California AHMCT Research Center
University of California at Davis
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# APPLICATION OF FIBER OPTIC COMMUNICATIONS AND OPTICAL SENSOR CONCEPTS TO GLOBAL STRATEGY FOR BRIDGE INSPECTION

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Illustrations and Tables

## Disclosure Section

All work was performed by Faculty, Staff, and students of the University of Southern California. No other contracts or subcontracts were involved in this research.

## Disclaimer Statement

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the STATE OF CALIFORNIA or the FEDERAL HIGHWAY ADMINISTRATION. This report does not constitute a standard, specification, or regulation.

# Forward

This report covers the research conducted on this contract between July 1, 1992, and the end of the funded effort, April 30, 1993, under CAL 92-7.

The effort was multidisciplinary because of the complex physical issues involved in bridge status and health monitoring, especially if the bridges are to be inspected automatically and continuously.

The multidisciplinary team involved the USC Civil Engineering Department, Electrical Engineering-Electrophysics (Center for Laser Studies), and Electrical Engineering-Systems[Communication Sciences Institute]. The team consisted of

Principal Investigator (PI) -- Prof. Antonio J. Mendez (Center for Laser Studies and Communication Sciences Institute)
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Co-PI -- Prof. Ahmed Abdel Ghaffer, Civil Engineering Department
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The Civil Engineering Department was responsible for defining the bridge dynamics, failure modes, and failure mode observables and precursors. The Center for Laser Studies was responsible for defining sensor suites (including acoustic, magnetic, electronic, and photonic sensors) which could monitor bridges automatically and continuously and also the Out of Plane Bending sensor and demonstration. The Communication Sciences Institute was responsible for defining sensor fusion and communication techniques so that the bridges status and health could be monitored remotely and automatically.

This multidisciplinary, comprehensive approach is the basis of this vision of a global strategy for bridge inspection.

# Preface

The work reported here begins with an examination of bridge dynamics and failure modes in order to define optimal sensor(s) and their location on the bridge structure in order to maximize the sensitivity to incipient bridge damage or failure. Then the work identifies appropriate sensors which could operate continuously and without intervention of a bridge inspector.

The research defines the key sensor clusters (accelerometers and fiber optic sensors) and communication means (cellular telephone) which can be used as the basis for a global strategy for bridge inspection.

The philosophy of approach was guided by the principle that the solution be applicable to both new construction and retrofit projects.

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# 1.0 Introduction

Bridges constitute an important part of the national infrastructure. Evaluation, repair and rehabilitation of bridges are increasingly important topics in the effort to deal with the deteriorating infrastructure. The major factors that have contributed to the present situation are: the age, inadequate maintenance, increasing load spectra, and environmental contamination of these bridges.

Several diagnostic procedures exist for the evaluation of structural performance. They include techniques to identify the critical parts or elements of the structure, identify the cause of distress, monitor structural performance, warn against failure and provide statistical data for the development of design and evaluation criteria.

The need for efficient (accurate, inexpensive, long-lasting, easy to install, non-obstructive to occupants or users) monitoring devices techniques is obvious. These monitoring devices would be used in various types of constructed facilities, including bridges.

There is a need for procedures to evaluate the following parameters:

(1) actual state of the structure (stress, strain, deflections, cracks, their presence, location, width, permanent deformations);

(2) current load carrying capacity of the structure;

(3) accumulated damage (state of corrosion, section loss, changes in material properties, fatigue damage accumulation, deformations);

(4) load history of the members, connections or structures.

The purpose of diagnostic procedures is to evaluate the existing state of structure, establish causes of problems and select the remedy. The procedures include analytical methods, nondestructive test, and combinations of analytical methods with experimental approaches. Structural analysis provides efficient tools for calculation of forces and deformations. However, there is usually a considerable degree of uncertainty associated with load and resistance parameters. Particularly important is the knowledge of defects or weak links in the structure. The accuracy of information about the actual material properties, defects, load sharing and bridge (structure) performance in general can be improved by special field or laboratory observations and tests.

The objective of this research project are

(1)identify and describe the causes of defects in (steel and concrete) bridges
(2)identify and describe the bridge structural parts which must be monitored (by inspectors or unattended sensors) to keep track of the bridge status and health
(3)identify and describe suitable unattended sensors which can carry out the above monitoring
(4)identify and describe suitable optical sensor candidates, including those which can be powered-by-light
(5)identify and describe means of sensing, fusing, collecting, and disseminating the sensor array data
(6)identify, describe, develop, and test a candidate sensor (we selected a critical measurement -- OUT of PLANE BENDING -- for this research)
(7)make follow-on recommendations based on the above six objectives

These objectives have been met on this project and the information can be found in subsequent sections as follows:

The causes of defects in bridges, both steel and concrete, and the description of the measurable or detectable defects can be found in Section 2.0 (Steel Bridges) and Section 3.0 (Concrete Bridges).

In order to know where the inspector should look for the defects, or where the unattended sensor arrays should be placed, it is important to know where the defects manifest themselves. These data are presented in summary form in Section 4.0.

Section 5.0 provides a survey of the sensors capable of detecting the defects described above. Most of them are currently used in bridge inspections or monitoring. Most of them cannot be used in an unattended fashion. Most of them are not compact or of low power dissipation. Most of them cannot report remotely through existing or developmental communication systems. This leads us to pose the question whether photonic sensors, using fiber optic communication systems and power-by-light, might not lend themselves to unattended sensing/remote reporting. Thus, we close this Section with a discussion of some such photonic sensor candidates.

Section 6.0 is devoted to optical sensor concepts, including the status of power-by-light as a means of activating and powering these.

Since the defects are distributed in various locations on a bridge, Section 7.0 examines means of sensing and collecting these data, as well concepts for distributing the sensors on the bridge. This Section treats the communications aspects of the problem, also.

One of the most important defects in bridges is the OUT-of-PLANE BENDING, because it is not normally or easily detectable and because of the effects it induces. Thus, we elected to demonstrate a simple, fiber optic OUT-of-PLANE SENSOR on this Project. The experiment was based on a configuration which did not require a laboratory environment in order to make unambiguous detections of the out of plane bending. In order to make the experiment more immune to environmental effects and more fieldable, the sensor was of a differential type. This experimental demonstration was quite effective and it is described in Section 8.0.

Section 9.0 describes the follow-on recommendations, based on the contributions from the Civil Engineering Department, the Center for Laser Studies (Electrical Engineering-Electrophysics), and the Communication Sciences Institute (Electrical Engineering-Systems).

Section 10.0 provides the list of applicable references used in this research.

# 2.0 Identification and Description of Defects in Steel Bridges

The most important reasons of defects (cracking, deterioration and failure) of steel bridges are corrosion and fatigue.

## 2.1 Corrosion.

Corrosion of steel is the deterioration and eventual destruction of the metal due to its reaction with the environment.

The main causes of failures of steel bridges are the environmental effects which include temperature, humidity and the exposure of the material. High temperatures increase the rate of corrosion although this is usually not significant in bridges. The amount of ambient moisture is important to the rate of corrosion. Exposure is important in corrosion rates since wind and sun can quickly dry areas and decrease corrosion rates, whereas sheltered areas retain water and corrode more rapidly. Impurities such as salts can make water more efficient electrolytes and speed up corrosion. Because of the greater availability of impurities, structures and bridges in coastal areas, or where deicing salts are used can corrode more rapidly than in more benign environments.

Other factors affecting corrosion include atmospheric pollutants, bacteria, animal deposits, and stray electric currents.

There are four main categories of corrosion effects on the structural integrity of a bridge:

1. *Loss of section*: This is the most important concern. The reduction in member section leads to lower bending, axial, and shear capacity.

2. *Creation of stress raisers*: The formation of holes and notches due to corrosion creates stress concentration and can initiate cracks.

3. *Introduction of unintended fixity*: When corrosion freezes moving

parts of the bridge, such as expansion devices or hangers, the structure behaves differently than the way it was designed. Members can be subjected to unexpected high stresses.

4. *Introduction of unintended movement*: Corrosion build-up in constricted areas can generate pressure that bends or moves bridge components with damaging effects.

## 2.2 Fatigue.

Fatigue is the tendency of a member to fail at a lower stress when subjected to cyclical loading.

Age of a structure and heavy loading are the main sources of fatigue.

Fatigue cracking under loading occurs in two stages: crack initiation and progressive crack extension.

Typical conditions which encourage fatigue cracking are the termination of welded cover plates or a beam where high local stresses are combined with irregularities in geometry, at riveted and bolted connections, and where there is corrosion in high-stress areas. Cracks in tension members and cracking in an angle diagonal of a truss usually start from a rivet or bolt nearest the edge of the member. The crack then progresses to the edge of the leg and may continue through the other leg to complete failure.

Highway bridges experience fatigue problems which generally are a result of poor design details or faulty fabrication. When these are present, especially with welded members and details, fatigue crack propagation in regions of high stress may be more extensive.

Tests have shown that the total range of fluctuating stress is the most important factor in fatigue crack growth, rather than the magnitude of the maximum stress. The conditions which encourage fatigue cracking usually are found where the local stress is high, such as at connections or at changes in geometry.

A typical condition that encourages fatigue cracking is the termination of a welded coverplate on a beam. Because of the abrupt change in flange crossection, a severe stress concentration is produced in the fillet weld at the end of the coverplate and a fatigue crack may form at the toe of the fillet weld if the decreased strength was not taken into account in the design. Similar conditions exist at the butt-weld transitions of plate girder flanges. Other conditions that frequently produce fatigue cracking include plug welds of web holes, beneath rivet heads, and at coped flanges of diaphragms.

The sources for fatigue damage in welded steel bridges can be summarized as:

a) load induced fatigue and
b) displacement-induced fatigue.

Load induced fatigue is a result of primarily in-plane displacements caused by in-plane loads (traffic loads etc.) and displacement-induced fatigue is usually associated with relatively small out-of-plane displacements caused by lateral loads imposed by connecting lateral beams and diaphragms or cross-bracing.

### 2.2.1 Load induced fatigue cracking.

Cracks due to load fatigue can be described in more detail for steel orthotropic deck bridges.

Cracks in steel orthotropic decks can be found at the rib-to-deck plate junction, either in the plate when it is 10mm thick, or at the soffit, in the fillet weld connecting the rib to the deck plate at the rib-to-floor beam junction, and in the peripheral fillet weld (Figure 1).

Most of the cracks in deck plates range in length from 100mm to 1m when they are discovered and affect either one edge or both edges of a rib, making the deck plate more or less uneven and leading sometimes to the formation of longitudinal strips.

The cracks in the welds joining the discontinuous ribs to the floor beams are generally developed from the bottom of the web to the top, on one side only or both sides, and they sometimes propagate themselves into the rib-to-deck plate welds adjacent to the floor beams or join at the bottom of the ribs (Figure 2).

In steel box bridges (Figure 3) cracks can be located at the lower end of diaphragm connection plates. These vertical plates are welded to the box girder web, in contact with the bottom (tension)

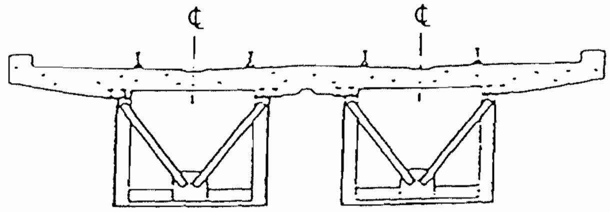


Figure 1. Typical cross-section of steel box bridges.

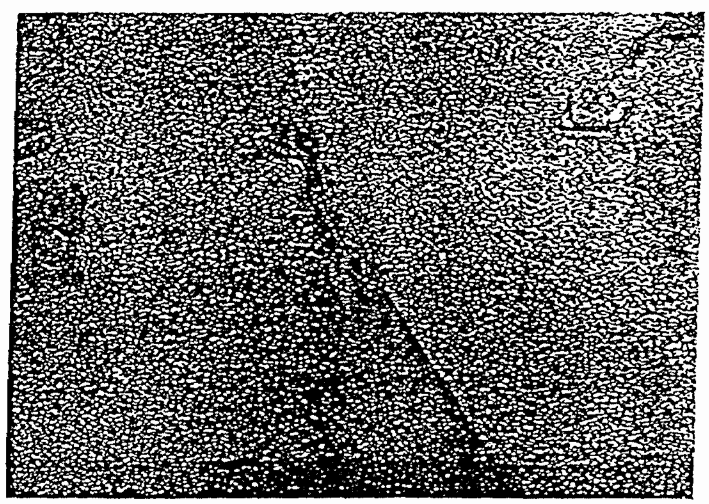


Figure 2. Fatigue crack in web at end of diaphragm connection plate.

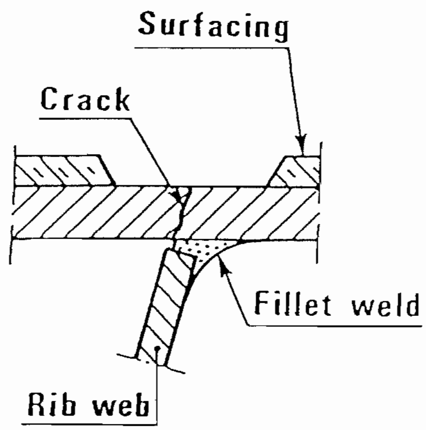



Figure 3. Fatigue crack at the rib-to-deck junction.

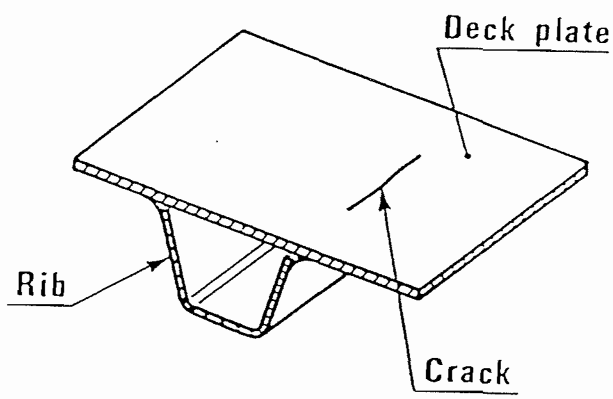



Figure 4. Fatigue crack in deck-plate.

flange but not attached to it. This arrangement follows the tradition of avoiding transverse welds to tension flanges.

The cracks developed in the box girder webs within the gap are formed by the cope of the diaphragm connection plate (Figure 4).

### 2.2.2 Displacement induced fatigue cracking.

**Displacement-induced fatigue cracking is epidemic on steel bridges.** The description and location of the cracks is presented here for welded steel bridges.

*1. Cracks at the ends of transverse stiffeners.*

Cracks can be formed at the weld toes at the end of the stiffeners adjacent to the tension flange (Figure 5).

Cracks can be formed in the weld at the ends of the stiffeners. These cracks that occur in the weld at the ends of the stiffener can extend completely across the weld and be visible in the web.

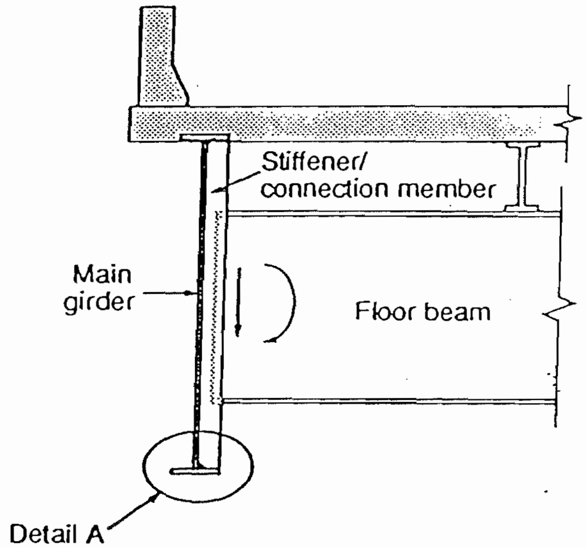
*2. Cracks in web gap between connection plate and flange.*

Several bridges have developed web cracking at the ends of floor-beam connecting plates (Figure 6).

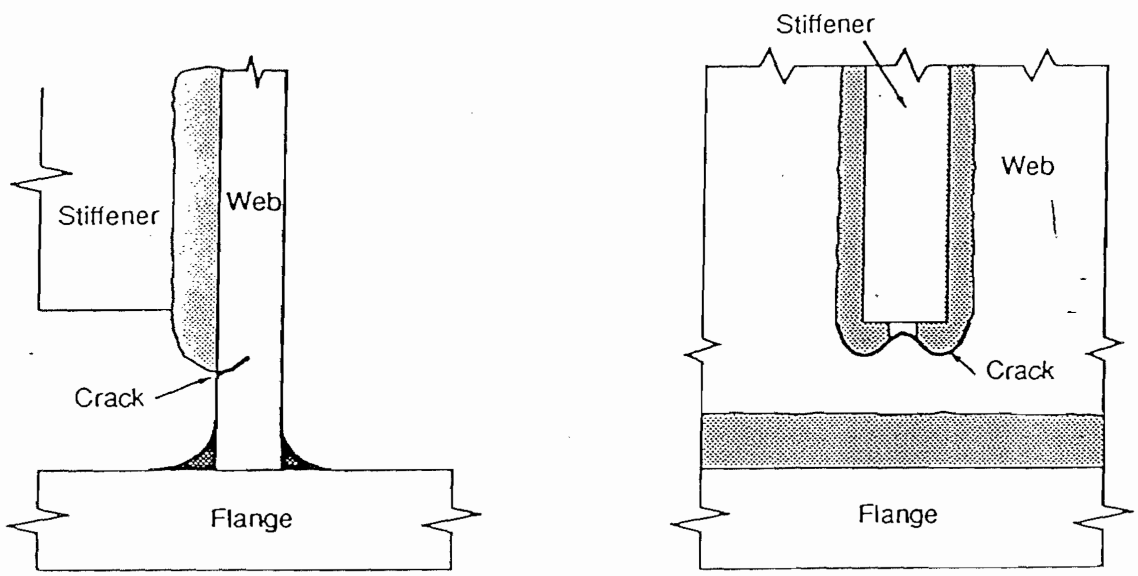
*3. Cracks in cantilever bracket tie plates.*

Fatigue cracks have been discovered in the tie plates connecting transverse floor beams and cantilever brackets across the main girders of several bridges. The crossection of the structure is shown in (Figure 7). The detail of the tie plates which connected the brackets at the floor beams and girders are shown in (Figure 8).

The tie plates have been observed to be cracked in several instances across their entire width. In one edge structure the cracks started at the edge of the tie plate from a tack weld. In several other bridges the cracking started at rivet holes (Figure 9).




Detail A




Cross section

Elevation

Figure 5. Schematic of web crack at the end of transverse stiffener welds.

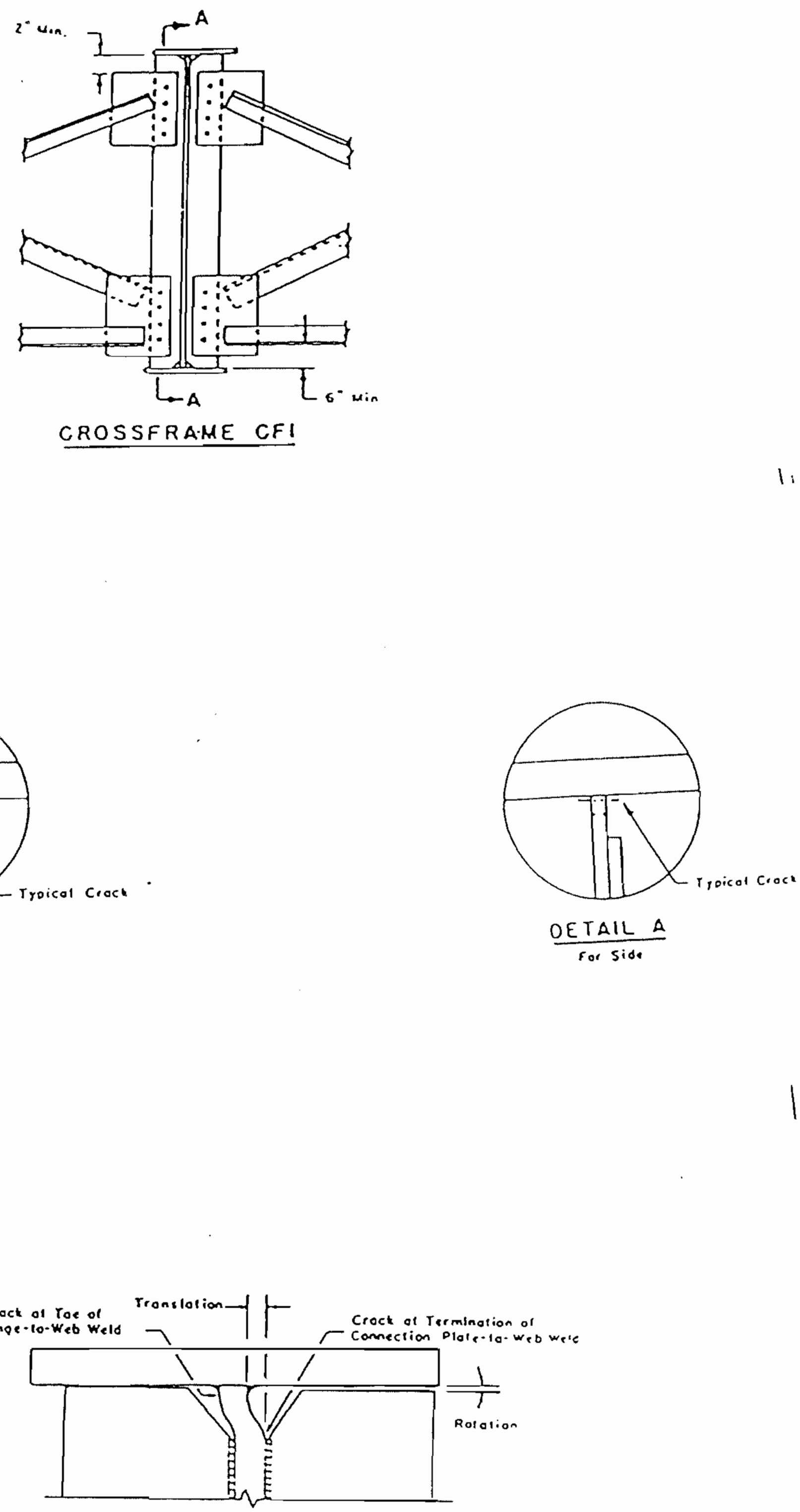



Figure 6. Typical location of web crack at cross-frame diaphragms.

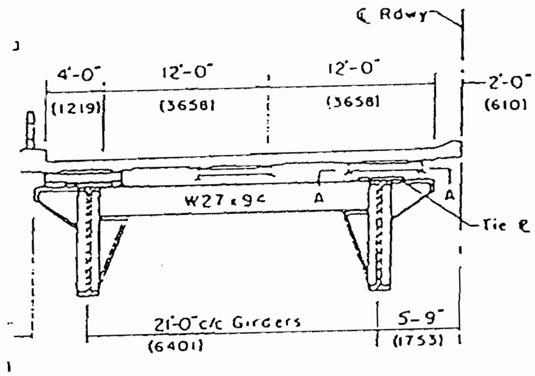



Figure 7. Cross section of bridge.

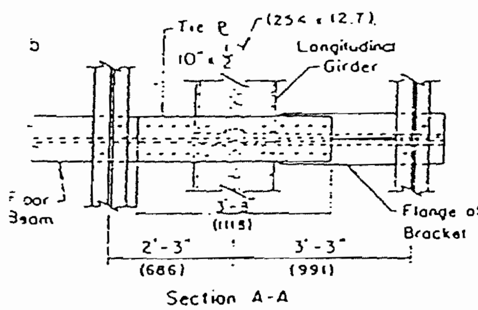



Figure 8. Tie plate detail at the floor-beam bracket connection

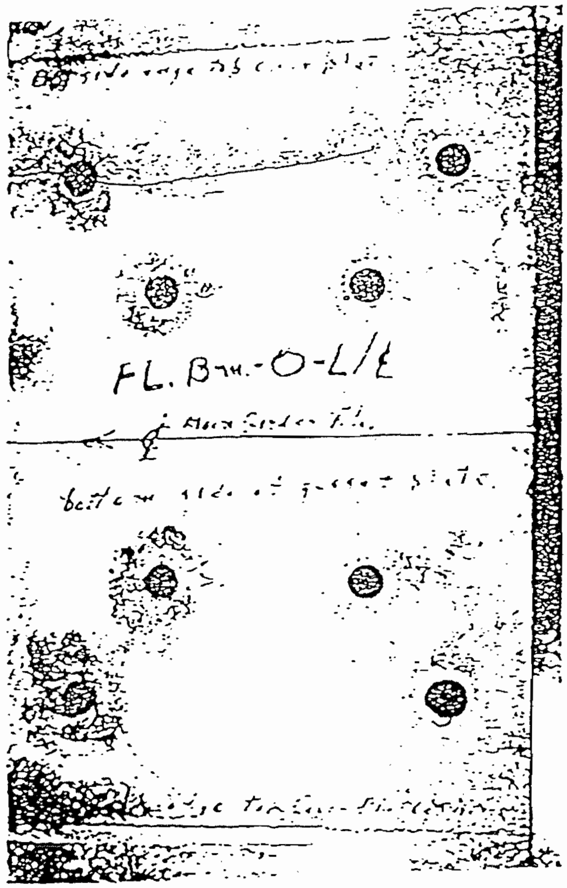


Figure 9. Crack in tie plate originating at a rivet hole.

## 3.0 Identification and Description of Defects in Concrete Bridges

In reinforced and prestressed bridges, the structural defects are often clearly apparent due to corrosion of the steel and subsequent spalling of the concrete.

### 3.1 Reinforced concrete bridges.

The principal reasons for the appearance of defects in many concrete bridges are the following:

- •Wear and tear due to age;
- •Greater traffic density;
- •Steadily rising loadings;
- •Traffic accidents;
- •Intensely injurious environmental influences, such as carbon dioxide and sulfur dioxide;
- •Usage of road salt for several years;
- •Temperature and shrinkage effects;
- •Defective concrete cover;
- •Inhomogeneous internal structure and porosity of concrete in various locations;
- •Possible errors in planning and/or execution;
- •Lack of maintenance work;

The defects in the concrete bridges can appear in several locations as described below:

- •Longitudinal cracks due to load and/or restraint in bridges can appear in the carriage way slabs, the span and support areas of slab bridges;
- •Cracks in the webs, sometimes extending through the full depth of the web and in the bottom slab. Causes can be temperature and shrinkage effects as well as additional stresses which can arise during the different phases of construction;
- •Vertical cracks in the middle of column piers which can be caused by temperature and shrinkage effects together with an unfavorable cross-section;
- •Corrosion of the reinforcement;

- Spalling due to corrosion of the reinforcement especially in the region of hinges and construction joints(Figures 10, and 11);
- Deformation, blisters and cracks in the carriage way surface.
- Damage in the region of the hinges due to leaking expansion joints;
- Damage in the concrete bridge coping due to road salt attack;
- The bridge deck concrete can be penetrated to a depth of several centimeters by chlorides in the region of the defective bridge sealing;
- Color alterations of beams and slabs.

### 3.2 Prestressed concrete bridges.

The principal reasons for the appearance of defects in many prestressed concrete bridges are the following:

- Underestimation of the effects of the redistribution of the hyperstatic reaction by the creep of the concrete, which affects bridges for which the static schema of construction differs from the final schema in-service;
- Neglect of the effects of exposure of the upper side of the deck to sunlight, which produces a temperature gradient in the structure in which strains are restrained, and induces large loadings;
- An actual prestress in the structure that is less than the design estimates (relaxation of tendons underestimated, friction of the cables in their ducts greater than assumed in the design and highly dependent on the quality of the construction work, etc.);
- Excess permanent loads (overlaying of pavements and underestimation of equipment weight, etc.);
- A prestress counted at the full value starting from its anchorage, with no allowance for a diffusion length;
- A deficient participation by the bottom slab because of the cracking cause by the unopposed downward thrust of the continuity cables;
- Internal damage of the structural concrete;
- High chloride content in the concrete and the grout for the transversal prestressing tendons;
- Heavy corrosion in parts of the transversal prestressing tendons.

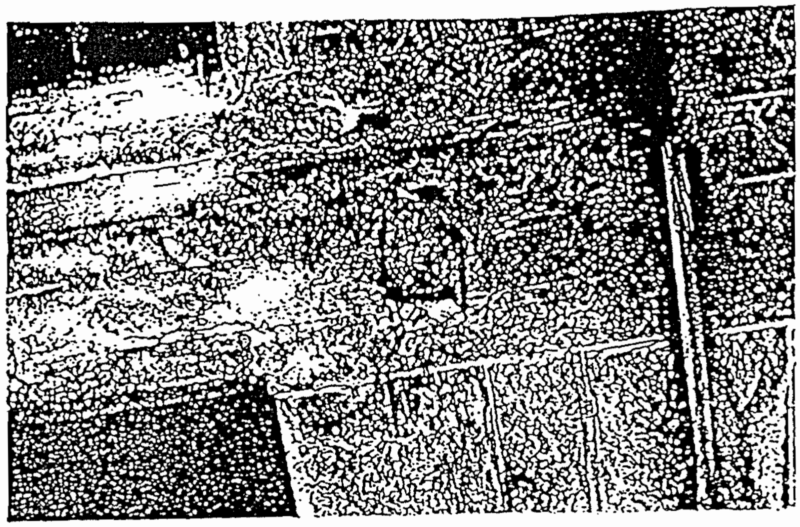


Figure 10. Concrete spalling in the region of hinges (bottom view)

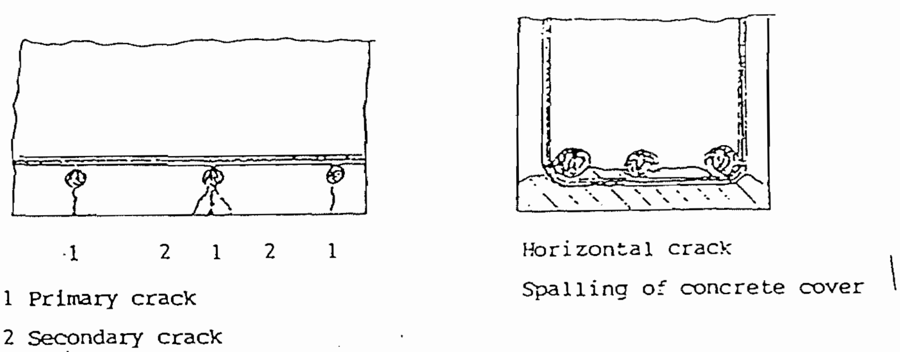



Figure 11. Longitudinal cracks due to steel corrosion

The defects in the concrete prestressed bridges can appear in several locations as described below:

- •Cracks reflecting insufficient bending strength can be found towards the middle of the span and in the *zero moment zones* (Figure 12); In box girders, they most often extend completely across the bottom slab and upward in the webs, where they may be inclined in the vicinity of the bearings, because of the shearing stress (Figure 13); They most often originate from the joints between segments, a zone of reduced strength; they may be quite open at the bottom of the box girders;
- •Cracks can be developed close to the cable anchor points when the passive reinforcements are insufficient (Figures 14 and 15);
- •Down thrust cracking, or longitudinal cracking of the bottom slab in the middle of variable depth spans, caused by transverse bending of the insufficiently reinforced bottom slab by the downward thrust of the curved continuity cables; the wider the box girder, the greater is this bending (Figures 16 and 17);
- •Several cracks can be observed in the diaphragms above the supports in box girders; A lot of cracks can appear on the top of the web's outside and at the bottom of the web's inside (Figure 18);
- •Defects (cracks of the pavement, leakage of the insulation) can be found within the truck lane of the carriage way.

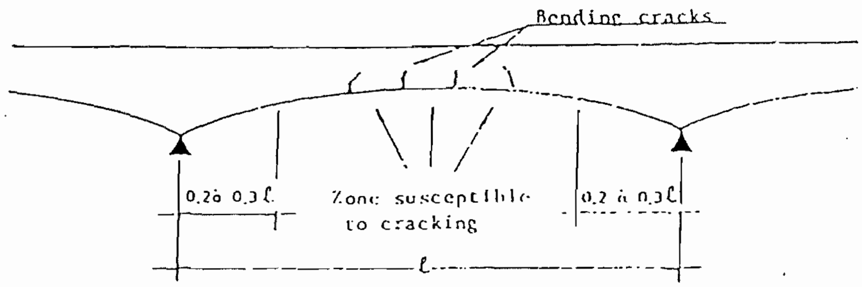



Figure 12. Zone susceptible to bending cracking

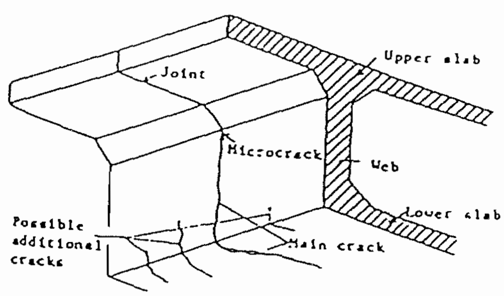



Figure 13. Detail of bending cracks

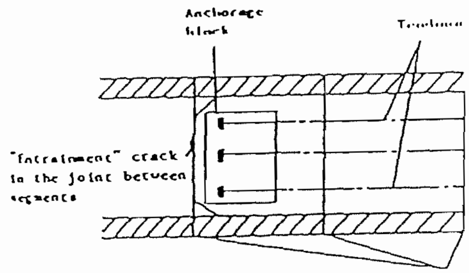



**Figure 14.** Entrainment crack in a slab

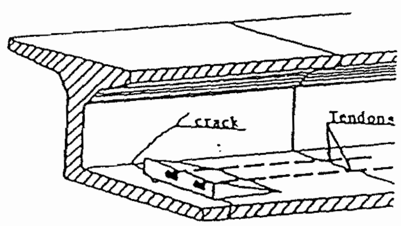



Figure 15. Propagation in the web of a diffusion crack in the slab

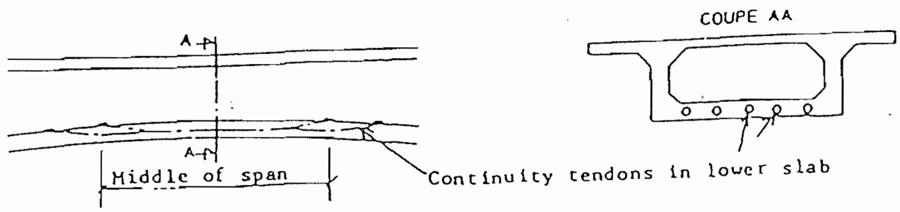



Figure 16. *Down trust* in the middle of a span

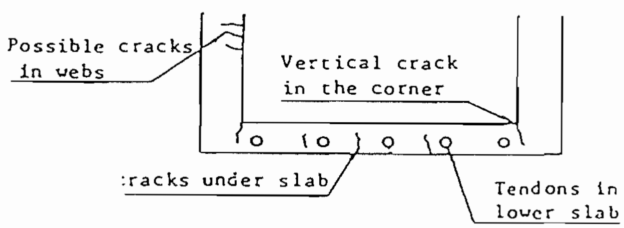



Figure 17. Location of *Down thrust* cracks

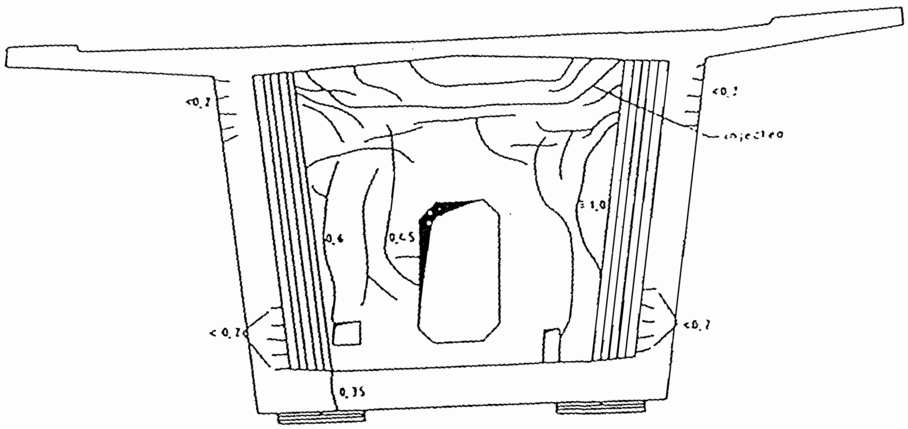



**Figure 18.** Cracks and their width (mm) in the box girder and in the diaphragm

## 4.0 Summary of Most Important Defects in Bridges and Their Location.

In a typical bridge the inspector should look for duress of defects that can have a catastrophic effect on the structure. Defects or indicators of defects can be more critical in certain defined locations.

Any moving or growing cracks in concrete can be considered important. If these cracks are at high stress locations such as near the support or near the middle of a span they can be critical.

Cracks in steel members, particularly welded components, can be serious. All such cracks should be investigated by knowledgeable personnel.

Parts of a structure where reinforcing steel terminates, such as joints or beam column connections in a reinforced concrete structure, can be considered as critical locations and should be closely inspected. Bearing plate attachment locations are probable locations for cracks or other duress.

Any nonredundant member such as a cantilever or corbel has a critical location near its support. These types of members have a maximum moment and shear occurring at the same location. Furthermore, if a maximum moment is reached, that is, the steel yields there is no place for the moment to be redistributed. Therefore, the attachment end of a cantilever or corbel is a critical location.

In prestressed members, a critical area to look for duress is at the termination points of the prestressing steel. Cracks here due to overstress near an anchor can be serious.

Settlement or movement needs to be evaluated as to cause, rate of movement, and potential effect on the structure. Sometimes observation is sufficient, but other times resetting of bearings, stabilization of soil or other corrective action is necessary.

## 5.0 Candidate Sensors for Monitoring of bridges.

There is a need for efficient diagnostic procedures of the current capacity of a structure, for means of monitoring of load and resistance history, and for means to evaluate accumulated damage. Some of the available nondestructive techniques that can be used for the detection of defects in a bridge are reviewed in this Section.

### 5.1 Transducers.

Transducers are devices which transform energy of one type into another.

Abnormalities present in a structure, such as fatigue fractures, breakdown of material, change in material properties or permanent deformation, will cause changes in the flow of acoustical and vibrational energy through the structure. The detection of such acoustic or vibrarional phenomena may be carried out by using various sensors, including accelerometers, velocity transducers, displacement transducers, load cells, strain gauges, and other means.

A set of this type of sensors, located at critical points, could provide information on the response of the structure to various types of loads. Devices mounted on actual bridges, used to monitor the structure over time, could provide information on how the response of critical parts changes as the structure ages. A set of these sensors could share a simple communication network linked to a local or remote computer for data analysis and alerting bridge inspection teams (see Section 7.0 for details).

### 5.2 Ultrasonic Testing.

The propagation of ultrasonic waves is heavily disturbed by inhomogeneities and porosity in the volume of the structure material. Depending on the composition and humidity of materials considered, phase velocities of ultrasonic waves vary between 3-5 km/s. Ultrasonic waves are attenuated by scattering and absorption.

Inhomogeneities and cracks can only be detected if their dimensions are greater than the sampling wavelength; this means that only relatively large defects can be detected.

In general, the sensitivity and capability of the ultrasonic techniques for non destructive testing (NDT) of bricks, stones and concrete is limited. The same holds for testing reinforcing metal bars inside concrete.

## 5.3 Acoustic Emission.

A promising non destructive evaluation (NDE) technique entails the monitoring of acoustic emissions (AE) from bridges and the correlation of these emissions with the integrity of the structural members. However, the user of the AE methodology faces many problems due to the environment, complexity and the size of bridges. The uncertainty of internal defect excitation places even further limitations on the AE technique. However, the main limitation with present AE technology is the ability to relate AE signals to specific source events.

This method uses the effect that acoustic signals are limited in the material during the formation of defects (cracks, debondings, fractures) or during other processes (friction, phase transformation, solidification). When materials are subjected to stresses which cause them to be strained beyond their elastic limit, localized deformations will occur. The occurrence of these deformations in the form of dislocation movement or microcrack growth results in the release of stored strain energy. The release of this energy causes the propagation of rapid elastic waves throughout the material. These elastic waves can be detected as small displacements by sensors placed on the surface of the material.

Decent efforts havem led to development of a microprocessor-based acoustic emission monitoring system that can detect, locate and characterize flaws in welds during the welding process.

The welding environment is a very difficult area for application of acoustic emission monitoring due to the extremely high ambient acoustic noise levels present. These high noise levels preclude the application of conventional acoustic emission monitoring techniques because of the high level of AE signals that result from benign or non-flaw related sources.

The problem of detection of flaw-related-AE that is masked by a high noise background is not unique to the in-process weld monitoring application. Rather, it is typical of a wide range of potential AE applications, such as the in-service monitoring of bridges for flaw growth.

Unusual load procedures such as heavy proofing loads are not necessary to excite AE activity from a crack which is already experiencing sub-critical growth due to service loading. In-service-AE monitoring of a suspect area for a period of less than four hours should be sufficient to detect fatigue cracks on steel bridges subjected to normal structural loading patterns. Structural discontinuities which are harmless will not generate any AE activity and, therefore, will be below some pre-established threshold for detection.

AE testing, incorporating the equipment and techniques described above, has demonstrated three attributes which make it a desirable NDE method for inspecting structures such as bridges:

a) Good operator productivity.
b) The ability to detect and define bridge defects (cracks).
c) The ability to complement (confirm) other NDE methods.

## 5.4 Magnetic Testing.

Magnetic testing methods are mainly used to detect the position of reinforcement steel bars in the concrete. The maximum of the voltage amplitude as a function of the transducer's position indicates the local position of the steel bar in a projection at the surface.

## 5.5 Microwave Imaging System.

A microwave imaging system (so-called "microwave camera") for NDT has been developed. Using frequency ranging, and measuring the microwave backscattered field, this system allows the obtaining of mappings (topographic images) of concrete structures under investigation and to detect the presence of rebars. The original technique provides fast and accurate measurement of the microwave scattered field at different discrete frequencies. The imaging algorithms used to form the images allow the display of pseudo-color images within a few minutes with a microcomputer.

## 5.6 X- or Gamma rays.

These methods are slow (except for the radioscopic technique) but, above all, very burdensome, heavy to handle, and require qualified personnel. Moreover, it is absolutely essential to have access to both sides of the investigated structure (measurement by transmission).

## 5.7 Copper Wire Sensors.

Several sensors have been developed for the monitoring of the prestressing elements and the stress/strain behavior of the concrete.

The application of strain gauges on the prestressing steel or the measurement of the prestressing forces with the aid of load cells is not possible in the case of prestressing with post-bond. Moreover, it is not a durable solution in case of prestressing without bond.

To control prestressing elements made of glass fiber reinforced polymer rods during their service life, copper wire sensors can be integrated into the rods. By measuring the electrical capacitance and pulse echo sequences it is possible to analyze the integrity, the state of elongation and local water penetration into the environment of the elements.

The integrity of all prestressing rods can be verified during the service life of the construction, while with the conventional prestressing steel reinforcement it is known to be possible only in special cases.

Using copper wire sensors, several items of information can be gained from the permanent soil anchor on the condition of inaccessible parts of the structure in its prestressed, grated state:

a) Faults and rod cracks can be accurately located
b) Elongation can be measured and
c) Local water penetration in the jacket tube can be registered.

The capacitance of the integrated wire and/or the timing of electrical pulses is measured. The fiberglass/resin mix between the wires is a dielectric and thus raises the capacitance relative to air (or vacuum) by a factor of e=5. The capacitance is also proportional to the length of the wires. This means that when the rod stretches as a result of loads acting on the structure, the copper wires will go through the same deformation and the measured capacitances will represent a measure of the elongation.

Besides the monitoring of the prestressing elements, the observation of the stress/strain behavior of the concrete in the zone subject to tensile forces is very important. Therefore, the tensile zone above the piers and the spans must be monitored permanently.

## 5.8 Fiber Optic Sensors.

Fiber optic sensors offer a number of advantages including: high-bandwidth, immunity to electromagnetic interference (EMI), the capability of multiplexing several transducers on a single line, the ability to be embedded inside the concrete and geotechnical structures, and (in certain configurations) measuring spatially distributed quantities.

One of the first application of fiber optic sensing technology to bridge structures was to use a microbend sensor to monitor the tension in a concrete post-tensioning cable. Microbend sensors are based on the principle that light is attenuated when propagated through an optical fiber that has been bent through a tight radius. The cable tension transducer operates by using a fiber optic spiral wrapped with the tension carrying strand. As the tension is increased the spiral wrappings tighten and restrict the flow of light through the fiber. When the post tensioning strand looses tension, light flows through the fiber and can be detected. Microbend sensors are relatively easy to manufacture, and are inexpensive since they require only a simple light source, such as an light emitting diode (LED), a microbend mechanism, and a photodetector. They are also relatively reliable. One of the biggest drawbacks are that they are usually intensity-based or amplitude modulated(AM)-type devices. The signal from the transducer is the intensity of light that is detected by the photodetector. The light intensity can be modulated by factors other than by the microbend sensor, such as by fiber or connector faults. (See, however, Section 8.0 for a technique which measures light intensity DIFFERENTIALLY, hence overcomes these drawbacks.)

Another mechanical transducer that is based on the principle of modulating the amount of light transmitted is a fiber optic crack detector. If an embedded fiber is tightly bound to the concrete, it will crack at a location near to a crack in the concrete. The two ends of the cracked fiber will separate with the crack in the concrete, thereby reducing light transmission. This can be used to indicate the presence of cracks in fibers.

The location of a crack in a fiber can be detected by optical time domain reflectometer (OTDR) techniques. The OTDR technique works by launching a short pulse of light down an optical fiber. The light pulse interacts with junctions, breaks, discontinuities, and inhomogeneities in the fiber be reflecting a portion backwards down the fiber. The time of arrival of these echo pulses can be used to detect and locate discontinuitiesin a fiber due to either connectors, cracks, splices, defects, etc.

Fiber optic chemical sensors can be constructed by taking advantage of changes in optical properties of media induced by the presence of chemical constituents. Several different techniques have been employed for sensing the presence of chemicals. Of particular interest are the techniques that can be used to detect the presence of ions, since they are often the precursors or byproducts of corrosion processes. The presence of ions is often detected using a fluorescence technique where a chemical is bound to the fiber surface that selectively interacts with a specific ion and becomes fluorescent. High-powered laser light is sent down a fiber and the fluorescent glow is transmitted back, usually on a different fiber, and the level of ion concentration can be ascertained. Point or distributed sensors can be utilized, depending upon the geometric configuration.

There is extensive work in this technical area on-going in Universities, Government Laboratories, and Industrial Laboratories (Refs 32 to 36).

However, most of this effort is not applicable to the theme of this contract because (a) it does not involve unattended sensors, (b) requires a benign, laboratory environment, (c) is not real time, (d) the sensors are not compact and energy efficient, (e) the sensors or sensor suites do not measure and monitor the characteristics determined to be important in this survey (Sections 2.0, 3.0, 8.0), and (f) the sensors do not lend themselves to sensor fusion (which is required to assure high probability of detection of a defect together with a low false alarm rate).

## 5.9 Magneto-Optic Imaging (MOI)

Defects and cracks may lead to discontinuities which may be detectable as variations in a polarization image of a surface. The scheme requires the illumination of a surface by polarized light and the detection of the reflected light by means of a polarization sensitive camera. These observations can be carried out with a specially prepared video camera (Ref. 31). The surface may have to be prepared (e.g., the paint scraped off) since the depth of sensitivity is limited.

## 5.10 Photogrammetric Sensors

Photographic techniques may be used where the cause and effect take place over many events extending over a long period of time. This is the case, for example, where barges on a river hit and displace bridge supports over an extended period of time. The analysis of these data may well need take place in a laboratory environment (Ref. 27). These techniques are also important when large displacements are involved.

## 5.11 Image Enhancement

Visual inspection techniques, whether they are sensing contrast changes in video images or polarization changes in magneto-optic images (both due to the causes and effects of cracks), can be better evaluated by using signal processing which gives image enhancement. Such generic techniques are being explored by CALTRANS at the New Technology Development Program (Ref. 41).

## 5.12 Power-by-Light

Some sensor candidates can operate at voltages less than 27V and at power dissipation of less than 1W. Such sensors, and their associated signal processing, are candidates for power-by-light (Refs. 37 and 38).

## 5.13 Distribution and Multiplexing of Multiple Sensors

We envision the requirement of multiple sensors and sensor clusters on a particular bridge. We envision that these sensors need to be polled and that their data would be fused and processed prior to transmitting the processed data to the bridge inspection command post. This requires that the sensor type and sensor cluster location on the bridge be distinguishable. The sensor distinction and localization can be effected by means of wavelength division multiplexing, time division multiplexing, or code division multiplexing (Refs 35, 39, and 40).

We anticipate that the processed data will be transmitted by means of copper, fiber, or cellular telephone means. This means that the transmission media will be bandwidth limited, and bandwidth compression techniques will have to be included in the global strategy for bridge inspection.

## 5.14 Summary of Sensor Considerations

All of the above data will be considered in Sections 6.0, 7.0, and 9.0 when we make sensor, communication, and follow-on research recommendations.

# 6.0 Applicable Optical Sensor Concepts Including POWER BY LIGHT

In this Section we will summarize the findings on bridge defect causes and effects, then we will identify the sensor concepts which are applicable for monitoring these causes or effects, commenting on whether power-by-light is applicable.

## 6.1 Causes and Effects Summary

Figure 19 shows the cause and effect relationships for steel bridges. We see that the "defect causes" group-into "environment and aging/loads". Correspondingly, the "effects" group-into "corrosion and fatigue". Thus, appropriate sensors are those which monitor these causes and effects.

Figure 20 shows the cause and effect relationships for prestressed concrete bridges. Now the causes group-into "environment, loads/aging, and design problems". Correspondingly, the effects are "corrosion of prestressing tendons; cracks at the carriageway, reduction of tension of the prestressed tendons, cracks in the middle of the span, and downtrust cracking; and cracks at the cable anchor points".

Figure 21 shows the cause and effect relationships for concrete bridges. It shows again that the causes group-into "environment and loads/restraints". The corresponding effects are grouped-into "cracks in webs and column piers, corrosion, and spalling; and crack in webs and longitudinal cracks".

## 6.2 Sensor Concepts

Figure 22 shows the critical points in a typical bridge that need to be monitored for the causes/effects listed in Subsection 6.1.

The figure shows three categories of sensors:

(a) accelerometers
(b) displacement transducers
(c) strain gauges/photonic (optical or fiber optic) sensors.

Note that the concept of global strategy for bridge inspection requires integrated distributed sensors and processors.

## Steel Bridges

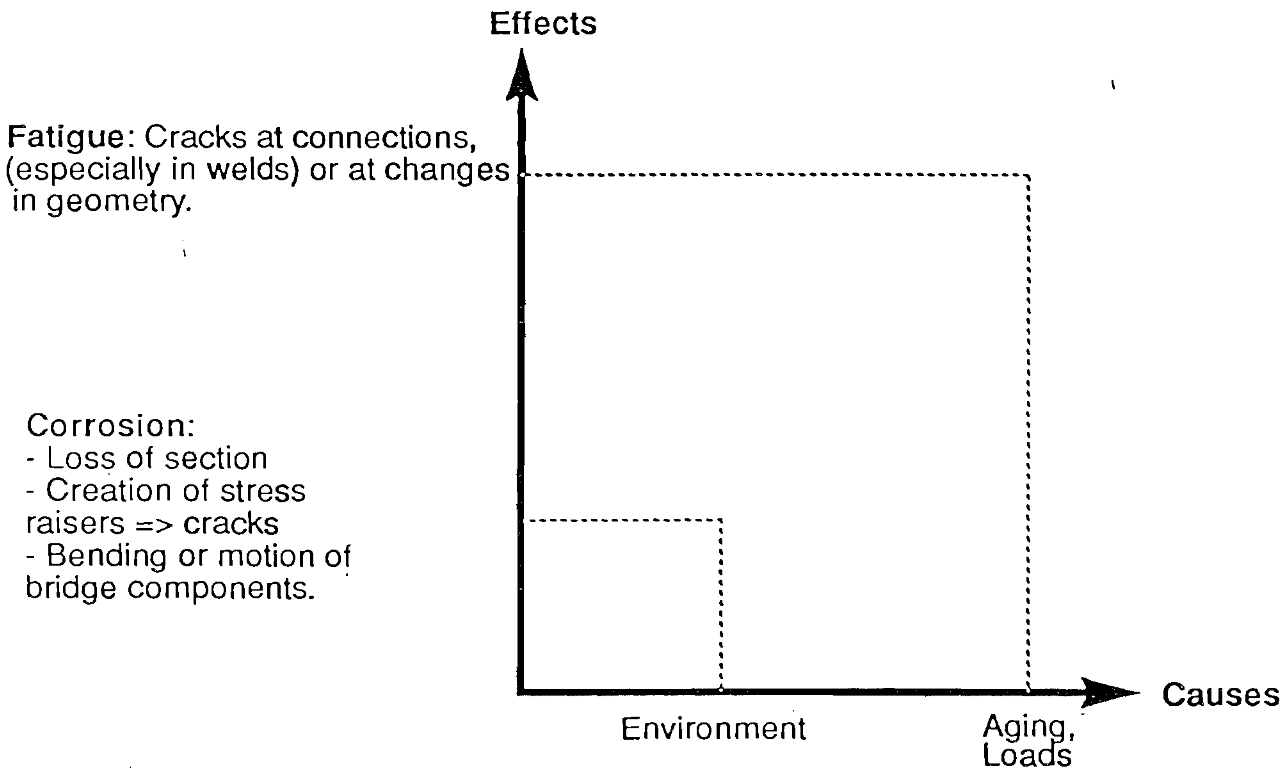



Figure 19. Relationship Between Causes and Effects for Steel Bridges.

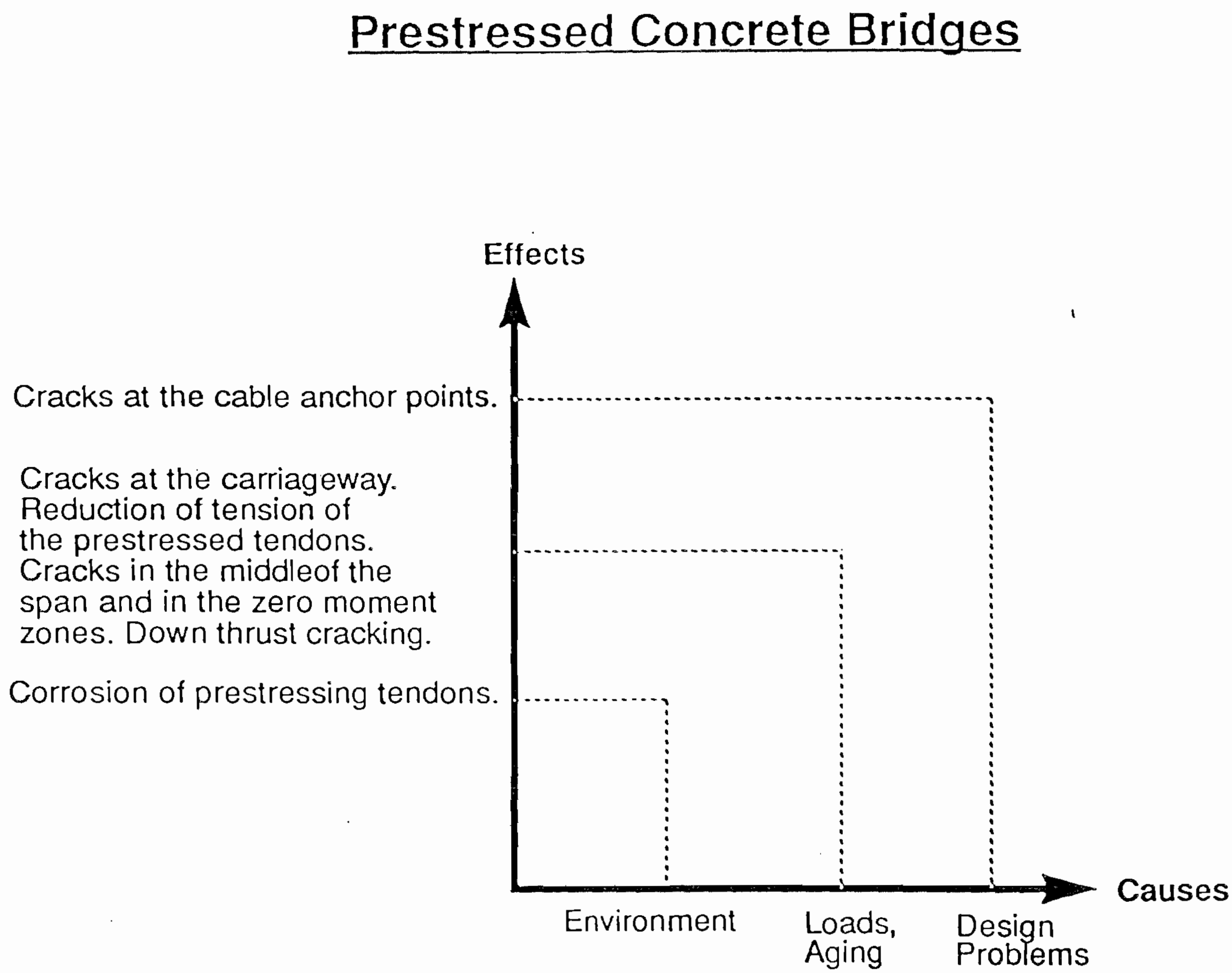



Figure 20. Relationship Between Causes and Effects for Prestressed Concrete Bridges.

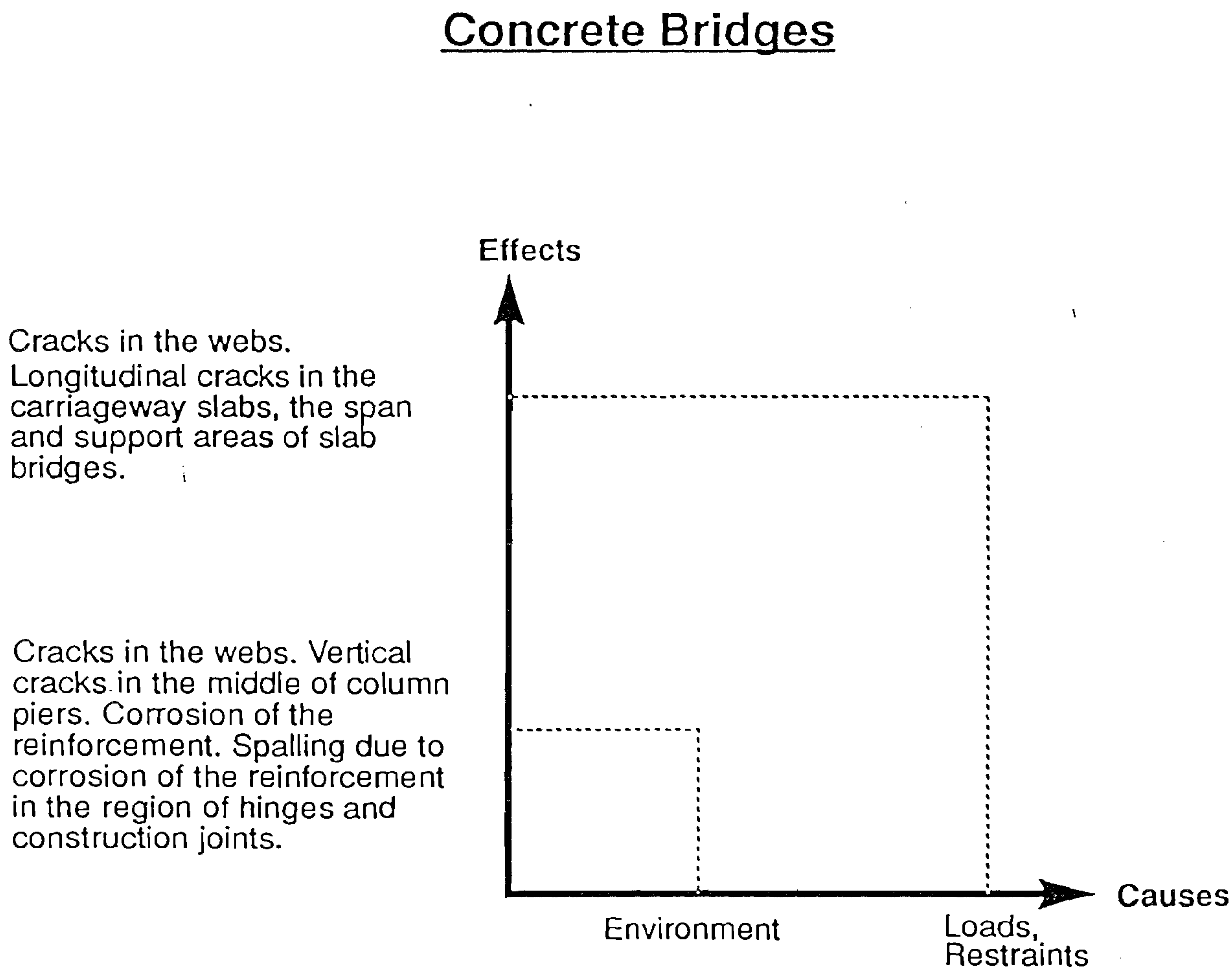
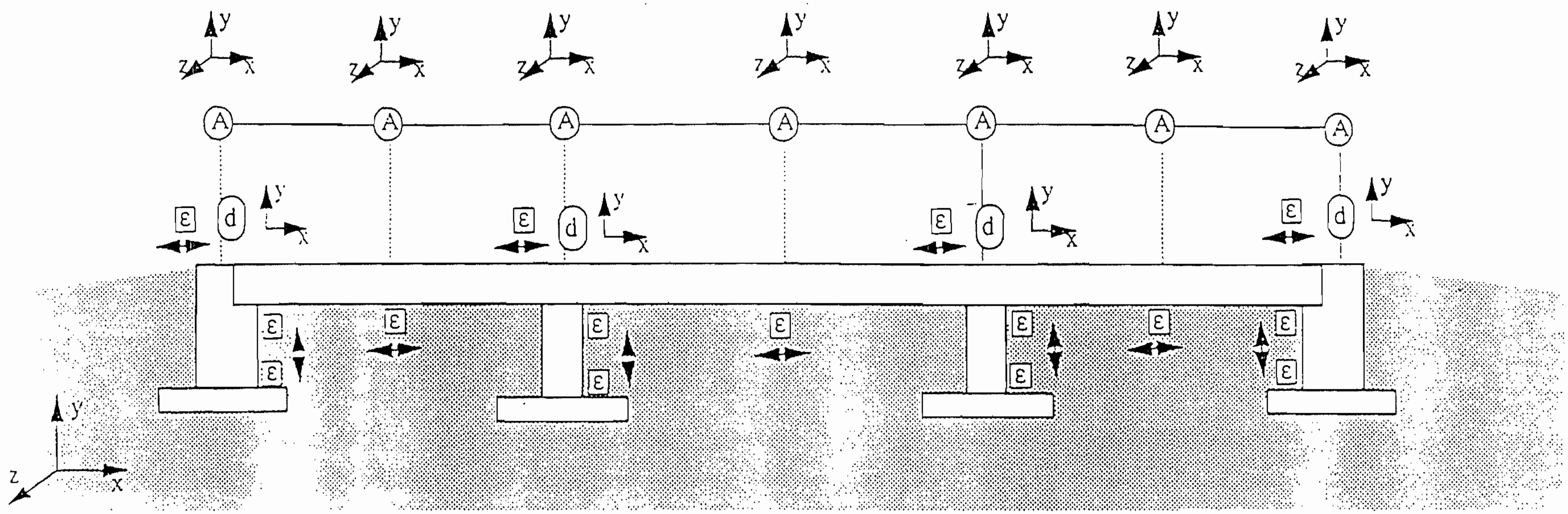
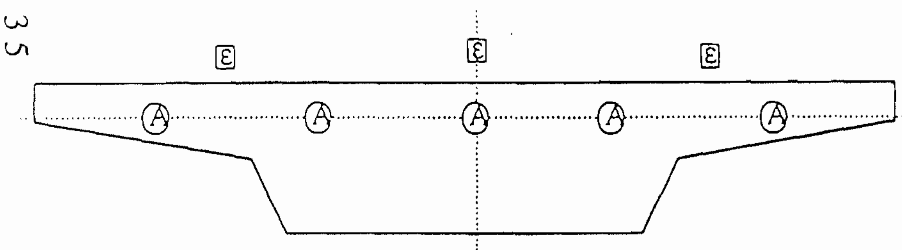


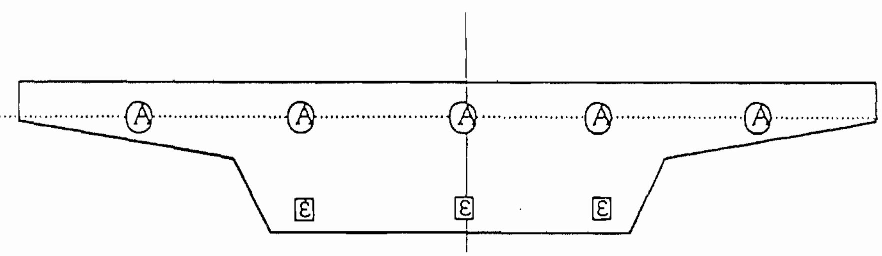

Figure 21. Relationship Between Causes and Effects for Concrete Bridges.



LONGITUDINAL SECTION



CROSS SECTION AT SUPPORTS



CROSS SECTION AT SPANS

Figure 22. Recommanded NDE Sensors and Their Locations on a Bridge.

Notes: In prestressed concrete bridges each tendon should be integrated with optical sensors (strain gages).
In steel bridges optical sensors should be put at connections.
The displacement of the bridge (as a whole) should be monitored.

Ⓐ : accelerometer

ⓓ : displacement transducer

ε : strain gage, optical sensor

Of the three class of sensors, the accelerometers (Ref. 42) and strain gauge/photonic sensors (Refs 32, 33, 34, 36, and 42) may be powered by light (Ref. 37 and 38).

A displacement sensor that is compact, real time, power efficient, unattended, fieldable, and emplaceable on a given bridge or bridge location is NOT DEFINED AT THIS TIME.

## 6.3 Recommendations

The above emplacements and recommendation are compatible with those stated by Nickerson (Ref. 43) and Stolarski (Ref. 44). Our recommendations go further in that they remove the man from the loop, thus allowing more extensive, more complete, and more continuous coverage of critical structures.

# 7.0 Sensor Data Retrieval

## 7.1 Introduction

Data generated from sensors embedded on bridges or structures must be accurately retrieved and delivered to a specific destination. At this location the data can then be manually observed, recorded, or retransmitted, depending on the system concept. The role of the communication subsystem is to perform this data retrieval, maintaining high reliability while delivering the data as efficiently and cost effectively as possible.

A simplified system block diagram is shown in Figure 23. A set of sensors (Accelerometers, strain gauges, etc.) embedded on or in a structure performs the required monitoring of the structure state. Each sensor, when active, generates data bits at a specified rate to indicate its measurement. The sensors are interconnected to a data retrieval subsystem that forms the basis of the communication operation. The retrieval system combines or multiplexes the sensor data into an integrated data stream can be serially recorded, demultiplexed and processed in parallel, or retransmitted to an external communication link, such as telephone or terrestrial microwave.

The multiplexing format depends on the type of sensors and the monitoring scenario. If each sensor is to be continually monitored in real time, the multiplexing requires some form of data addressing. This addressing permits the individual sensor data to be separated, even though all are simultaneously in operation. The simplest form of data addressing is via direct bit addressing prior to transmission and retrieval. If the sensors can be intermittently polled (either the sensor is periodically turned off or its data is stored and dumped) the data can be time multiplexed and spaced according to a clocking schedule. In this case the data can be packetized and addressed in the packet header. Each sensor would then transmit only at prescribed times.

Research at USC has been focused on the development of fiber optic data retrieval that can operate with multiple sensors in a non synchronous format. This permits multiple sensors to be monitored continually in real time. The bandwidth advantage of the fiber optic communication allows the data of the sensors to be individually addressed, transmitted, and retrieved with relatively simple low cost hardware. In addition, fiber has the advantage over metallic cable of withstanding rusting, weathering, and interference, and is easier to embed than larger diameter cabling.

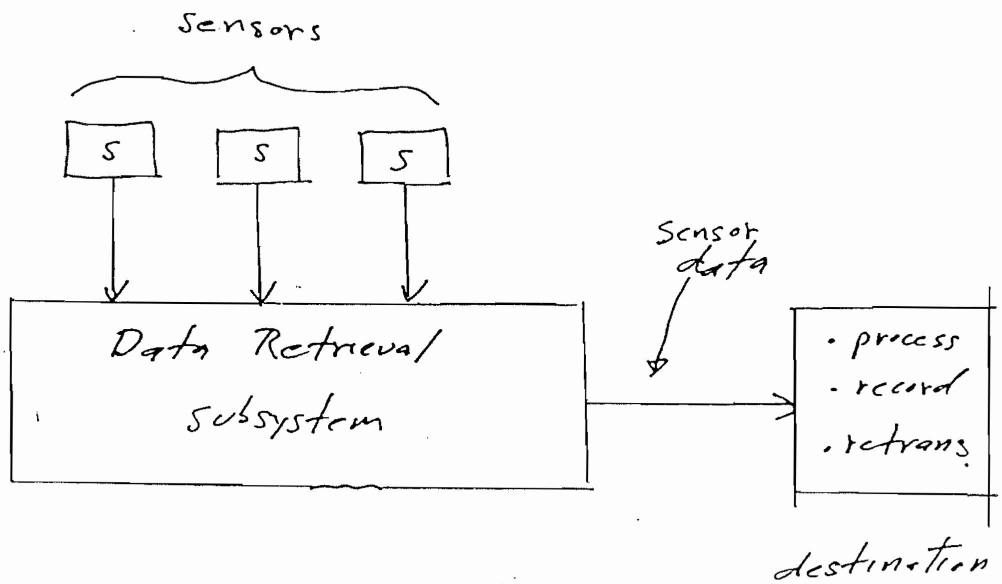



Figure 23. Sensor Data Retrieval System Block Diagram.

## 7.2 Fiber Optic Data Retrieval

In the fiber optic version of data retrieval subsystems, sensor data bits are converted to coded light pulses via an electro-optic converter (Figure 24) that can be directly mounted to the sensor. An interconnecting fiber carries the light pulses to the retrieval system into the destination. Here the light pulses are decoded back to sensor data for subsequent processing. If multiplexing in time or addressing was inserted, the data bits must demultiplexed and serially formatted. The sensor data rates, the number of sensors, and the data accuracy all become important parameters that must be determined in terms of realistic hardware requirements.

Data can be retrieved in a fiber system in any of three basic ways. A bus line system (Figure 25) uses a main fiber line as a pipeline, or roadway, onto which all sensors insert their light pulses. Each sensor simply adds its modulated light fields to the bus, which carries all light to the destination. In a continuous, nonclocked system, all sensor light fields are superimposed, and no attempt is made to separate light until the destination. The bus line is the simplest type link, but has the disadvantage that each sensor light field passes throughout the connectors of all subsequent sensors. Since each connector is inherently loose, the total loss multiplies up rapidly for initial sensors. Thus unequal power distribution over the sensor data becomes a design problem.

In a regenerative bus (Figure 26) the light field in the bus is decoded at each sensor, reformatted with the new sensor data inserted, and retransmitted. Thus each sensor connector contains an optical receiver, baseband processor, and optical transmitter. Regenerative buses are more expensive, but have the advantage of higher power levels due to the retransmission, and uniform power distribution for all sensor data. In addition, data from one sensor can be transferred to another sensor during formatting, if desired. This latter requirement does not appear to be mandatory for the bridge inspection application, and may preclude the necessity to consider this option.

The third type of fiber data retrieval is the star, or combiner, topology, as shown in Figure 27. Here all sensor light fields are carried by separate fiber to a common combining point, where the fields from all fibers are added to a single fiber for transmission to the destination. The system uses excess fiber, but has the advantage of reduced losses and uniform power distributions. Each fiber field undergoes a fixed 1/N los during the combining, which could become significant with many sensors in the system.

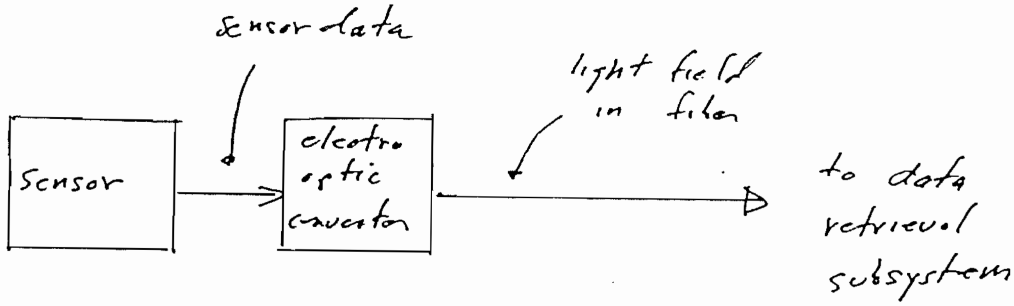



Figure 24. Fiber Optic Data Retrieval Subsystem.

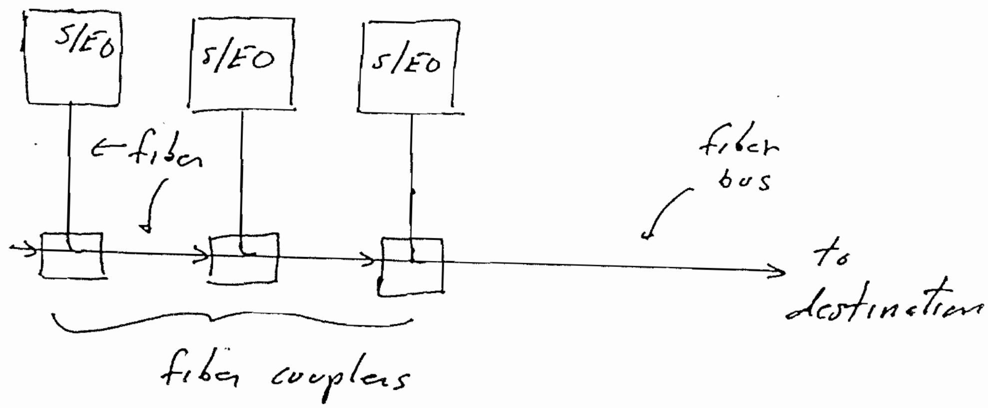



Figure 25. Bus Topology Fiber Optic Data Retrieval.

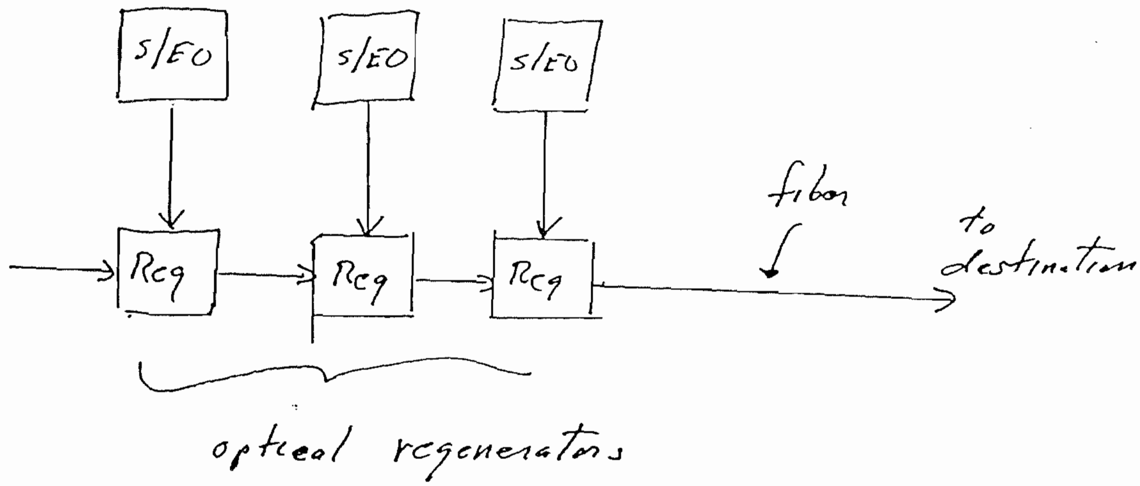



Figure 26. Optical Regenerators or Repeaters Topology and Configuration.

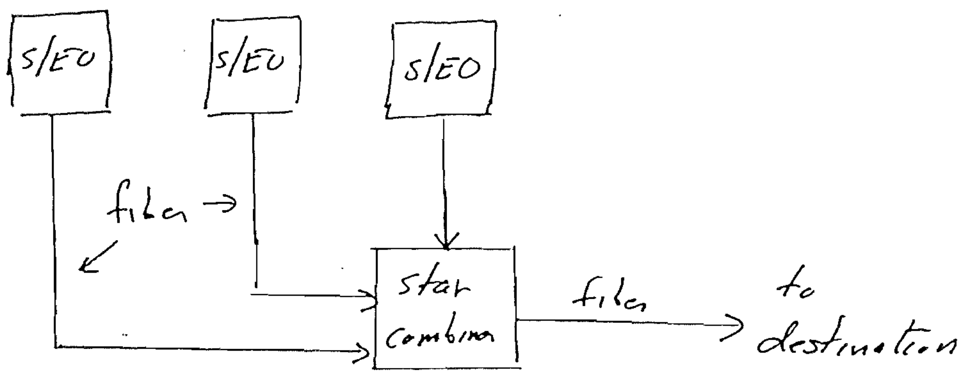



Figure 27. Star or Coupler Topology for Fiber Optic Data Retrieval.

## 7.3 Sensor Data Multiplexing

The data light fields from the individual sensors must be multiplexed to separate and identify at the destination. In a time multiplexed format, each sensor must be externally clocked to transmit in prescribed time intervals. This requires additional circuitry to provide the timing signals. Each sensor bursts its data when polled, so that the overall data rate is much lower than the burst rate. This resulting data rate will decrease as more sensors are added to the clocking cycle. The resulting multiplexed data appears in the fiber at the burst rate for retrieval transmission. Hence the burst rate must be tied to the rate at which data can be handled at the destination.

In an addressed system each sensor data bit is converted into a unique light pulse sequence that can be recognized at the destination. Each sensor separately sends these coded bits independent of all other sensors, using its own code sequence, over the bus or star to the destination. At the destination tuned correlators decode only the bits from a specific sensor, effectively correlating out all other sensor data. Thus each sensor can be individually interrogated, either in serial or parallel formats, to recover the sensor information.

The design of such bit addressing hardware is being pursued at USC, with the objective of developing low cost, simple, power efficient components. The design of the unique coded sequences needed to represent the sensors become a key part of the system design, and has been extensively studied at USC. The code selection is important since it relates the sensor data rate to the optical bandwidths, the data accuracy, and the number of sensors being coded. Figure 28 shows a plot of the achievable number of sensors that can be uniquely coded at a prescribed sensor data rate and optical bandwidth, while data retrieving with the bit error probability shown. This therefore places limits on the size of the sensor network that can be used in this monitoring scheme. We emphasize that this is a sensor limit imposed by the data retrieval subsystem, and not by the physical problems of actually installing the sensors. The matching of the optical fiber hardware to the desired sensor types and monitoring scenarios, using performance curves similar to Figure 28, is a prime objective of this study effort.

It is expected that a key requirement in future bridge monitoring in this manner will be the ability to collect and observe sensor data from a remote location. This implies all multiplexed data must be retransmitted over telephone or terrestrial lines. Such

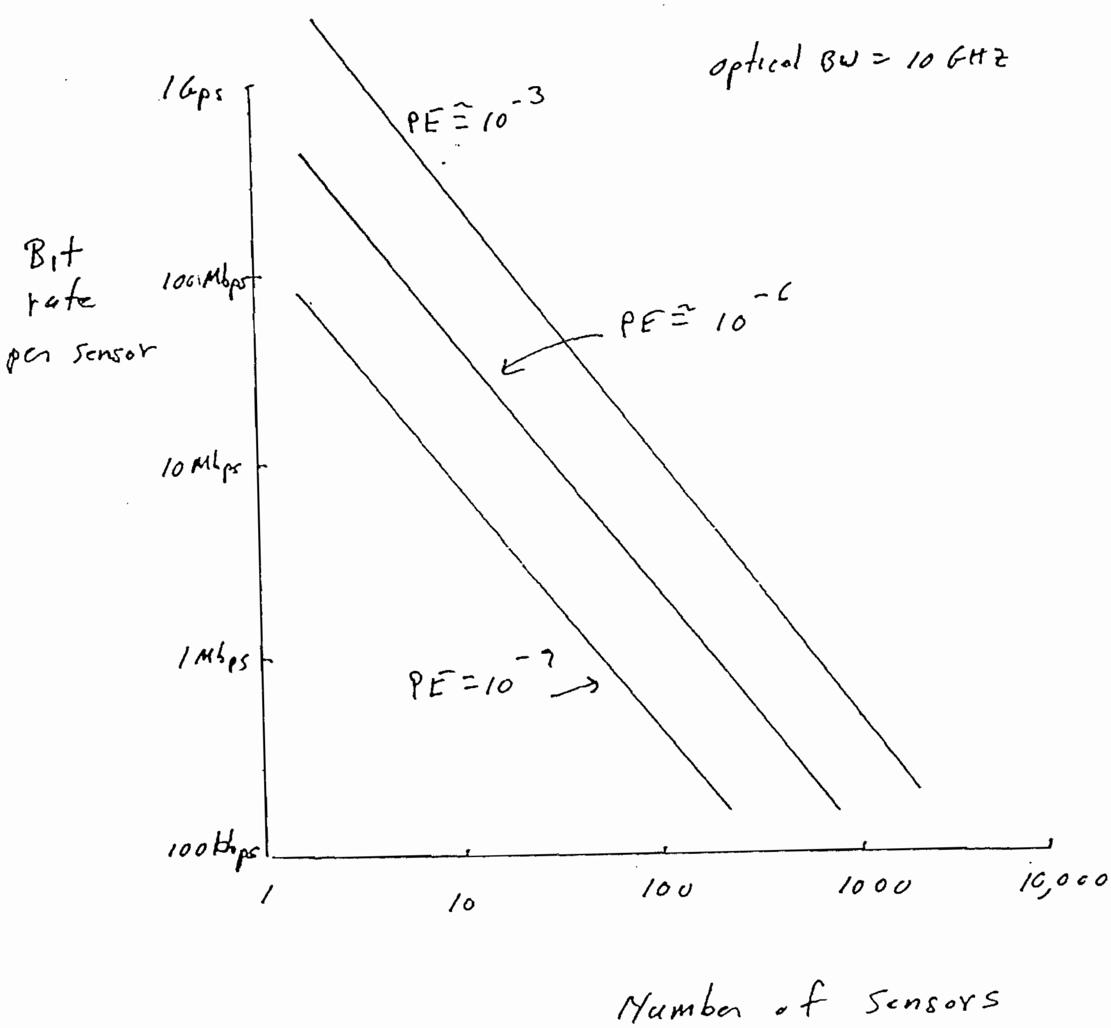



Figure 28. Relationship Among Optical Bandwidth, Number of Sensors, and Their Bit Error Rate.

communication links are inherently limited in their overall data handling capability. Hence the data retrieval constraints must be further folded into the external link requirements. The results of a preliminary study of this effect has produced the results shown in Figure 29. The figure indicates achievable multiplexed data rates produced by data retrieval from sensors using fiber optics with the optical bandwidth shown. The sensor data is retrieved, decoded, then multiplexed into the bit stream at the rate shown. Design curves of this type help to derive hardware parameters and identify possible shortfalls. For example, fiber retrieval of 100 sensors, each producing 2 kbs data, at a bit error accuracy of 10-9 would be converted into a 200 kbs multiplexed rate, and would require an optical bandwidth of about 10 MHz. Scoping the design problem in this way is important to sizing hardware prior to any breadboarding and fabrication.

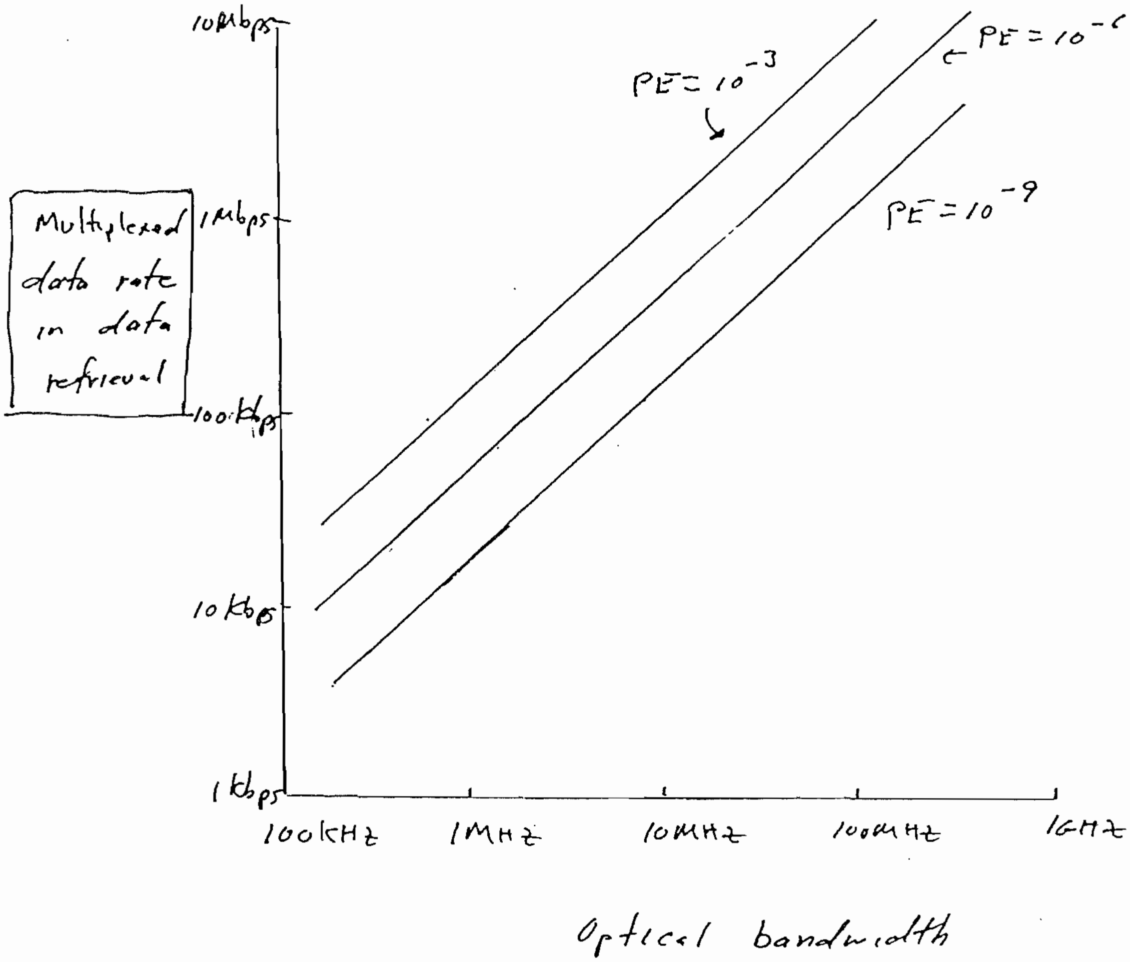



Figure 29: Relationship Between Optical Bandwidth and Multiplexed Data Rate.

# 8.0 An Out Of Plane Bending Sensor Design And Laboratory Demonstration

Our literature survey and discussions with cognizant bridge inspection experts at CALTRANS indicate that OUT-OF-PLANE-BENDING is a critical defect that must be detected. Most sensor aided and visual NDE techniques are inadequate for this detection function, especially at onset of this phenomenon.

In this Section we describe the concept and feasibility demonstration a fiber optic sensor for detecting OUT-of-PLANE BENDING.

## 8.1 Sensor Concept

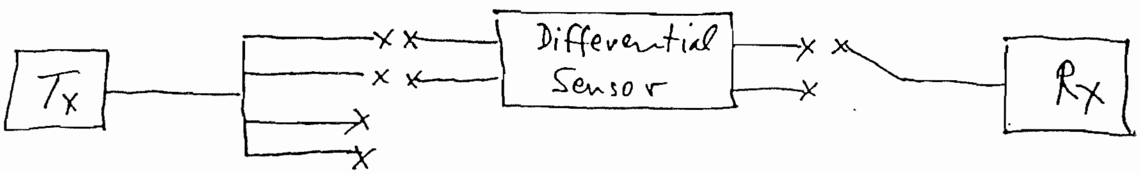
The sensor is based on monitoring the light transmission of a fiber that is subjected to bending. The fiber is sensitized to bending by inducing microbends on the fiber (Ref. 45). The fiber sensor is further sensitized by using a reference fiber for differential detection.

Figure 30 describes the layout of the feasibility demonstration version. A CW laser diode source is split by means of a 1xN coupler (N>2). The output of the coupler is coupled into N Fibers. N-1 fibers have microbends; the reference fiber (number N) does not have microbends. The N fibers are attached to the test plate. The test plate is subjected to varying degrees of bending. The output of the N fibers is monitored by a receiver; the N signals are plotted against bending (or deflection).

In our feasibility demonstration, the test plate consisted of a sandwich of steel plates. The sampling fibers were clamped between the plates with 1mm to 2.5mm pitch screens to generate the microbend pattern on the fibers. The reference fiber was attached to the outside surface of the sandwich. Small C-clamps were used to apply pressure on the fibers and to hold the sandwich together. The configuration is shown in Figures 30 and 31. The 1mm - 2.5mm pitch was selected according to the algorithm in Ref. 45.

Mar 31, 1993

# CALTRANS Out of Plane Bending Sensor




Tx = 3M Photodyne Laser Source 1710 – 0850 – T

Rx = 3M Photodyne Fiber Optic Power Meter Model No. 2285XQ

Differential Sensor

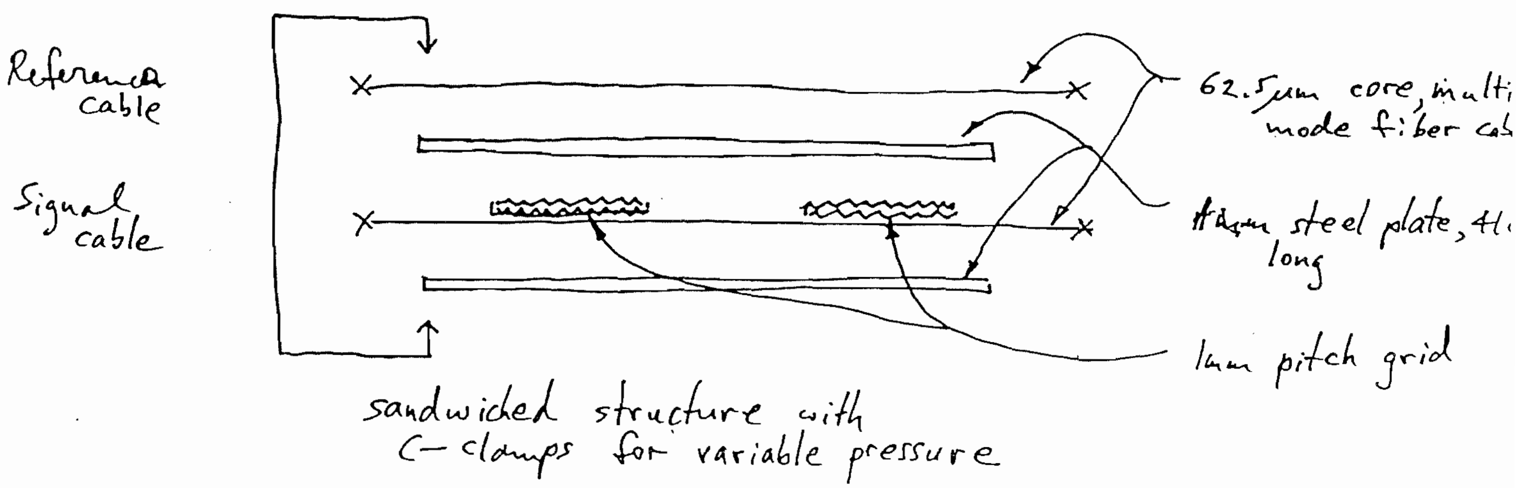



Figure 30. CALTRANS Out of Plane Bending Sensor.

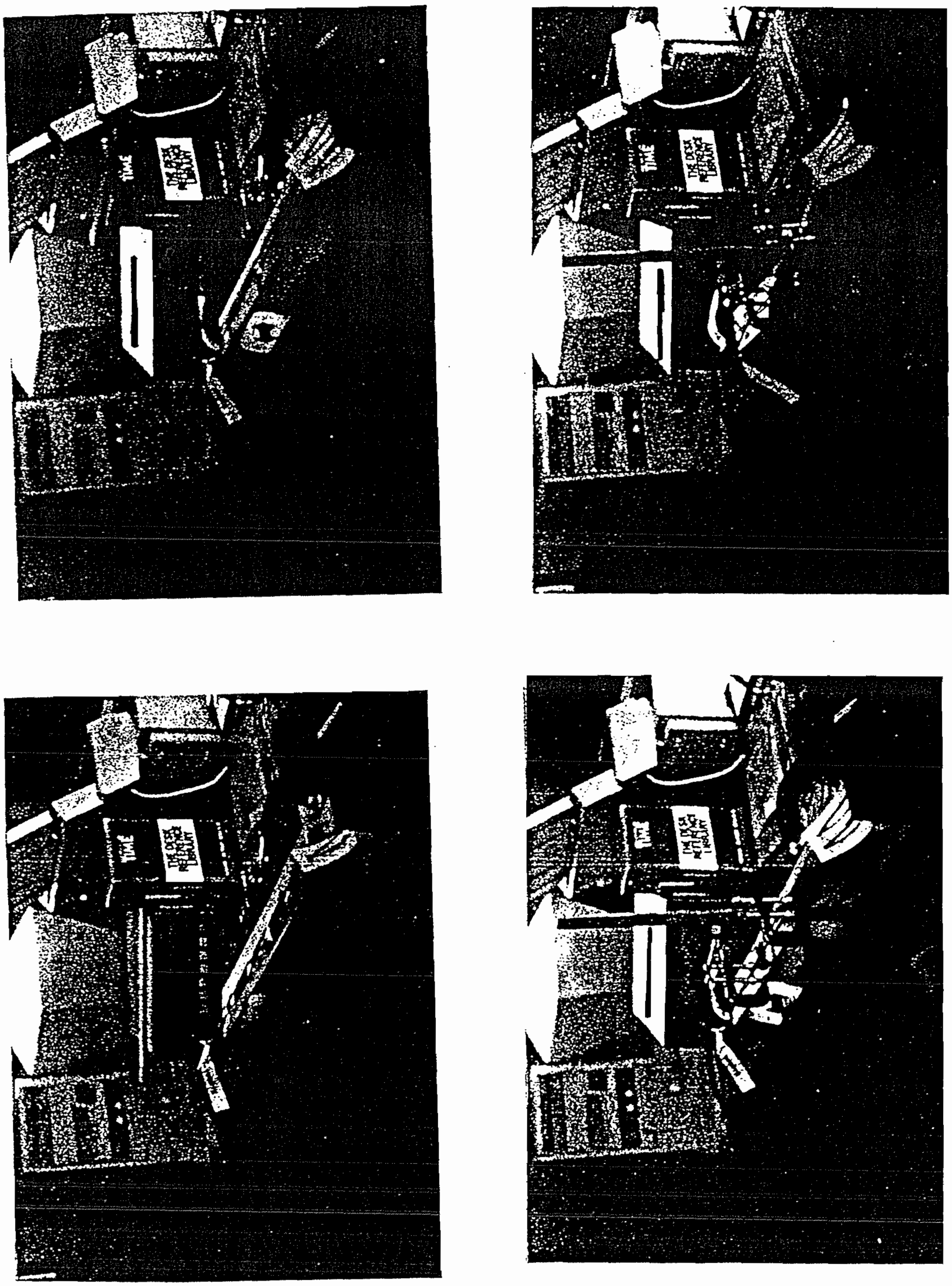


Figure 31. Photograph of the OUT of PLANE BENDING Fiber Optic Feasibility Demonstration Sensor.

## 8.2 Test Plan

Figure 32 shows the experimental arrangement. A force was applied to the sandwich plates which were placed on two pedestals as shown in Figure 31 and 32. At each force level the deflection of the plates is measured, together with the light transmitted by the sampling fiber and the reference fiber. The data are plotted as shown in Figure 32.

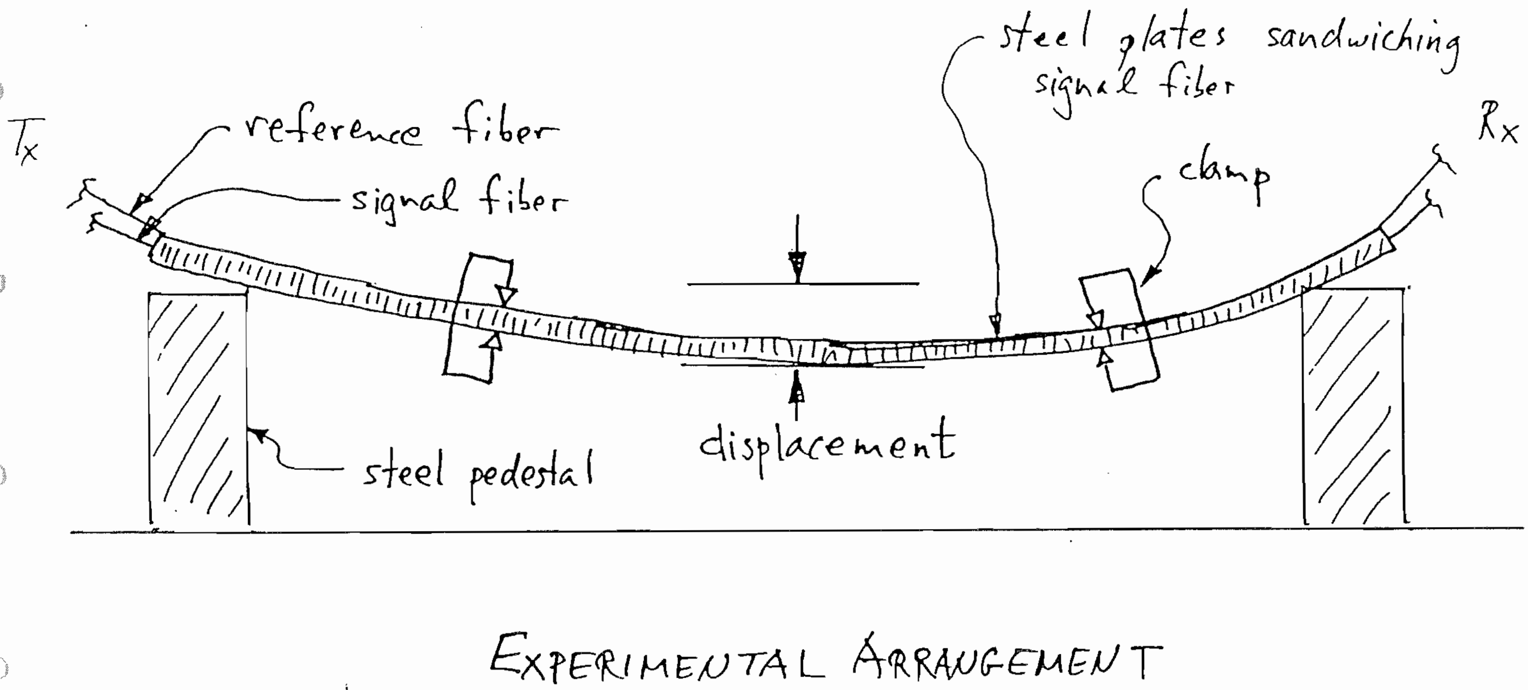
## 8.3 Experimental Results

Measurements were made on the feasibility sensor per the Test Plan. The test runs included measuring light attenuation with

- (a) no pressure on the C-clamps (i.e., no microbending on the fiber),
- (b) 1mm pitch grid straddling the test plate center,
- (c) 1mm pitch grid at the test plate center (midpoint),
- (d) 2.5mm pitch grid at the test plate center, and
- (e) reference fiber, for all cases (a) through (d).

The data are plotted in Figure 33 in the form required by the Test Plan.

We see that the reference arm shows no detectable signal variation as a function of deflection. All sampling fibers show a decreasing signal as a function of deflection. The signal shows some oscillation because we did not use a mode stripper (Ref. 45). The fiber with the grids straddling the center shows the best slope (sensitivity) and least oscillation because the pair of grids act as mode strippers.



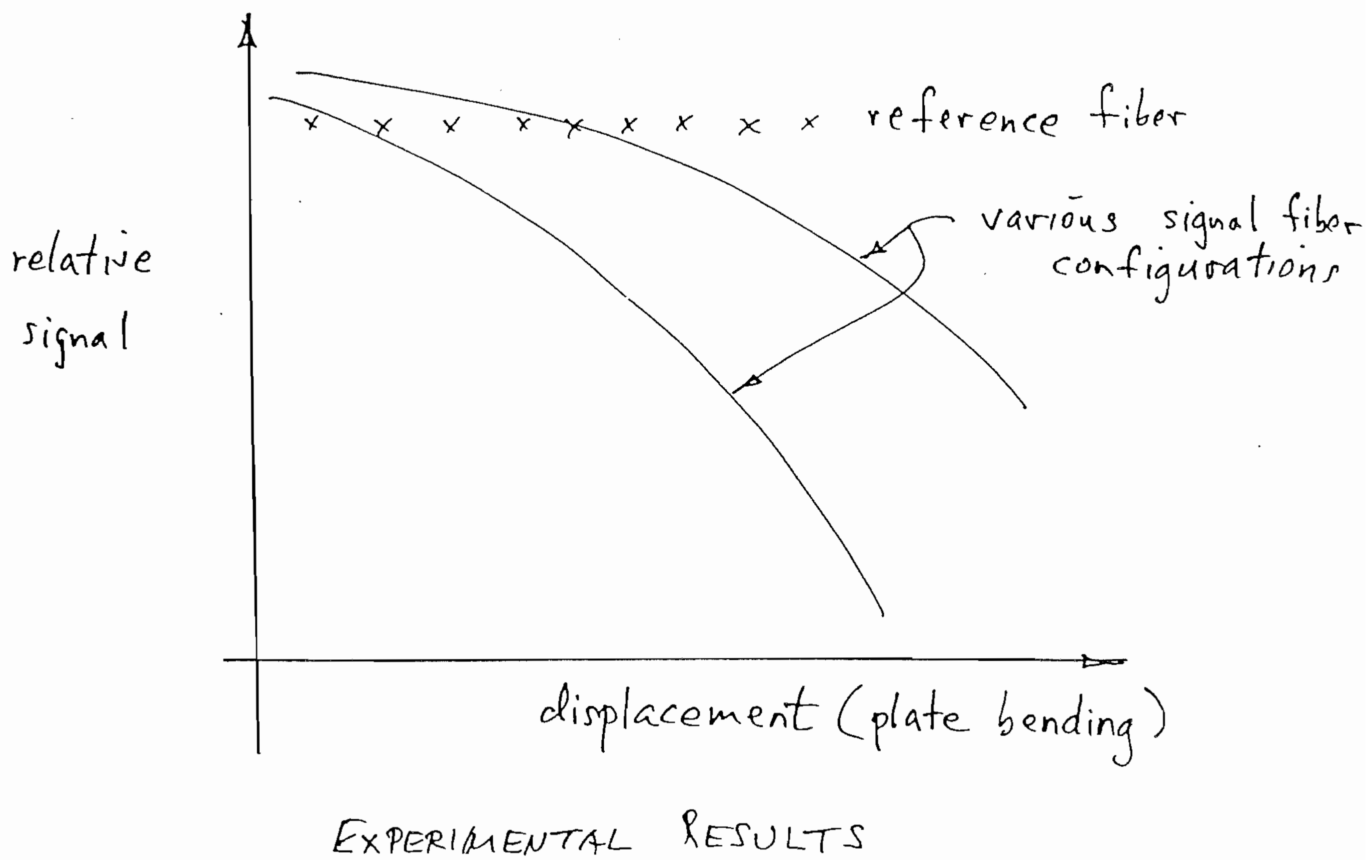




Figure 32. Experimental Arrangement and Anticipated Experimental Results.

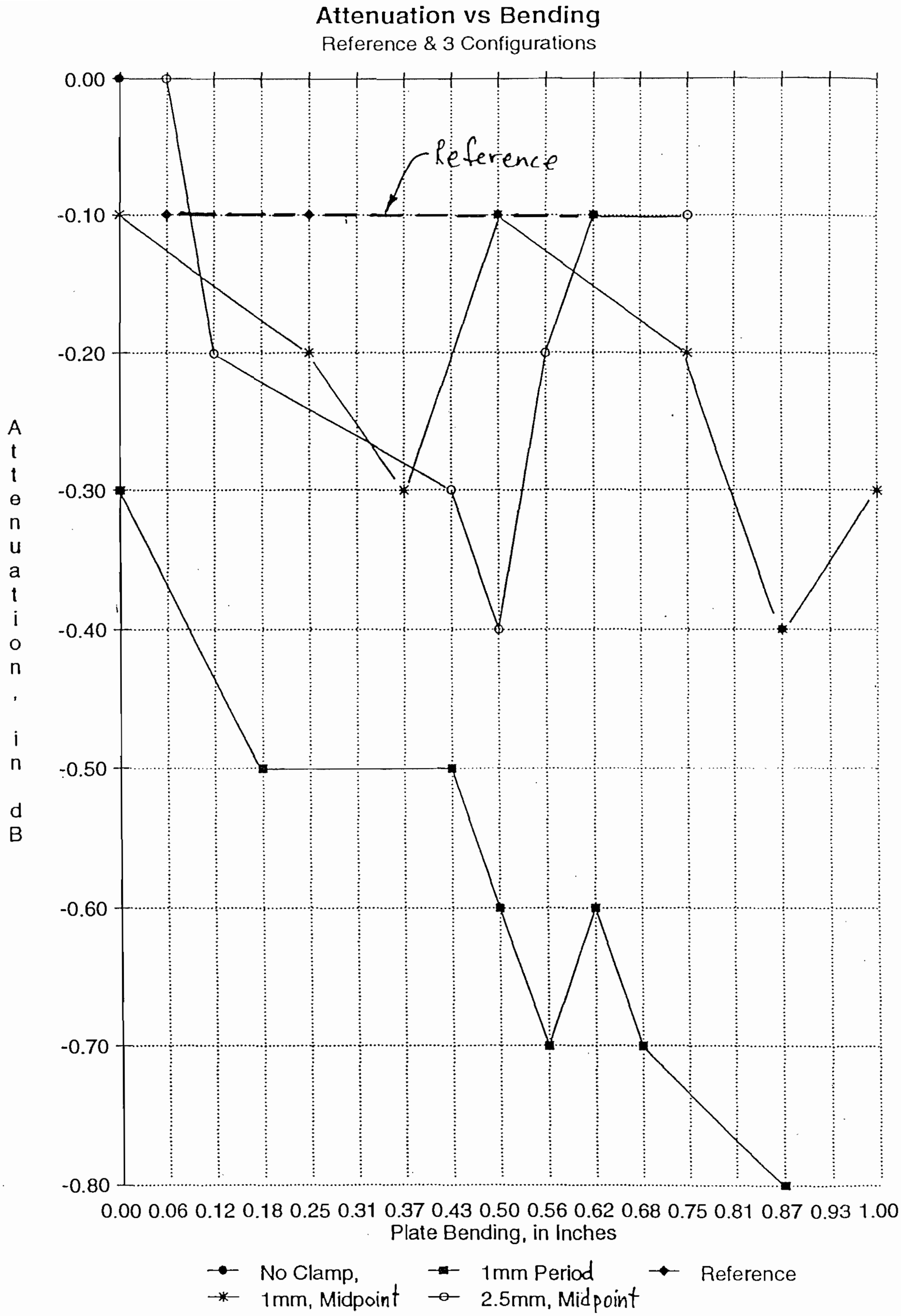



Figure 33. Actual Experimental Results for Three Sensor Configurations.

The signal to noise ratio was very high. The signal change is relatively small, but detecting the reference and sample signals in a differential scheme would provide excellent sensitivity as well as a high signal to noise ratio. The difference signal can be normalized to the sum signal to provide immunity from drifting and aging of the active and passive components.

This kind of differential out of plane sensor is compatible with power by light.

We believe that this demonstration provides a good foundation for developing a refined, updated version in the follow-on phase.

The follow-on phase should include the multisensor package described in Section 6.0:

*A - an accelerometer with power by light
*ε - a fiber optic sensor such as the one described in this Section, with power by light
*D - a displacement sensor, to be defined

# 9.0 Recommendations For a Follow-On-Project

a Proposal for a Follow-on Effort

by

the UNIVERSITY OF SOUTHERN CALIFORNIA

a Planning Purpose Proposal
for
Multi-sensor Development and Testing
for
Continuous, In-situ, Remote Reporting
Non Destructive Bridge Inspection

* a follow on to Contract 32J804-7 *

CALTRANS Project Monitor: Kishore Rao (916) 227*7156
UC Davis Project Monitor: Prof. Steven A. Velinsky (916) 752*4166
USC Principal Investigator: Prof. Antonio J. Mendez (213) 740*4243

April, 1993

PLANNING PURPOSE

PROPOSAL FOR FOLLOW-ON EFFORT

## 9.1 Introduction

This proposal addresses a follow-on effort to CALTRANS Contract 32J804-7. That contract, entitled "Applications of Fiber Optic Communications and Optical Sensor Concepts to Global Strategy for Bridge Inspection Program", performed a literature survey to (1) define bridge damage cause and effects, (2) define multi-sensor concepts to detect the damage in-situ, in real time, non-destructively, and (3) report the measurements to CALTRANS monitoring stations via fiber optic and cellular telephone means.

This contract included a concept demonstration that proved successful and is the core of the proposed follow-on.

## 9.2 Background

The key experiment performed during the initial contract was to demonstrate that out-of-plane bending could be detected by means of a fiber optic sensor. The experiment was successful and is described in this Final Report (Section 8.0).

The experiment was performed using a CW setup. What is required in the follow-on is to carry out the experiments with a sensor with higher sensitivity and also with a larger bandwidth, so that dynamic characteristics can be captured. At the same time, especially because the structural engineers require cause and transfer function data in order to assess damage and determine fixes, it is also required that the follow-on sensor package include an accelerometer. Furthermore, it is required that analysis be performed to establish correlations between the fiber optic and the accelerometer sensors.

## 9.3 Scope of Effort

The follow-on phase should be one year long and shall consist of developing a more sensitive, fiber optic out-of-plane sensor, integrating it with a three axis accelerometer (see Figure 34 captioned "Bridge NDE Sensor Proposed for Follow-On-Effort", attached), installing it in a laboratory shake table capable of

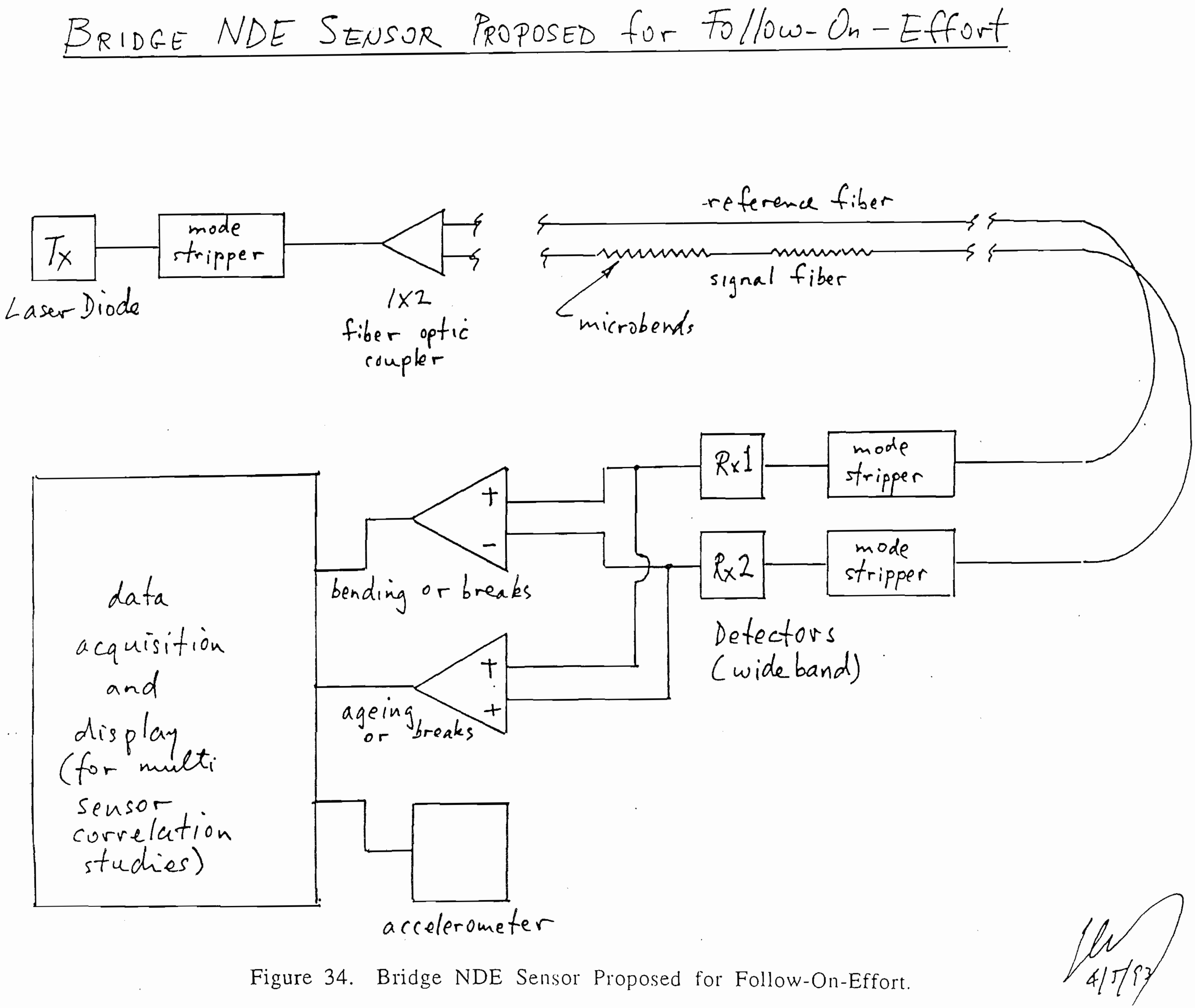



Figure 34. Bridge NDE Sensor Proposed for Follow-On-Effort.

## 9.3 Scope of Effort

The follow-on phase should be one year long and shall consist of developing a more sensitive, fiber optic out-of-plane sensor, integrating it with a three axis accelerometer (see Figure 34 captioned "Bridge NDE Sensor Proposed for Follow-On-Effort", attached), installing it in a laboratory shake table capable of simulating real environment conditions, taking data, developing sensor correlation algorithms, and designing a portable, fieldable version for taking data at real CALTRANS bridges and structures for further refinements of the concepts.

## 9.4 Deliverables

Deliverables shall include quarterly reports, a final report, data, program reviews, and design of a portable, fieldable data acquisition multi-sensor package.

## 9.5 Participants

The USC participants will include:

| | | |
|---|---|---|
| Principal Investigator | - | Prof. Antonio J. Mendez (Electrical Engineering), |
| Co-PIs | - | Prof. Elsa Garmire (Electrical Engineering; Director of the Center for Laser Studies), |
| | - | Prof. Robert M. Gagliardi (Electrical Engineering, Communication Sciences Institute), |
| | - | Prof. Sami Masri (Civil Engineering) |
| Other participants | - | Postgraduate, Graduate, and Undergraduate students (Electrical and Civil Engineering) |

## 9.6 Program Schedule

| TASK | 1Q | 2Q | 3Q | 4Q |
|---|---|---|---|---|
| | Quarters After Go-Ahead | | | |
| 1. Design of refined fiber optic sensor | xxxxxx | | | |
| 2. Procurement of fiber optic components and accelerometer(s) | xxxxxxx | | | |
| 3. Fabrication/assembly/ integration of multi-sensor package | | xxxxxxxx | | |
| 4. Installation/checkout on laboratory set-up | | xxxxxxxxx | | |
| 5. Calibration on laboratory set-up | | | xxxxx | |
| 6. Data acquisition in laboratory set-up | | | xxxxxxxx | |
| 7. Data analysis; development of sensor correlation algorithms | | | xxxxxxxx | |
| 8. Recommendations for follow-on field experiments | | | | xxxxxx |

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