases, waterway. These loads generally transmit short term, time dependent loads to the structure. "Other Effects," for the purposes of my presentation, are considered to be due to air, water, shock, vibration or machinery. Air and water could be considered as pollution causing deterioration and infiltration. Building facades are subject to hostile air and water environments. Their response to the environment has to be measured.

ELEMENTS OF THE PROBLEM

We must ask ourselves some simple questions to focus on our goals. What is there to measure for performance of structures? To borrow a cliche' from the movie title, we need the "Right Stuff." For us to properly evaluate what the right stuff is, let us break down our problem into its fundamental parts. Key words of our workshop are <u>measurement</u> and <u>performance</u>. What is performance? It is the response of a system to its environment. There are three important words; environment, which implies load; system, which implies the characteristics of the structure; and response, which implies the output of the

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structure due to the input or load. We must consider measurements in all three areas.

Some examples for measures of the environment or load are:

- o Depth, related to hydraulic head, buried structures or snow loads
- o Location related to snow drifting
- o Density related to weight of snow
- o Meteorology related to snow load
- o Motion related to ground transmitted vibration
- o Pressure
- o Count related to occupancy loads
- o Radiation related to light and thermal loads
- o Size, weight and shape related to occupancy loads
- o Anthropometry related to human occupancy activity
- o Chemistry related to air and water pollution

Measures of system characteristics can be described in several ways. The following are examples:

- o Modulus
- o Stiffness
- o Natural frequency
- o Damping
- o Resistivity
- o Density
- o Conductivity
- o Transmissibility
- o Strength related to yield, endurance and ultimate strength
- o Weight
- o Chemistry related to the chemical makeup of the system

- o Dimensions

Response is the output of the structure and is measured in many ways.

- o Strain resulting from deformation
- o Corrosion resulting from chemical attack
- o Acceleration resulting from traffic or vehicular loads
- o Velocity resulting from dynamic loads
- o Displacement resulting from both slowly and rapidly applied loads
- o Color or color change resulting from chemical environment
- o Deterioration resulting from physical or chemical breakdown of the structure.

MEASUREMENTS FOR ASSESSMENT OF PERFORMANCE

Now that we have the definitions and examples of the elements of our problem, the load, the system and its response, we need to ask ourselves other questions. Our assignment at the workshop is the assessment of performance. What parameters are needed to assess performance? Before we can determine what parameters are required, we must address the criteria that are used to assess performance. Our measurements to assess performance must be consistent with the assessment criteria or our measurements may be useless. On the other hand, if we have no choice on the type of measurements to be made, then our criteria may need to be changed. We should not create criteria for assessment for which measurements cannot be made.

Measurements can be made on the in-service system to assess performance. Also, models can be used.

- o Apply similitude for larger than or less than full scale physical models.
- o Analytical or computer models.

As was stated previously, the type of measurement should be consistent with the assessment criteria. If our assessment criteria relate to time, for example, the structure should last 10 years, or if the structure should not resonate for a dynamic load that has a duration of less than a second, then the measurements have to be consistent with these time frames. Various types of instrumentation should be considered.

- o Passive instrumentation can be left in place, unattended, that provides either visual or chemical indications of response
- o Active measurements using electronics, mechanical devices, etc.
- o Remote measurements

- o On-site and in situ measurements

The measurement technique also has to be compatible with the criteria and our ability to analyze the data obtained by the technique. These techniques also have to be considered with respect to the accessibility and type of structural system.

- o Nondestructive
- o Destructive
- o Disruptive
- o In situ
  - o Obtrusive
  - o Unobtrusive

Information processing is one of the more costly items to be considered. Choices can be made of off-the-shelf and custom software. What should we do with the measurements once we get them? Often too much information is gathered and it becomes difficult, if not impossible, to retrieve and analyze it. Some of the types of processing we have available to us are:

- o On-line or simultaneous
- o Real time
- o Off line
- o Hand processing or visual

Instrument technology has offered us a wide range of choices in both transducers and conditioning equipment.

- o Solid state
- o Servo-mechanical
- o Mechanical
- o Visual
- o Electrochemical

Measurement of the performance of a structure is essentially an experiment and the experiment has to be designed. Measurements are made and interpreted to provide the response of the system. Are these measurements what we want and can they be interpreted with the level of reliability necessary? Simple things should be considered:

- o Size of sample
- o Representative samples

In our process of measuring the performance of structures and assessing them, the application of the assessment should enter into the overall design of our measurement systems. Some of the applications of assessment are:

- o Fix
- o Renovate
- o Maintain
- o Surveillance
- o Demolish
- o Input for the design of other systems
- o Evaluate to meet specifications

The cost of measurements and the time available for assessment must be constantly kept under consideration. It is unusual, but sometimes it is the case that cost is of no concern but there is limited time to perform the assessment. This is as provocative a problem as having plenty of time and limited funds. Most all of us attempting to make measurements to assess the performance of structures are confronted with these issues. Therefore, the type of measurement, our data processing and the value to the assessment continually need to be addressed.

This presentation is intended to be a series of questions and challenges more than answers. We must address them as we progress through our deliberations in the workshop.

SUMMARY

In summary, let us re-examine what these challenges are.

- o What should we measure? Simply put, it should be the "Right Stuff."
- o The performance of a structure is the response of a system to its environment where:
  - o Environment implies load
  - o System implies the characteristics of the structure
  - o Response implies the output of the structure, i.e., deflection, strain, acceleration. deterioration, etc.

Measurements may have to be made in all of these areas.

- o The parameters to assess performance have to be determined and addressed
- o Criteria for assessment have to be established before the assessment is undertaken
- o Where should the measurements be made in the system?
- o What measurement technology should be applied?
- o How should the information be processed?
- o What instrumentation technology should be used: passive, active, remote, in situ, etc.?
- o The assessment should be considered as an experiment and the experiment should be designed carefully
- o The application of the assessment should be examined before any performance evaluation is undertaken. Is the structure to be fixed, renovated, demolished, or is information to be gathered for design?

And, last but not least of all

- o The cost and time available for the assessment may dominate decisions made on all considerations.

It is hoped that these challenges will be addressed throughout our workshop. Some may appear to be mundane and too fundamental; however, it has been my experience that many are overlooked in the assessment process and become major barriers to the success of the program.

SENSOR TECHNOLOGY

Timothy A. Reinhold*

INTRODUCTION

The objective of this paper and presentation at the International Workshop on Sensors and Measurement Techniques for Assessing Structural Performance is to provide an overview of sensor technology to help focus discussions during the task group working sessions. The paper begins with a review of requirements for various types of full-scale measurements and outlines the types of measurements conducted. The second section discusses sensor performance requirements, signal conditioning and the transmission of signals. The third section discusses levels of complexity in sensors and data systems as the technology moves towards "smart" sensors. The paper closes with a brief outline of challenges for the future.

MEASUREMENT REQUIREMENTS AND TYPES OF MEASUREMENTS

Measurement requirements for various areas of activity related to structural performance were defined at an earlier National Science Foundation sponsored workshop on "Field Measurements." Participants at that workshop considered and established measurement requirements for earthquake ground motion, wind speeds, wind pressures, dynamic response of structural frames, dynamic response of components and long-term creep or settlement. The measurement requirements for bandwidth, sensitivity, dynamic range and resolution required for engineering and research applications in these areas are summarized in Table 1.

There is a wide variety of sensors on the market which are capable of producing output signals proportional in either a linear or nonlinear way to a desired quantity such as force, displacement, velocity, acceleration or some other characteristic of interest. Table 2 provides a listing of some of the devices and technologies used. Generally, these devices employ measurements of some basic quantity or quantities such as displacement, velocity, acceleration, force, temperature, light or time to produce derived quantities such as length, width, thickness, position, level, surface quality, strain, vibration frequency, speed, rate of flow or a myriad of other quantities.

SENSOR PERFORMANCE AND SIGNAL CONDITIONING

Sensor performance can be defined in terms of linearity, dynamic response, sensitivity and repeatability or accuracy. The linearity relates to the degree of complexity of the relationship between the basic and derived quantity or quantities, hysteresis, stability or creep, and elastic after-effect. The

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TABLE 1. MEASUREMENT REQUIREMENTS
(FROM NSF WORKSHOP ON FIELD MEASUREMENTS)

	Bandwidth	Range of Sensitivity	Dynamic Range	Sensitivity	Resolution
o GROUND MOTION (E.Q.)	0.01-50 Hz	1×10^{-4}g-2.0g	86 db	1×10^{-4}g	1 in 20,000
o WIND SPEEDS	2.8×10^{-4}-20 Hz (60 min)	3 - 150 mph	40 db	0.1 mph	1 in 1,500
o WIND PRESSURES	8.3×10^{-4}-30 Hz (20 min)	1 psf-130 psf	40 db	0.1 psf	1 in 1,300
o FRAME RESPONSE (Dyn.)	0.01 - 20 Hz	1×10^{-4}g-3.0g	90 db	1×10^{-4}g	1 in 30,000
o COMPONENT RESPONSE (Dyn.)	0.1-200 Hz	0.005-15g	70 db	.001g	1 in 15,000
o CREEP OR SETTLEMENT	2.0×10^{-7} Hz or less (10yrs or more)	.01 in - 6 in.	55 db	.01 in	1 in 600

TABLE 2. DEVICES/TECHNOLOGIES

- o Accelerometers
  - Seismic
  - Servo
  - Piezoelectric
  - Force Balance
  - Micro-machined on Chips
- o Anemometers (wind/fluid velocities)
  - Cup
  - Propeller
  - Sonic
  - Hot Wire
  - Hot Film
  - Split Film
  - Ultrasonic
  - Laser
- o Dial Gages/Extensometers
- o Dynamometers (forces)
- o Force Balances
- o Laser (displacement, velocity)
- o Load Cells
- o LVDTs (displacement, velocity)
- o Optical (location, displacement)
- o Pressure Transducers
  - Capacitance
  - Inductance
  - Diaphragm/Strain Gage
  - Piezoelectric
- o Radar (location, displacement)
- o Radiation (location, displacement)
- o Sonar (location, displacement)
- o Strain Gages
  - Semiconductor
  - Foil
  - Piezoelectric Film
- o String Potentiometers (displacement/velocity)
- o Ultrasonic (displacement/location)
- o Fluid Velocity Measurements
  - Disks (drag)
  - Perforated Balls (drag)
  - Solid Balls (drag or frequency of vibration)
  - Vibrating Cylinders (vortex shedding frequency)
  - Semiconductor
  - Laminar Flow Elements (pressure drop)

dynamic response is related to the damping and admittance function of the sensor between input and output. This can make the sensor more or less suitable for sinusoidal, step function and transient inputs. The sensitivity and repeatability or accuracy of the sensor depends on the compensation for temperature changes, degradation of response and/or sensitivity due to exposure, contamination or deterioration. Finally, the accuracy of the sensor and the dynamic range depend on its signal to noise ratio.

Even when the sensor or sensing element meets all the basic requirements for the application, other problems related to signal transmission and recording can degrade the quality of the measurement. These problems can be lumped together as signal conditioning and noise. First, there can be pre-conditioning noise or errors which arise from sensor location in an unfavorable or electrically noisy environment, and electrostatic or electromagnetic transmission noise arising between the sensor and the signal conditioner.

The signal conditioning unit itself can be a significant source of noise and the components must be capable of at least the same dynamic range as the sensor or the accuracy of the output will suffer. While noise can be removed or at least reduced with a good signal conditioning unit through filtering and common mode rejection, additional noise can arise from offset errors due to mismatching input impedances, gain errors by discrete component tolerance and drift, and by the dynamic range of individual components.

Once sensor output has been conditioned, and this usually includes producing high level signals which are less susceptible to noise, the signals are transmitted to the recorder. Again, noise can contaminate the signals during that transmission and the recorder itself may introduce quantizing noise or aliasing if proper filtering has not been accomplished.

SENSOR/SYSTEM COMPLEXITY

Sensors are a part of any measurement system. They can range in complexity from a simple strain gage which measures a basic quantity to a system which turns an entire building or bridge into a transducer. There are those who suggest that sensors need to become as sophisticated or "smart" as possible in order to handle things such as compensation, sending, conversion of units, linearization, self-calibration and checking. There are others who want the sophistication and checking placed in a central computer system, thus leaving the sensors as basic, inexpensive components. Some of the logical levels of complexity are suggested in Figure 1. The challenge is to find the appropriate balance between distributed and central intelligence for the particular application.

FUTURE CHALLENGES

The challenge for the civil engineering community is to more effectively use sensors to monitor and evaluate our structures. Modern racing craft with their use of sensors to monitor masts, sails, and other key elements, all connected to a central computer which controls the various functions essential to the structural integrity of the craft, point to the possibilities. While we may not be close to relying on control systems to ensure structural safety, we may find applications of monitoring and control useful in applications such as post disaster evaluation or structural serviceability.

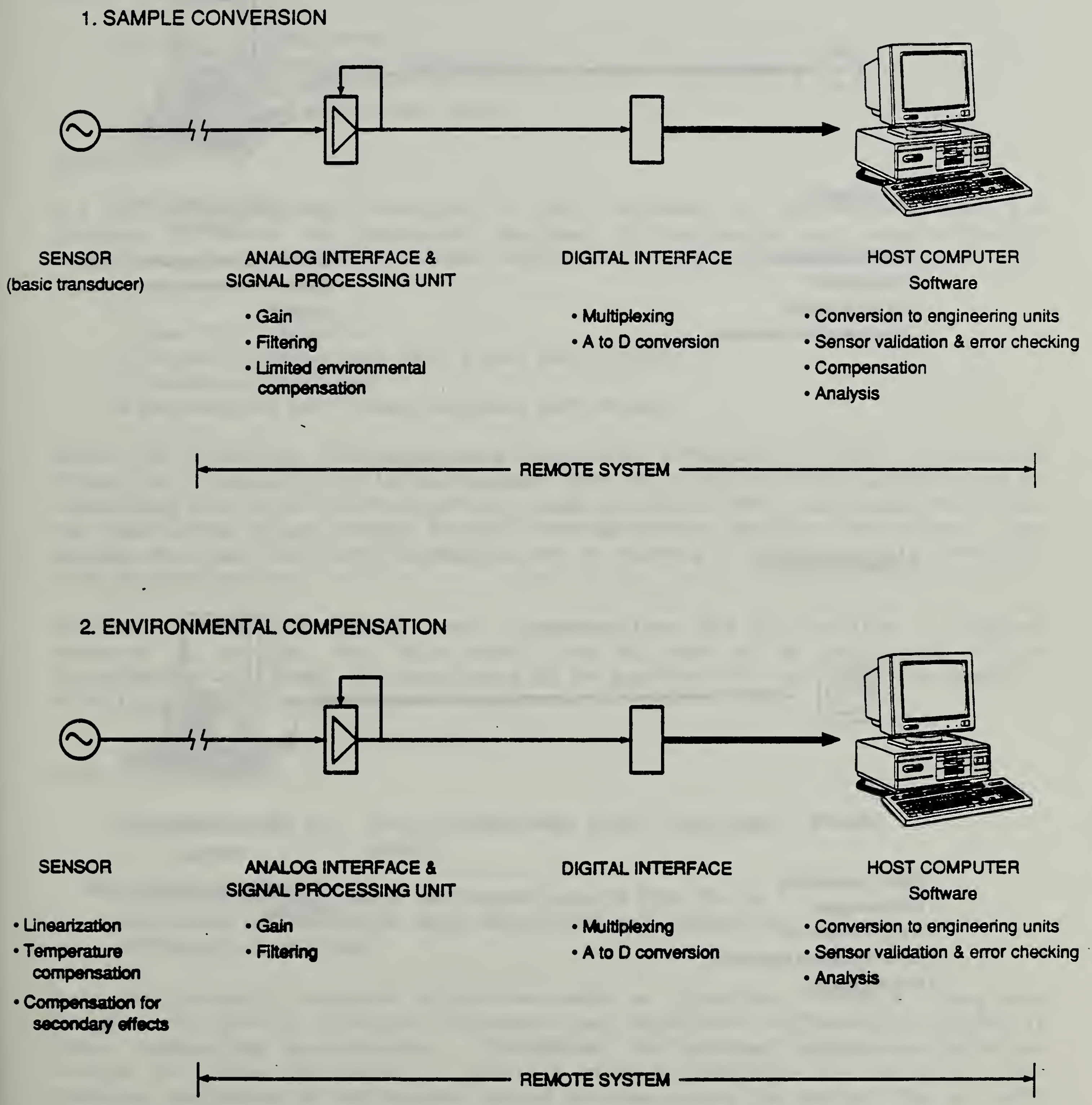
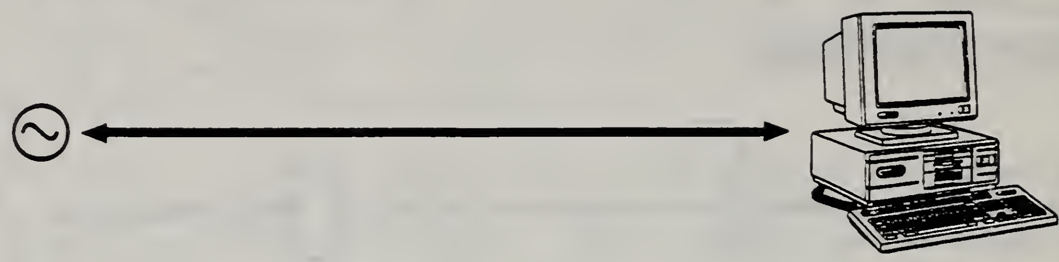


Figure 1. Levels of sensor complexity

3. COMMUNICATIONS CAPABILITIES



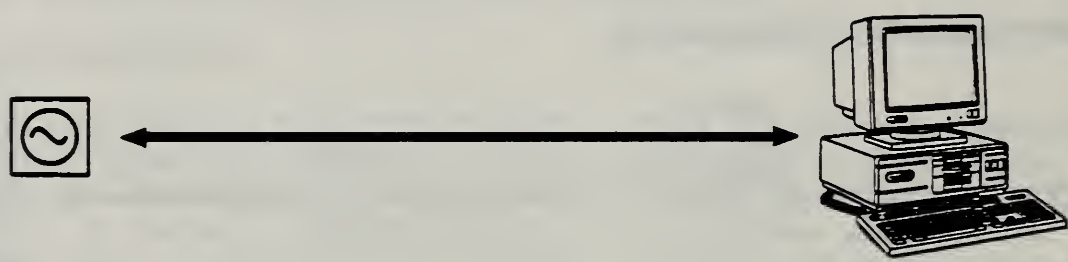
SENSOR

- Signal conditioning
- Compensation
- A to D conversion
- Communications interfacing

HOST COMPUTER
Software

- Conversion to engineering units
- Sensor validation & error checking
- Analysis

4. DIAGNOSTICS



SENSOR

- Signal conditioning
- Compensation
- A to D conversion
- Communications interfacing
- Self diagnostics

HOST COMPUTER
Software

- Conversion to engineering units
- Analysis

Figure 1 (Cont.) Levels of sensor complexity

RESEARCH OPPORTUNITIES

TASK GROUP A
SEISMIC EFFECTS

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BACKGROUND:

The 16 recommendations developed at this workshop in the seismic area are intended to assist the structural engineer in the design and construction of safe, economical seismic resistant structures. The recommendations cover four broad categories:

- o Free Field Effects
- o Seismic Interactions With Soils and Liquids
- o Structural Response
- o Cooperation and Common Projects With Others

While the following recommendations have been arranged in order of priority within each category, it is recommended that prioritization be accomplished by consulting the major instrumentation teams in the country, including the USGS, the California State Strong Motion Instrumentation Program and others. An attempt was made for each recommendation to address a separate topic; however, some overlap occurs.

Because of time limitations some recommendations did not receive a complete write-up as desired, but this should not be seen as an indication of low importance. All items are considered to be important as this list represents a distillation of a longer list of topics.

FREE FIELD EFFECTS:

RECOMMENDATION A1: THREE-DIMENSIONAL DENSE INSTRUMENT ARRAYS

THREE-DIMENSIONAL DENSE INSTRUMENT ARRAYS NEED TO BE INSTALLED FOR MEASURING BOTH FREE-FIELD AND FOUNDATION DIFFERENTIAL MOTIONS

Long horizontally extended structures such as pipelines, tunnels, long-span bridges and general lifeline structures can experience differential motion at their supporting points/sides. Therefore, no rational earthquake-resistant design for these structures is possible without knowledge of the spatial and temporal variation of earthquake ground motions along the axial line at their supporting points/sides. In addition, these structures are located at sites with various ground conditions and some of them are underground. Thus, the effects of earthquake ground motions to which these structures are subjected normally differ as the propagation, attenuation, and amplification characteristics of seismic waves vary with soil conditions. Therefore, dense instrument arrays of differential seismic motion by many accelerographs as well as displacement meters should be deployed on the ground and underground (down holes) in specific areas of representative free-field and soil-structure interaction sites in highly active seismic zones. Such arrays can give valuable information on attenuation characteristics by local topography and geological conditions. Such efforts should be coordinated with appropriate federal and state agencies.

RECOMMENDATION A2: LONG-PERIOD GROUND MOTIONS

STATE-OF-THE-ART SENSORS SHOULD BE DEVELOPED AND DEPLOYED FOR THE MEASUREMENT OF LONG-PERIOD GROUND MOTIONS

High frequency motions attenuate much more rapidly with distance from the center of seismic energy release than do low frequency motions. Accordingly, at distant locations there is an appreciable effect of long-period ground motion. In addition, due to the technical difficulties of accurately extracting long-period motions (3 seconds and longer) from typical accelerograms and due to the importance of earthquake-resistant design of long-period structures such as tall buildings, long-span cable-supported bridges and fluid containers, there is an urgent need to develop and deploy strong motion instruments for long-period measurements. The data from such sensors would also be valuable for comparative studies of routinely processed data (such as integrated velocity and displacement histories) from accelerograms.

SEISMIC INTERACTIONS WITH SOIL AND LIQUIDS:

RECOMMENDATION A3: DISPLACEMENT AND ROTATION

DEVELOP COMPACT AND INEXPENSIVE MEASUREMENT METHODS FOR DISPLACEMENT AND ROTATION

Most of the time history records of ground and structural motions are acceleration records because of the convenience of measurement. But to assess the safety of structures during earthquakes, the displacement is the most important parameter to measure because strains and stresses in the structures depend on the displacements. Displacements are difficult to obtain from acceleration records. Needed research includes the development of compact sensors and less expensive measurement procedures to accurately capture ground and structural displacements. In addition, the development of improved methods of velocity measurement should be encouraged.

RECOMMENDATION A4: SOIL DYNAMIC SHEAR STRAIN

INNOVATIVE INSTRUMENTATION TO MEASURE DYNAMIC SHEAR STRAIN IN SOIL SHOULD BE DEVELOPED AND DEPLOYED

Data on dynamic characteristics of soil at large amplitudes are scarce. In addition, due to earthquake-induced large-amplitude dynamic strain in soils and earth structures during damaging earthquakes, there is an urgent need to accurately measure values of shear strain of deformed soils at free-field sites, in relatively poor soils surrounding large foundations, inside earth dams and embankments, and in zones of potential soil liquefaction. Efforts should be focused on the development of cost-effective and accurate sensors. The data obtained from such measurements would be very valuable in verifying existing analytical techniques of nonlinear constitutive modeling, nonlinear dynamic soil-structure interaction, and seismic analysis of earth dams and embankments.

RECOMMENDATION A5: DYNAMIC PRESSURES IN SOILS AND LIQUIDS

DEVELOP IMPROVED INSTRUMENTS TO MEASURE DYNAMIC PRESSURES IN SOILS AND LIQUIDS

The dynamic influences of various soils on large foundations and walls under seismic loading need more correlation with analytical studies. This can lead to improved design procedures and improved (and hopefully less costly) designs. An economical, rugged, compact and reliable sensor which can remain buried and operational for a long period of time is needed. Applications could be expanded to measure the variation in vertical pressure under spread footings which are generally conservatively designed. Other applications would include tunnels and other underground structures.

RECOMMENDATION A6: FORCES IN PILES

THE BEHAVIOR OF PILES AND THE FORCES IN PILES DURING EARTHQUAKES SHOULD BE MONITORED AND RESULTING DAMAGE SHOULD BE DOCUMENTED

The safety of structures supported by piles is greatly affected by the dynamic behavior of the piles. But there are not enough observational response data available for piles under seismic loads. Measurement techniques should be developed to measure deflections and strain/stress in the piles and instrumentation to accomplish this should be deployed. Such data would be valuable for soil dynamics and foundation design.

STRUCTURAL RESPONSE:

RECOMMENDATION A7: DEFLECTION TIME HISTORIES

OPTICAL AND VIDEO TECHNIQUES FOR THE MEASUREMENT OF TIME HISTORIES OF STRUCTURAL DEFLECTIONS NEED TO BE DEVELOPED

Most current seismic measurements involve the placement of sensors at various locations on the structure with extensive cabling to connect each sensor to a remote recording system.

Current video and optical technology permits the overall structural response to be recorded and data from many locations to be recorded simultaneously on video tape. The advantages of such a system would be lower initial costs and flexibility in post-earthquake analysis. In addition, a visual observation of damage would be possible which could aid in collapse potential studies. The system would also be used on very complex systems which would require up to hundreds of channels of conventional sensors. In addition, the response of inaccessible systems such as those located in toxic or high voltage areas could be measured.

RECOMMENDATION A8: MOBILE DATA ACQUISITION SYSTEM

A MOBILE DATA ACQUISITION SYSTEM SHOULD BE DEVELOPED TO CAPTURE GROUND MOTION AND STRUCTURAL RESPONSE DATA

At the present time it is not well understood how structures having large base dimensions respond to a series of on-coming ground motions. Such structures include long-span bridges with multiple supports and buildings of large plan dimensions. Usually these structures are designed with an assumption that all parts of the base of such structures are subjected simultaneously to the same ground motion. It has been shown that this assumption may lead to unconservative design. Accurately defined ground motions are needed for realistic evaluations of the response of structures to seismic events.

In order to obtain ground motion data an array of portable instruments should be deployed immediately following the initial event of a major earthquake to capture free-field ground motions as well as responses of assorted structures. It is not cost effective to install a large number of costly instruments at a particular site and wait for a major event to occur. Several mobile units, perhaps 5 or 6, should be placed in seismically active regions with each unit assigned to cover certain preselected sites.

RECOMMENDATION A9: ACTUAL LOADS ON MEMBERS

DEVELOP IMPROVED METHODS TO MEASURE ACTUAL LOADS ON STRUCTURAL MEMBERS

The researcher and designer are primarily interested in the actual forces (axial force, moment, shear) in various components of a structure. Compact, reliable instruments which output forces directly would be very useful. The basis for such an instrument would be the measurement of strain. VLSI technology could be used to output useful engineering data directly.

COOPERATION AND COMMON PROJECTS WITH OTHERS:

RECOMMENDATION A10: COOPERATIVE STUDIES WITH OTHER COUNTRIES

DEVELOP OPPORTUNITIES WITH OTHER COUNTRIES FOR COOPERATIVE STUDIES TO OBTAIN STRUCTURAL RESPONSE DATA ON A TIMELY BASIS

Opportunities to collect response data from actual structures are limited in the U.S. due to the infrequent occurrence of strong earthquakes and winds at sites where candidate structures are located. For example, Japan has many bridges and buildings which are designed based on advanced design concepts and are subjected to frequent strong earthquakes and winds (5 or 6 times per year). These structures serve as ideal full-scale laboratories to obtain valuable dynamic response data of full-scale structures as well as to evaluate the effectiveness of instruments. At the present time, the UJNR Panel on Wind and Seismic Effects provides an effective channel to undertake cooperative work with Japanese researchers and engineers. This mechanism could be utilized further to explore cost effective research.

RECOMMENDATION A11: IMPROVED DATA ACQUISITION

IMPROVED EARTHQUAKE DATA ACQUISITION SYSTEMS FOR GROUND MOTION AND STRUCTURAL RESPONSE MEASUREMENTS NEED TO BE DEVELOPED

Efforts should be directed toward the improvement of data acquisition systems for central recording of free-field, interaction systems and structural-response motions. Specifically, the following items are considered essential:

1. Remote interrogation, including data transmission
2. Use of PC technology as an upgrading path
3. Pre-event memory capabilities
4. Analog signal outputs and A/D and D/A converters
5. Data storage and display

RECOMMENDATION A12: DEPLOYMENT OF SEISMIC SENSORS

GUIDELINES SHOULD BE ESTABLISHED FOR THE DEPLOYMENT OF SEISMIC SENSORS

To make the most of the recorded motions of the ground and structures observed at various places, deployment guidelines should be established. This will also encourage people who would like to measure earthquake motions but don't know how. One possible way to do this would be through a workshop. Input should come from engineers and sensor manufacturers and the workshop should be international in scope. The published guidelines should include the details of the measurement method, and explain just what is being measured and why.

RECOMMENDATION A13: INTEGRATION OF RESPONSE DATA IN SMART BUILDINGS

MEANS SHOULD BE EXPLORED TO INTEGRATE BUILDING STRUCTURAL RESPONSE DATA INTO THE CONTROL SYSTEMS FOR HVAC AND SECURITY IN SMART BUILDINGS

Increasing numbers of new buildings are being controlled using a system which controls internal environment, transportation and security. The system is dependent upon information continuously supplied by sensors placed at strategic locations throughout the building. It is cost effective to incorporate the system for the collection of wind and seismic response data.

RECOMMENDATION A14: COMMON MEASURING SYSTEMS FOR WIND AND SEISMIC EFFECTS

DEVELOP COMMON MEASURING SYSTEMS FOR THE MEASUREMENT OF SEISMIC EFFECTS AND WIND EFFECTS

When wind and seismic systems exist side by side in a structure, guidelines should be developed and systems should be perfected to utilize common data channels and data acquisition systems for both types of data. Savings would include the elimination of duplicate systems and reduction in maintenance operations.

RECOMMENDATION A15: SYSTEM IDENTIFICATION TECHNIQUES

IMPROVED SYSTEM IDENTIFICATION TECHNIQUES AND SIGNATURE ANALYSIS PROCEDURES NEED TO BE DEVELOPED

The development and deployment of improved instruments for ground-motion and structural-response measurements should go hand-in-hand with the development of sophisticated system identification and signature techniques. More research is needed in areas such as: nonlinear (both time and frequency domains) system identification, multi-input multi-output systems, random decrement analysis, damage detection techniques and nondestructive evaluation methodologies. Verification of existing system identification techniques via experimental and observational studies is also needed.

RECOMMENDATION A16: DATA STANDARDS

DATA STANDARDS FOR SEISMIC DATA NEED TO BE DEVELOPED

There is a need to develop formal standards for the format of seismic (and wind) data along the lines of applicable ANSI standards. This is especially so for computer data to permit easy interchange of data between researchers. The standard could be expanded to be international in scope.

TASK GROUP B
WIND EFFECTS

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BACKGROUND:

The eight recommendations developed by those individuals who addressed wind effects are concerned primarily with improved instrumentation and techniques for measuring wind speeds and associated pressures in and on structures. In particular, the difficult problems of measuring wind speeds around large structures and establishing a suitable reference pressure in full scale studies were addressed.

RECOMMENDATION B1: IMPROVED WIND SPEED MEASUREMENTS

TO BETTER DEFINE THE WIND LOADS ACTING ON STRUCTURES, SEVERAL IMPROVEMENTS ARE NEEDED IN THE MEASUREMENT OF WIND SPEED AND DIRECTION, AND IN THE ANALYSIS OF THESE DATA

Improvements are needed in the type of wind speed data provided by the national network of NWS stations. It is these long-term records which are used to predict wind loads. Data are currently reported in difficult to use forms such as fastest mile speeds and these data should be replaced with more directly usable information. Current instrumentation and data acquisition systems need to be combined into a system which will provide wind records of direct use for structural design purposes. If accepted by NOAA, these systems and an expanded network of reliable wind recording stations could provide valuable data for structural design purposes.

RECOMMENDATION B2: DEVELOPMENT OF PORTABLE UNITS FOR THE MEASUREMENT OF WIND SPEED AND DIRECTION

SELF-CONTAINED PORTABLE UNITS NEED TO BE DEVELOPED FOR THE RECORDING OF WIND SPEED AND DIRECTION IN THE STORM PATH

The wind resistance of structures is often assessed through post-storm damage surveys. In many cases the wind speed records are insufficient to allow full correlation of the damage to wind speeds. A portable, rugged, self-contained unit is needed for recording wind speed and direction to help overcome this lack of data. An array of these units could be installed in the path of a storm to provide spatial and temporal wind speed values. Such portable units could also be used to provide velocity profiles within the roughness layer near low-rise buildings.

RECOMMENDATION B3: REMOTE SENSING DEVICES

DEVICES ARE NEEDED WITH WHICH TO SENSE WIND SPEED AND DIRECTION AROUND BUILDINGS AND OTHER STRUCTURES

Often the need develops for the remote sensing of the velocity field around a structure. For example, the horizontal velocity distribution upwind of a bridge or the vertical wind profile approaching a large building is needed. Advanced remote sensing devices for wind speed should be developed which will operate satisfactorily in such applications, thus eliminating the need for masts or other fixed mounting devices.

RECOMMENDATION B4: MEASUREMENT OF STRUCTURAL DISPLACEMENTS

IMPROVED TRANSDUCER TECHNOLOGY AND BETTER DISPLACEMENT TRANSDUCERS ARE NEEDED FOR MEASURING STRUCTURAL DISPLACEMENTS

Wind induced displacements of structures and structural components have traditionally been measured by placing a limited number of sensors at carefully chosen locations on the structural system. This provides a measure of deflection at the location of each sensor station. If the overall behavior or response of the structure is under investigation, it is necessary to evaluate relative displacements of the sensor stations as a set. Displacements between sensors must be inferred. It is often necessary to use sensors which do not measure displacements directly, e.g. accelerometers. This dictates that measurements must be properly converted to the desired physical quantity before application. For situations where displacements must be monitored in or near occupied spaces, it is necessary to keep the installation simple by using compact and unobtrusive sensors. Where sensors are exposed directly to harsh environments, they must be weather resistant, rugged, and protected from lightning and other voltage surges.

Although existing sensors have generally been usable, they do not enable the comprehensive and direct measurement of system displacements (i.e. mode shapes and amplitudes) and component displacements (local failure) that are needed for evaluating structural performance. A new sensor, possibly based upon fiber optic technology, should be developed which will enable continuous measurement of structural displacements along the full height as in the case of tall buildings or towers, and along the full length as in the case of long-span bridges. The sensor technology should also address the need for measuring small-scale, local displacements within structural components. The sensor development should result in a design which is unobtrusive, simple to install, and rugged.

RECOMMENDATION B5: MEASUREMENT OF WIND EFFECTS

AN INTEGRATED SYSTEM NEEDS TO BE DEVELOPED FOR THE MEASUREMENT OF WIND EFFECTS ON BUILDINGS AND OTHER STRUCTURES

A system with which to measure wind effects on buildings and structures can be thought of as being made up of three major components: (1) A central computer system for managing the data acquisition, analysis and recording; (2) The equipment needed for initial processing and transmission of the data from the sensors; and (3) The individual transducers. A smart transducer might incorporate both (2) and (3) or one version of (2) might suffice for several transducers.

Control systems in the form of PC's are readily available and can be adapted easily to the needs of a data acquisition system. New systems are in continuous development and need not be of concern to this group. The electronics for smart transducers are also under development by many others. However, it is important to take advantage of all these developments and to incorporate them into the design of individual transducers. For example, use of telemetry would be an excellent method of controlling and getting the data from individual sensors. Today the tendency is to use existing phone cables or special purpose cables. Use of telemetry could possibly reduce the cost of this part of the system and also would eliminate the constant repairs to cabling encountered in buildings due to inadvertent damage by daily maintenance and repair personnel. However, the telemetry system must be robust and free from outside interference. Thus the major concern in developing acquisition systems for buildings and other structures will be in the area of the transducers and sensors to be used in such systems.

RECOMMENDATION B6: ABSOLUTE PRESSURE TRANSDUCER

AN ABSOLUTE PRESSURE MEASURING TRANSDUCER AND STEADY REFERENCE PRESSURE PROBE NEED TO BE DEVELOPED

Wind interacting with the surfaces of a building or other structure causes pressures to act on those surfaces. It is current practice to monitor these pressures, either in the wind tunnel or in the field, using differential pressure transducers. The difficulty with using differential pressure transducers in the field is the requirement for a steady reference pressure. Wind induced pressure can be measured reliably if an absolute pressure transducer is developed. The new transducer will be useful in determining pressures on building cladding surfaces that are in distress, in obtaining field data of wind induced pressures, as well as in measuring pressures on model surfaces in wind tunnels. The development of an absolute pressure transducer will not only reduce the cost of pressure measurements, but also will permit pressure measurements on a wide variety of structures that are not possible at present.

RECOMMENDATION B7: LOW-PROFILE LOAD CELLS

DEVELOP A LOW-PROFILE LOAD CELL WHICH CAN BE ATTACHED TO BUILDING SURFACES

A need is perceived for inexpensive, easily installed low-profile load cells which could be attached to the surfaces of buildings to measure wind loads. Such transducers and associated signal conditioning and data transmission systems should be as unobtrusive as possible in order to gain acceptance by building owners.

These transducers should be capable of operating in the range of $\pm$ 200 psf and be insensitive to moisture and temperature changes. Their deployment on a large number of buildings would greatly improve our knowledge of actual wind loads. They could also be used for wind tunnel applications. In both cases the lack of a need for a reference pressure would greatly facilitate their use. Recently developed pressure sensitive films or other miniaturized load cells might also prove suitable for this application.

RECOMMENDATION B8: AIR FLOW THROUGH BUILDING ENVELOPES

A METHOD IS NEEDED FOR THE DETERMINATION OF INTERNAL PRESSURES

The distribution and size of leakage paths through the building envelope determine the internal pressures. A measurement technique is required to collect representative field information in order to develop reliable methods for cladding design. In addition to structural loads, this information is essential for assessing wind effects on a) moisture accumulation in the wall assembly (affects durability), b) indoor air quality and building ventilation needs, c) smoke control measures (fire), and d) energy efficiency. Airflow in the plane of the enclosure presents a major challenge. Candidate techniques include a) tracer gasses, b) pressurization of isolated components and flow measurements, and c) thermography.

TASK GROUP C
EFFECTS DUE TO OCCUPANCY, TRAFFIC, SNOW & OTHER LOADS

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BACKGROUND:

These recommendations provide guidance for the development of improved, more cost effective and safer design and assessment criteria for structures. The major elements of measurement considered here fall into three general categories:

- o Environmental loads to which a structure is exposed
- o System (structure) characteristics
- o Response

It is important to recognize that measurements alone cannot be utilized effectively for the design of new structures and the assessment of existing structures unless criteria for application of the measurements exist. It may be necessary in some instances that measurements be made without criteria to demonstrate the need for criteria and their development.

CORROSION:

Billions of dollars have been spent on repair and maintenance of structures where corrosion is occurring. Much research has been done to determine the causes, mechanism and debilitating effects of corrosion. The most obvious effect is loss of cross-sectional area of the corroding element. Secondary effects, such as stress corrosion cracking, freezing of mating surfaces and lateral pressure due to the expansion of the corrosion product have also led to structural distress.

Research is needed to develop methods and devices which can quantify corrosion activity. Research is also needed to develop acceptable criteria for corrosion evaluation. Measurement techniques should focus on monitoring of hidden steel surfaces since such surfaces cannot be easily inspected nor directly measured. Examples of hidden steel elements are reinforcing bars, prestressing strands, masonry anchorages, retaining wall tiebacks and steel connections in timber and steel structures.

RECOMMENDATION C1: EXISTENCE OF CORROSION

DEVELOP A NON-DESTRUCTIVE MEASUREMENT TECHNIQUE TO VERIFY THE EXISTENCE OF CORROSION AND QUANTIFY THE RATE OF CORROSION OF "EMBEDDED" OR HIDDEN STEEL ELEMENTS

Existing methods of corrosion measurement are the half cell potential method (ASTM C 876-87) for reinforced concrete, optical borescope for steel behind masonry cavity walls, and physical exposure and direct measurement of the corroding element. All of these methods are cumbersome to implement and difficult to interpret. The instruments developed should be passive, inexpensive, reliable and accurate for embedded devices. They should be easily portable, inexpensive and easy to use as field testing devices.

RECOMMENDATION C2: LOSS OF CROSS SECTION

A NON-DESTRUCTIVE TEST METHOD IS NEEDED TO MEASURE LOSS OF CROSS SECTION DUE TO CORROSION

Develop a non-destructive test method to measure the loss of cross section due to corrosion. Traditionally, for hidden elements, this could only be accomplished by exposing the element and measuring the cross section directly. This method is destructive and expensive. The device and method developed should be similar in function to those described under Recommendation C1 above.

OCCUPANCY LOADS:

Occupancy loads are those live loads which are due to the occupants of a structure and due to readily moveable objects and equipment. In a building this would include people, furniture, carts, etc. The occupancy loads for a bridge would be he vehicles crossing the bridge. Equally important are construction loads. These loads are the loads due to construction personnel and the temporary stacking of materials and equipment.

RECOMMENDATION C3: REAL-TIME ANALYSIS OF OCCUPANCY LOADS

STUDIES SHOULD BE CONDUCTED TO DEVELOP THE NECESSARY MEASUREMENT TECHNIQUES AND MEASUREMENTS SHOULD BE MADE OF REAL-TIME OCCUPANCY LOADS FOR BRIDGES AND BUILDINGS AND LOADS DURING CONSTRUCTION

The real-time analysis of live loads would result in the generation of an improved and more complete statistical data base which could be utilized to develop improved live load specifications for both bridges and buildings. An additional use of the measurements would be to facilitate search and rescue operations due to knowledge of the location of occupants in the event of a structural collapse. The data would also be useful in evaluating the use of structures.

Although it is possible to use the structure itself as a transducer (e.g., bridge weigh-in-motion studies), development is needed of transducers that directly measure load. This may be in the form of pressure mats. The transducers would need to measure both the magnitude and location of the load.

SNOW AND ICE LOADS:

The snow and ice loads on a structure are a function of the geometry, the exposure, and the thermal characteristics of the structure. Present specifications need continued updating and improvement, particularly with regard to drifted snow.

RECOMMENDATION C4: DEPTH AND DENSITY OF SNOW AND ICE

AUTOMATIC AND CONTINUOUS METHODS ARE NEEDED TO MEASURE ROOF SNOW AND ICE LOADS

The determination of roof snow loads is generally a manual process which is inconvenient, potentially dangerous, and disturbs the quantity being measured. Measurement techniques need to be developed that provide a convenient and automated means of measuring snow depths and densities. The use of remote sensing should be considered for this. The resulting data will not only be of use in the assessment of individual buildings, but also in the accumulation of a sufficiently large data base for code development. In particular, improved ground-to-roof conversion factors and the specification of drift loads will be accomplished. The data can be correlated with wind measurements to evaluate exposure effects.

RECOMMENDATION C5: THERMAL LEAKAGE IN ROOFS

STUDIES ARE NEEDED WHICH MEASURE THE THERMAL GRADIENT THROUGH A ROOF

A major factor affecting roof snow loads is the amount of thermal leakage that will cause melting of snow. With improved energy conservation methods, less thermal melting can be counted upon than in the past. Certain structures such as long-span flat roofs will be more susceptible than other types of structures. Proper criteria for the inclusion of thermal effects on design snow loads can only be accomplished through the measurement of roof thermal characteristics.

RECOMMENDATION C6: SNOW LOAD SPECIFICATIONS FOR MOUNTAINOUS REGIONS

MORE DETAILED SNOW LOAD INFORMATION IS NEEDED FOR AREAS IN WHICH THERE IS EXTREME LOCAL VARIATION IN SNOW LOADS

Numerous areas exist, particularly in mountainous regions, where there is extreme local variation in snow load. The design of structures in these areas requires snow load information that generally does not exist in sufficient quantities to be able to estimate, for example, 50-year snow loads. Research is needed which will provide better definition of these snow loads.

A multi-disciplinary effort will be required which will involve considerations of meteorology, climatology and geography. The important quantities that have to be measured to define the snow load environment need to be ascertained and identified. Measurements then need to be conducted with the aim of developing design criteria for snow loads in mountainous regions.

DETERMINATION OF DIMENSIONS:

In order to obtain a meaningful assessment of existing structures, it is necessary to field-measure the dimensions (length, cross-sectional area, thickness, etc.) of existing structural components. The structural components could include slabs, reinforcing bars in concrete, piles, main framing members, embedded connections, etc.

RECOMMENDATION C7: NEW OR IMPROVED IN-SITU MEASURING TECHNIQUES

STUDIES SHOULD BE CONDUCTED TO DEVELOP NEW METHODS OR IMPROVE EXISTING METHODS FOR ACCURATE DETERMINATIONS OF STRUCTURAL DIMENSIONS

Available measuring techniques cannot provide for reasonably accurate determinations of dimensions (length, cross section, etc.) of existing structural components through in-situ measurements. A research program should be undertaken to review present state-of-the-art methods and develop either new methods or improve present methods (pulse-echo, radar, x-ray or infrared technology) used in making these types of measurements. The program should include laboratory verification of prototype samples and field verification of various structural components. Ease of portability and accuracy of measurements under various field conditions should be considered.

RECOMMENDATION C8: DIRECT DATA PROCESSING FOR RECOMMENDED MEASURING TECHNIQUES

COMPUTER APPLICATIONS NEED TO BE DEVELOPED FOR AUTOMATED DATA INTERPRETATION AND TRANSFER

The reliability of any measurement technique or data acquisition system depends upon proper interpretation and analysis of the field data. In order to minimize human error and improve reliability and consistency, it is important that measurement techniques as described in Recommendation C7 be automated.

DURABILITY OF MATERIAL - ENVIRONMENTAL LOADS:

Consideration needs to be given to research into the environmental effects on structural systems, components and materials which lead to long-term aging, degradation, deterioration and changes in material properties. These environmental factors include chemical (acid rain and pollution), ultraviolet, thermal, freeze-thaw, moisture, and radiation effects. Not included in this section is durability of materials affected by corrosion or fire.

RECOMMENDATION C9: ENVIRONMENTAL EFFECTS

DEVELOP INSTRUMENTATION AND MEASUREMENT TECHNIQUES TO DETERMINE ENVIRONMENTAL EFFECTS ON VARIOUS STRUCTURAL MATERIALS USED IN BUILDINGS, BRIDGES AND OTHER STRUCTURES

The structural engineering profession is in dire need of design criteria to determine the long term environmental effects on various building materials and structural components. These materials include timber, plastics, concrete, steel, aluminum, masonry, gypsum, roofing, sealants, coatings, mortar, adhesives, and other bonding materials. Nondestructive test methods, laboratory testing, and instrumentation are needed to determine the presence or extent of deterioration caused by all environmental factors.

RECOMMENDATION C10: CONDITION ASSESSMENT

DEVELOP INNOVATIVE SENSING DEVICES TO DETERMINE EFFECTIVE LIFE OF EXISTING STRUCTURES

Probabilistic risk analysis and condition assessment methodologies need to be developed with which to evaluate environmental effects and the deterioration of existing structural components. This will make it possible to estimate remaining expected life and to formulate necessary repair, rehabilitation, or strengthening recommendations.

RECOMMENDATION C11: MATERIAL PROPERTIES

MEASUREMENT TECHNOLOGY IS NEEDED TO ASSESS AND MONITOR MATERIAL PROPERTIES AND EXTENT OF FAILURE, DEGRADATION OR PROPERTY CHANGES

Probes, sensors, instrumentation or measurement devices are needed to determine moisture content, species and grading of wood members; chemical content, hydration, void ratio and air content of concrete; fracture toughness, chemical content and fatigue cracking of structural steel; and chemical content, absorption, strength, and bonding properties of masonry and mortar.

INTEGRITY OF BUILDING ENVELOPES:

Air and moisture infiltration through exterior building envelopes is considered a critical environmental loading factor which affects overall durability and performance. Related factors are wind pressures, durability of cladding materials, sealants, caulking, adhesives and coatings, and environmental effects, including solar radiation, thermal and chemical effects.

RECOMMENDATION C12: PERFORMANCE OF FACADES AND ROOFS

THERE IS A NEED TO DEVELOP SENSORS, MONITORING DEVICES AND REMOTE MEASUREMENT TECHNIQUES TO EVALUATE PERFORMANCE OF CLADDING MATERIALS, FACADES, ROOFING AND RELATED JOINTS AND CONNECTIONS

Research is needed to develop indicators of satisfactory performance and durability of building facades and roofing systems. Infrared techniques, pressure or infiltration tests and measurement devices that are cost effective are desired. Warning devices are needed to indicate potential failure of these systems.

RECOMMENDATION C13: AIR PRESSURE AND AIR FLOW

MEASUREMENT DEVICES AND DATA ACQUISITION CONCERNING LOW VOLUME FLOW AND EXTERIOR AIR PRESSURES AND WIND DRIVEN RAIN

Correlation of measured data from existing buildings to laboratory experimental data is needed. Effects of temperature, humidity, solar effects on air pressures and airflow should be explored in relation to the continued integrity of building envelopes.

FIRE LOADS:

In the assessment of structures, especially reinforced concrete, that have been exposed to fire, it is necessary to evaluate the strength of the system after the fire. Structural components deteriorate because of high temperatures and duration of the fire. Data on which to base assessments of structural damage and loss of strength are generally not available.

RECOMMENDATION C14: FIRE LOADING

DEVELOP MEASUREMENT METHODS TO DETERMINE TEMPERATURE AND DURATION OF FIRE LOADING

Sensors, either passive or active, that can survive a fire should be developed for placement in or on structures to provide the required data.

RECOMMENDATION C15: DATA ON MATERIAL PROPERTIES

ASSIMILATE DATA ON MATERIAL PROPERTIES RELATING TO EXPOSURE TO FIRE AT GIVEN TEMPERATURES AND DURATIONS

In order to apply the data gathered under Recommendation C14, existing data should be assimilated so that properties of materials subjected to fire can be evaluated.

SHOCK AND VIBRATION LOADS:

Structures are subjected to shock and vibratory loads not ordinarily considered as being necessary for the design and assessment of structures. These loads include traffic (rail and highway), construction operations (temporary), mining and quarrying operations, operating equipment within a structure, and any other excitation that may cause vibration of a structure other than that of wind and earthquake loads.

RECOMMENDATION C16: HUMAN RESPONSE TO STRUCTURAL VIBRATIONS

MEASUREMENT TECHNIQUES SHOULD BE FURTHER DEVELOPED TO PROVIDE DATA FOR THE DEVELOPMENT AND IMPROVEMENT OF CRITERIA FOR THE RESPONSE OF HUMANS IN STRUCTURES AND THEIR CORRESPONDING TOLERANCE OF VIBRATIONS

Many forms of structural response have been measured. However, more specific measurements should be made regarding floor, wall and roof vibrations, thus providing input to excitation of components in a structure or excitation of human occupants.

RECOMMENDATION C17: SENSITIVITY OF SCIENTIFIC EQUIPMENT TO DAMAGE

THERE IS A NEED TO ESTABLISH THE SENSITIVITY OF SOPHISTICATED SCIENTIFIC EQUIPMENT TO DAMAGE BY BUILDING VIBRATIONS

Extremely sensitive equipment is housed on support systems that have to be designed to sufficiently isolate the equipment from vibratory environments. Improved criteria need to be supplied on the damage tolerance of this equipment.

TASK GROUP D
SENSOR TECHNOLOGY

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BACKGROUND:

Issues addressed by Task Group D included sensors and measurement techniques for obtaining data on loads, angular and lateral displacements, and accelerations. In addition to specific measurement problems, the task group discussed the need for standards in data acquisition system architecture and methods for disseminating information on instrumentation research and development.

RECOMMENDATION D1: ANGULAR DISPLACEMENT

DEVELOP SENSORS SUITABLE FOR MEASURING ANGULAR DISPLACEMENTS (ROTATIONS) IN STRUCTURES

Response of structures to applied forces during their life causes angular displacements as well as linear displacements. Knowledge of angular displacements can enhance understanding of the response as well as provide benchmark data for code verification. One advantage of angular displacement measurements over linear displacements is that the reference is easily established, i.e., the plumb line. Difficulties with existing transducers include their physical size, stability, sensitivity, hysteresis, the output signal level, and sensitivity to extraneous effects such as temperature and off-axis rotations.

The transducer should have the following characteristics:

Range: $\pm$ 3 degrees for θ_x
Sensitivity: 1 volt per degree (minimum)
Cross Sensitivity: $\pm$ 0.001 degree measured per 3 degree rotation about θ_y and θ_z
Temperature Sensitivity: $\pm$ 0.001 degree measured per 20 degree temperature change
Bandwidth: DC to 10 Hz $\pm$ 0.1 db

In addition, the transducer should have the following features:

- o Sealed against water intrusion
- o Maximum hysteresis: $\pm$ 0.001 percent full scale
- o Cross sensitivity: $\pm$ 0.001 degree measured per 1 g acceleration for the X, Y, or Z directions

The above transducer would be used for measuring wind and seismic response.

A second transducer type should be developed for the measurement of settlement characteristics. It would have specifications of the type described above, but with the numerical values selected to specifically be able to make measurements over a 30 year life and with the following special features:

- Built-in method for establishing (checking) zero position under static conditions at any time until the device is removed from the surface being studied.

- Construction materials selected for stability of performance for 30 year life.

RECOMMENDATION D2: DISPLACEMENT/DEFLECTION METERS

DEVELOP DISPLACEMENT/DEFLECTION METERS FOR MEASURING RELATIVE MOVEMENTS OF STRUCTURAL MEMBERS

Durable and rugged displacement/deflection meters need to be developed for measuring relative movements of structural members such as relative lateral displacement of the top of a building with respect to its foundation, and the vertical deflection of bridge spans with respect to piers and abutments. The meter would have to have long-term stability and remote-sensing capabilities. The displacement meter would also have to be able to function and provide meaningful data under outdoor environments.

Various ideas and suggestions for this type of meter were discussed in the task group. Ideas included, but were not limited to sonic devices, fiber-optic technology, the water-levelling method, video imaging with photogrammetry, usage of satellite technology, and laser technology. To evaluate the suitabilities of these technologies for the development of displacement meters, cost, bandwidth, sensitivity and resolution of each technique would have to be examined. In addition, the influence of temperature, relative humidity and other factors would have to be addressed and documented. The associated signal conditioning would have to be developed.

The investigation would also have to include deployment procedures on various types of structures such as steel, concrete, masonry and timber. Functioning of the meter under controlled laboratory conditions and in the outdoor environment would have to be checked and calibrated. Finally, the cost of manufacturing such a meter would have to be small in order to be practical and economical in general applications.

RECOMMENDATION D3: STRUCTURAL MONITORING SYSTEM ARCHITECTURE

STUDIES SHOULD BE CONDUCTED TO EXPLORE THE MOST EFFECTIVE DATA COLLECTION SYSTEM ARCHITECTURE FOR SPECIFIC STRUCTURAL SYSTEMS (e.g. BRIDGES, BUILDINGS, DAMS)

The procedures and equipment used to acquire data from instrumented structures have, until now, been selected on a case-by-case basis. Furthermore, existing knowledge of successful data collection techniques is generally proprietary.

Because of these factors, sophisticated and automatic instrumentation has generally been employed only for certain important structures, or for those cases mandated by law. An essential prerequisite, therefore, to enabling effective monitoring of a broad range of structures, whether for "smart" operation (buildings), safety, or life-cycle estimation, is the development of a standard data collection architecture. Such standardization is required to reap cost reduction through economy of scale. Standardization will also generate competition which will reduce costs.

Standardization needs to be developed initially for data transmission and processing, pre-event storage requirements, data collection synchronization, and the ability for sensors to be evaluated and calibrated remotely or autonomously.

Additional needed research includes identification of where "intelligence" is to be distributed. For example, a traditional architecture employs sensors attached to the structure and connected by wires to a central signal conditioning unit which is in turn linked to a central control and data storage device. This central device may include data processing software which reduces the incoming information to a useful engineering parameter, or it may simply store the data for subsequent transfer to another computer where the evaluation is carried out (as for example from remote seismic monitoring stations). An alternative at the opposite end of this spectrum might employ sensors which include their own onboard custom hybrid computer system. Such a system might consist of a single chip IC containing a single-channel signal conditioner, A/D converter, microcontroller, onboard non-volatile RAM for data storage, communications protocol (e.g. UART RS232), and an autonomous radio (telemetry) link to other sensors which form a high speed local area network. In this manner each sensor would be a system unto itself and thus would not be affected by failure of any other node in the system. Such redundancy could circumvent complete loss of data, as would occur in the event of a power failure in a centrally controlled system. Time synchronization could be achieved by independent threshold triggering. The sensor which first exceeds its preset recording threshold sends a radio signal which triggers the entire array of independent sensors. Data is stored locally until a portable mass storage device is brought to the site for final collection. The ideal middle ground between these two extremes needs to be identified for the general classes of structural systems previously mentioned.

A multi-man year effort will be required, both for the identification of optimal data collection architectures and for the development of data communication, storage, and hardware inter-connection standards.

RECOMMENDATION D4: LOAD SENSORS FOR ROOFS

SENSORS SHOULD BE DEVELOPED THAT WILL TRANSFORM ROOFS INTO TRANSDUCERS FOR MONITORING LIVE LOADS FROM SNOW ACCUMULATION

Whereas snow properties such as depth and density reflect the applied load, only the load magnitude is of consequence to the structure. Sensors with a sensitivity of $\pm$ 0.1 psf to measure a 5 to 50* psf pressure range should be developed. These sensors could be incorporated as part of the roof structure, i.e. surface or frame, and could trigger an overload alarm when the design load is exceeded and/or provide a load history over the projected life of the roof.

Building the sensor into the roof frame provides the advantage of being independent of the roof in the event of extensive roof repair or replacement. On the other hand, load/pressure sensors incorporated within the roof surfacing could serve additionally to detect moisture intrusion (an indicator of roof membrane failure). Following design, tests need to be conducted to verify durability/reliability of sensor elements, connectors and processing hardware.

* Or whatever the maximum required load may be.

RECOMMENDATION D5: ACCELEROMETER CHIP

A PROJECT SHOULD BE INITIATED FOR INDIVIDUALS INVOLVED WITH STRUCTURAL RESPONSE AND GROUND MOTION STUDIES TO IDENTIFY, INTERACT WITH AND SUPPORT THE DEVELOPMENT OF SILICON-CHIP BASED ACCELEROMETERS WITH THE SENSITIVITY RANGE OF 10^{-4} g TO 3 g AND FREQUENCY RANGES OF 0.01 HZ TO 50 HZ AND 0.1 HZ TO 200 HZ

There are low-frequency accelerometers available which have adequate sensitivity range (10^{-4} g to 3 g) and frequency response (0.01 to 200 Hz) to meet the current needs of researchers and practitioners. However, the cost of the units is one of the factors limiting the numbers and density that can be deployed. There are several silicon chip manufacturers working on the development of low-frequency and seismic-mass accelerometers.

A dramatic reduction in the cost of accelerometers suitable for structural performance studies may be possible by using semiconductor fabrication technology which would lead to mass production of the units. The availability of low-cost, low-frequency accelerometers would represent an important step towards making the dream of smart buildings a practical reality.

It would also make it more practical to meet national and international needs for more dense arrays of ground motion sensors. These dense arrays are needed to provide a better understanding of variations in earthquake ground motion on a scale more closely related to building site size.

RECOMMENDATION D6: PRACTICAL IMPLEMENTATION CONSIDERATIONS

EASE OF INSTALLATION AND MAINTENANCE, AND ECONOMY OF OPERATION ARE IMPORTANT CONSIDERATIONS IN THE IMPLEMENTATION OF A DISTRIBUTED SENSING SYSTEM

Attention to the following items in sensor development is considered essential:

(a) Emphasis on miniaturization to minimize the environmental and physical impact of the sensor and local processor.

(b) Development of devices which exhibit high reliability and stability and require little, preferably zero, maintenance throughout sensor or structure life.

(c) Production of environmentally rugged devices with adequate protection from or insensitivity to lightning, electrical and magnetic interference, moisture, chemical attack, temperature, etc. is required. Suggested schemes include optical isolation and onboard environmental control.

(d) Minimizing of power requirements. For large numbers of deployed sensors, provision of appropriate power may become impractical. Consideration should be given to high-output, self-powered transducers which will enhance ease of deployment and maintenance. Power requirements of local processing equipment should be minimized.

RECOMMENDATION D7: DISSEMINATION OF INFORMATION

MECHANISMS NEED TO BE ESTABLISHED FOR MORE EFFECTIVE COMMUNICATION AND DISSEMINATION OF INFORMATION BETWEEN RESEARCHERS INVOLVED WITH INSTRUMENTATION DEVELOPMENT

In the course of the discussions many needs were identified; at the same time, while few specific or quantitative responses to these needs were immediately forthcoming from the panel, it was nevertheless felt by all that there is, indeed, a wide variety of existing technology "out there" to meet these needs. At least, much of it could be available for rather direct adaptation to these needs.

A big gap for many researchers and/or users of sensors is the detailed knowledge of the range of sensors actually available. Therefore, means of bringing knowledge of the specific state of the art in each category to prospective users was actively discussed. Several modes for bringing this about were suggested:

- Creation by structural engineers of a journal specifically aimed at publishing accounts of sensors and their applications. (This might be an ASCE publication, for example).

- Setting up by some agency (such as an engineering society or NIST) of special instructional sessions to instruct structural engineers on available sensors, signal processing equipment, and to provide computer assistance thereto.

- The establishment in appropriate places (e.g. NIST library) of computerized data bases for the location and retrieval of pertinent information on sensors, their specifications, and their applications.

- The establishment of an appropriate clearing house for information on all phases of sensors and sensor technology appropriate to civil, structural, and geotechnical engineering applications. Such a clearing house could conceivably take one of the following forms:

(a) An active group maintained by one of the engineering societies, ASCE, SEM, or ASTM, for example.

(b) A working laboratory-equipped subsection of NIST that would, while undertaking active sensor research on its own, take responsibility for maintaining state-of-the-art knowledge on sensors from world-wide sources. This group might take the form of a kind of "sensor investigating" or study group, or "consumer products" evaluator, as well as a source of referral for wide varieties of inquiries on transducers, sensors, data acquisition and data-handling hardware and software.

There was some debate as to the propriety of an eventual role for NIST as the agency to take on this task. Some existing government agencies taking on analogous tasks were cited. In any event, the concept conveyed was of an active group, itself engaged in sensor development and/or use, that would be in touch with both user needs and the hinterland of sensor expertise capable of filling those needs.

Overall, the sense of the group on sensors was that, while a few specific lacunae exist, many sensors of strong capability already are available; however, stronger links of communication are needed in some form to connect users and developers of sensors: the users with what is available now, and the developers with the new specific needs to be filled.

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11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

This report identifies research and development efforts needed to advance the state-of-the-art in instrumentation and measurement techniques for assessing structural performance. Four topic areas consisting of 1) seismic effects, 2) wind effects, 3) effects due to occupancy, traffic, snow and other loads, and 4) sensor technology were addressed by respective task groups during a two-day meeting of international experts. The forty-eight specific recommendations presented in the report are intended to serve as a research agenda for use by universities, research establishments and funding agencies.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

bridges; buildings; instrumentation; loads; research; sensors; structural engineering; structural response

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