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Long-Term Structural Movement

February 1986

Iowa Department of Transportation

Sponsored by the Iowa Department of Transportation, Highway Division, and the Iowa Highway Research Board

report

Iowa DOT Project HR-275
ERI Project 1795
ISU-ERI-Ames-86205

College of Engineering
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Submitted to
the Highway Division of
the Iowa Department of Transportation
and the Iowa Highway Research Board

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1. INTRODUCTION

1.1. Statement of the Problem

Structural movements may occur over relatively short or long time periods. Directly applied loads such as traffic and wind, as well as daily temperature fluctuations, would be classified as causes of short-term bridge movement. Although detecting these movements may not be an easy task (as is true for obtaining any field information), it is easier and more accurate than detecting movements classified as long term.

Long-term movements may be caused by annual seasonal temperature extremes, which cause thermal expansion and contraction of highway bridges. In addition, any movement that occurs from infrequent disturbances or from unintentional means, such as from navigable river traffic, could be classified as long-term movements since the time between occurrences may be great. Bridge designers recognize the interaction between the substructure and superstructure and have established a range of bridge types that are suitable for specific limits of movement. Depending upon the bridge's span length and construction material, the bridge's tolerance to movement without sustaining structural damage is variable. Studies have indicated the types and magnitudes of movements that most frequently result in structural damage [1].

Measurement of movement associated with bridges must be known in order to determine the effects on the structure. Finding techniques that can accurately obtain long-term movement data is difficult. Field applications using standard laboratory methods have severe limitations for various reasons. In general, a nondrifting electrical reference point is difficult to achieve over a long time period. Harsh environmental conditions can also affect the accuracy of laboratory techniques. The use of mechanical devices is hindered by the difficulty of maintaining a fixed reference point. Recent technological advances have made the use of sophisticated equipment, such as the Navigational Global Positioning System (NGPS), possible. However, the costs associated with such systems are prohibitively large and rule out their common use. Potential measurement systems that are both reliable and cost-effective for field use are needed.

1.2. Background

There are many cases where the need to obtain long-term structural movement data exists. Each situation has to be reviewed carefully to determine any unique problems that may exist. Two specific applications that require attention in Iowa have been recognized and are addressed in this study. Before attempting field applications, a study was performed to address problems that may be associated with field applications and to determine how reliable and accurate data can be obtained.

A case of possible bridge movement related to impact from barge traffic occurred at the Mississippi River Bridge in Lansing, Iowa. Over the past few years these instances of impact have resulted in some visible damage to the main span concrete pier. However, the magnitude of additional pier and bridge damage is unknown.

Long-term structural movement data are also needed for the integral abutment bridge. This type of bridge has been used for short and moderate spans in Iowa and has been used increasingly in other states. The integral abutment eliminates the use of expansion devices, but in so doing piling stresses in the abutments are induced because of displacements caused by temperature changes. Recent studies at Iowa State University [2,3] have found that large lateral abutment movements can reduce the vertical load-carrying capacity of the pile. Before a design technique can be developed, the bridge's amount of movement due to temperature changes needs to be quantified.

1.3. Objective and Scope

This research is the first phase of a proposed two-phase research project. The first phase started with a literature study to determine methods of obtaining long-term structural movement data that have practical application based upon reliability and accuracy. Then the methods were tested in the laboratory to determine both the accuracy that could be attained and their applicability for field use. The results and conclusions of these tests are summarized in this report. Recommendations for specific applications have been made to address the proposed second phase of this study. Methods found to be feasible in the first phase of this project will be used in the field during the second phase.

2. LITERATURE REVIEW

A literature review was made to identify methods that have practical application for measurement of long-term structural movement. The scope of the review was limited to methods that had been applied in conditions identified as occurring over a relatively long time period.

The literature review that follows has been subdivided into three sections: methods related to structural engineering applications, methods related to surveying applications, and a discussion evaluating these various methods relative to the applications outlined in this study.

2.1. Structural Engineering Applications

Although numerous studies relating to the monitoring of structural deformation are available, far fewer exist that are related to long-term structural movement. Methods that involve strain gauges, displacement transducers, dial gauges, and accelerometers (for dynamic application) have been used. In addition, a number of methods involving innovative use of mechanical devices have been employed.

In a study related to temperature-induced movements and stresses in an integral abutment bridge [4], a 450-ft prestressed concrete box beam structure in North Dakota was monitored using slope indicators placed on the bridge piling. The indicators were attached near the top and bottom of the piles, and they measured the slope change between the two pile locations. Piling stresses were monitored with electrical resistance strain gauges that were protected from moisture. Measurements were taken monthly over a one-year period. However, unexpected high water levels caused erratic gauge readings and made the data unusable.

In a California study [5], the longitudinal movement of 12 concrete box girder bridges was monitored using a scratching scribe assembly installed at the abutments. This technique consisted of anchoring a steel rod approximately 40 ft behind the abutment in the approach fill. It was believed that this distance was great enough so that there would be no influence from active abutment movement. The scratching scribe assembly was attached to the other end of the rod and rested on a painted plate located inside the box girder. The rod was enclosed in a plastic pipe placed between the anchorage and scribe assembly. Figure 1 shows the details of the scribe assembly. Problems with this included loose connections and settlement of approach fills that caused deflection of the rods and subsequent raising of the scribes off the plate.

Tilt sensor instrumentation has been utilized to monitor settlement-induced rotations of treatment plant structures. According to a report by Cape [6], sensors were mounted on settling tank sidewalls and the angular change was continuously monitored in able to recognize when excessive tilt occurred. A threshold limit of the equipment was set to activate an alarm when a desired angular change occurred. The continuous monitoring feature of the sensor equipment was an essential feature for this project. The results to date have given no indication of problems with equipment accuracy or reliability.

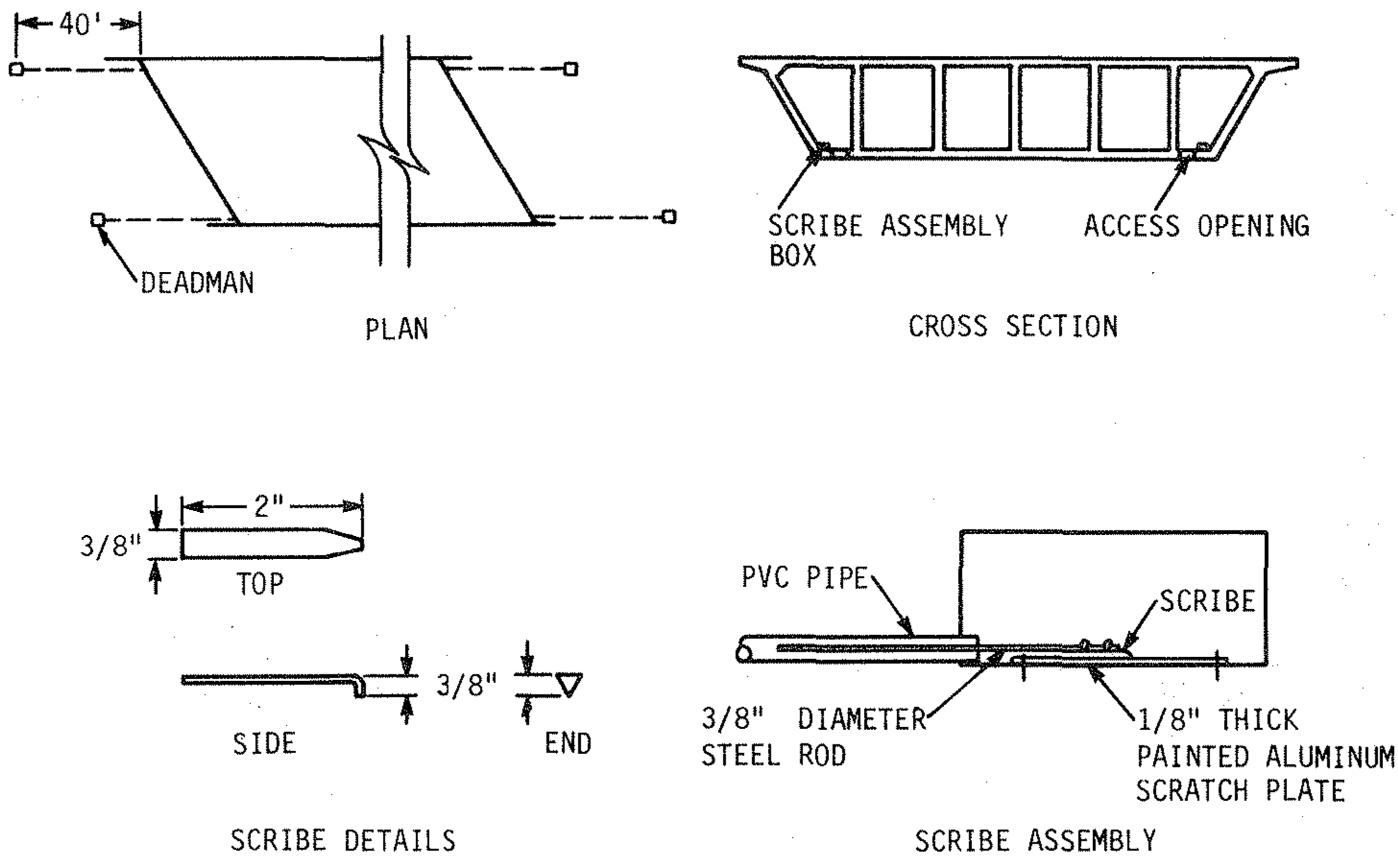


Fig. 1. Detail of assembly used in California study [5] to measure longitudinal movement because of temperature change.

Tilt sensing equipment was used to monitor long-term movements in a study of the Zilwaukee Bridge in Michigan [7]. Sensors were placed on the superstructure, on the bottom of one column, and two sensors were located at right angles to each other at the top of the column. The two sensors on the column top allowed monitoring of both longitudinal and transverse movement. Continuous monitoring took place, and a major data logging system was used to record the sensor data. Temperature-induced movements were recorded by the sensors, but since no temperature data were recorded, only qualitative checks of temperature versus time was used to verify this was the source of the movement. One conclusion of this study was that structural movement can be monitored to a high degree of accuracy using tilt sensing instrumentation. The system data compared closely with data obtained from mechanical measuring devices.

A study by Clarke and Jewell [8] involved monitoring a reinforced concrete reservoir using a number of different types of instrumentation. The reservoir was monitored during construction and periodically over a two-year service period. Both mechanical and vibrating-wire strain gauges were used to measure strains in the concrete. Modified laboratory dial gauges along with surveying levels were used to measure deflection. Conclusions related to the instrumentation were that the measured strains were strongly influenced by humidity changes. From this study the vibrating-wire gauge appears to be a very accurate method for making measurements, but it is sensitive to temperature. It is therefore necessary to measure the gauge temperature accurately. With regard to measured deflections, it was noted that fixed instrumentation was more stable than equipment that was demounted and re-set for each stage of monitoring, as was done with the levels and dial gauges. In general, the accuracy of the instrumentation was such that the results of the tests were questionable.

Over a one-year period Hoffman et al. [9] obtained deflection data on box beams using dial gauges in a study that was performed to address a temperature problem in a prestressed box-girder bridge. Temperature readings were also taken using thermocouples, and the data were correlated with deflection data to give an indication of temperature effects. The deflection data were reduced to obtain curvatures along the beams in order to determine temperature distribution behavior. The dial gauge data were taken on a daily basis with the gauges initialized at the beginning of each day. Since the gauges were reinitialized daily, no information related to long-term accuracy is available.

A study by Shiu [10] also attempted to determine seasonal and diurnal behavior of concrete box-girder bridges by obtaining longitudinal strain data and deflections. Readings were taken seasonally for a period of five years. In addition, four sets of 24-hour continuous readings were taken to monitor diurnal bridge behavior in the different seasons. No information regarding the accuracy of these methods is available.

For a period of six to nine months Burdette and Goodpasture [11] gathered data on temperature, strain, and abutment movement for a continuous, prestressed, concrete box structure with a total length of 2,700 ft. The bridge was made up of 29 spans, and the only provisions made for expansion were at the abutments. Continuous strain data were obtained from weldable strain gauges that were monitored by a Carlson Strain Meter. Longitudinal deflections were obtained using Stevens' Type F (Model 68) water level recorders that were adapted for use in measuring the relative movement between the abutment and selected girders. The recorder provided a continuous record of water level versus time, which was translated into longitudinal movement of the bridge deck. Thermocouples were also installed at various locations to obtain continuous temperature data. However, the only consistent information obtained throughout the entire testing procedure were the data related to abutment movement obtained from the Stevens' recordings. The electrical storms that damaged electrical equipment caused the data obtained by the strain gauges and thermocouples to be unreliable. Strain data were obtained manually after the storms until several gauges unexplicably quit working then all collection of data was terminated.

In a study by Nicu et al. [12], a pile-supported abutment bridge was instrumented to permit deflection measurements to be made. The piles were monitored for approximately nine months during the bridge's construction. A number of techniques were used to determine abutment movement. One method required modifying the piles by welding pipes to them. The pipes served as protection for the instrumentation used to monitor changes in angle of the pile. Aluminum casings were installed inside the pipes and were used with slope inclinometers to determine pile deflections. The piles also were instrumented with strain gauges that were placed just below the pile cap. In addition, several points on the abutments were monitored by surveying methods using a triangulation process. Nicu's study indicated that the strain data obtained were reliable and consistent with the observed behavior of the bridge. The inclinometer gave reasonable results that were in qualitative agreement with strain data. It was noted, however, that by comparison to strain data, the deflection readings were low. Perhaps the discrepency was due to yielding and the possible loss of the sand filling the annular space between the inclinometer guide casing and the protective steel pipe. The surveying results were unusable because permanent monuments used to gain control were accidentally disturbed.

2.2. Surveying Applications

Surveying applications of bridge movement utilize equipment and techniques generally associated with surveying. This may include measurement by steel tape, level instruments, transits or theodolites, electronic distance measuring (EDM) devices, and photogrammetry techniques.

In the North Dakota study mentioned earlier [4], surveying techniques were also used to monitor bridge movement. A steel tape was placed between two permanent markers, and temperatures were taken in order to make corrections. A level was also used to obtain vertical movement data. A level circuit was run nearby to serve as a control. Because the magnitudes of the movements were so small, the data which were obtained were questionable.

Surveying techniques were employed in a study by Hilton [13] using a Wild N-III level and thermocouples to monitor temperature. In the study, long-term camber loss was monitored in the bridges heat-curved girders. The level was mounted on a trivet set in stationary bronze lugs on top of a pier cap. Specially designed scales were installed at various girder locations and were adjusted vertically to intersect the level line of sight. There was excellent agreement between the measured and theoretical dead load girder deflection. Also, at a number of monitored locations, the measured thermal deflections were reasonably close to those calculated.

In 1979, the U.S. Army Corps of Engineers undertook a project to determine the practical and economical potential of using analytical photogrammetry for monitoring structural deformation [14]. The methodology consisted of photographing suspect movement areas at regular intervals and measuring the coordinates of targets. The relative displacement of these targets were then determined by a computation process. A modified Wild BC-4 ballastic camera was used to take the 100% overlap convergent photographs from three to five camera stations. The orientation angles of the photographs were measured by a Wild T4 theodolite and by a striding level. A Wild A-7 autograph was used as a monocomparator to measure the photo coordinates. One conclusion of the study was that for field investigation the base error should not exceed ±0.01m.

Close-range photogrammetry was used to monitor bridge deflection in a study by Bales [15]. Before monitoring bridges in the field, a laboratory test was performed on a test beam. Deflection was measured from metric camera photographs by use of a comparator and was compared to manually obtained measurements. A number of bridges were then monitored using the photogrammetry technique, as well as a leveling procedure, to determine vertical deformations of the girders. Although Bales' study did not consider effects or possible problems associated with long-term measurements, the study concluded that the photogrammetry technique has promise for measuring structural movement. However, the test results related to accuracy and reliability were inconclusive.

The determination of longitudinal displacements due to temperature effects was one task performed in a study by Holowka [16]. Tests were conducted on a 140-ft simple span structure to determine the reactions, strains, and deflections used in an analytical model. The bridge superstructure was composed of two trapezoidal composite steel box girders. Deflections were obtained using a Zeiss level and special level rods attached to the underside of the bridge. Data were obtained both during the performance of a static load test and intermittingly for a three-month period. The measured deflections were smaller than those predicted by the analytical model, which used other data from the tests; however, the trends in the deflections were similar. No conclusions were made regarding the accuracy of the deflections obtained from the surveying technique.

2.3. Evaluation of Methods

With regard to monitoring long-term deflection, the methods reviewed in the literature study appear to have both advantages and disadvantages. The technique's most important requirement is to provide stable or consistent results. Any deviation or instability from an initial reference position may cause significant errors. The ability to obtain continuous data is also a high priority. In most cases a somewhat subjective evaluation had to be made as to the method's applicability for long-term measurement because of limited information regarding accuracy. A discussion of each of the identified methods follows.

2.3.1. Strain Gauges

One major advantage of the strain gauge is the continuous recording capability. The gauges are highly sensitive to member curvature and are relatively inexpensive.

One difficulty with strain gauge use for long-term monitoring is the problem of maintaining stability of the readout signal. Temperature-induced problems for the most part can be overcome by using protective coatings or by using weldable gauges. However, the problem of signal drift from a zero position still exists, and it is difficult to overcome.

Using strain gauges for long-term movement application presents two important problems. The most important is the ability to maintain a stable reference point from which strains can be measured. The second deals with the protection of the gauge from moisture.

Research studies have concluded that electrical resistance strain gauge installations are not stable over an extended period of time [17]. The gauges have a tendency to leak resistance or drift, and therefore they require fixed electrical reference points from which to compare readings. Different types of strain gauges are available, but all use essentially the same grid to measure strains, therefore all are subject to drift.

Attachment methods for gauges vary, ranging from connections made with adhesives or pastes to weldable gauge connections. Each has its own advantage over the other for a specific application. Despite protective coatings, moisture continues to be a problem for these gauges. It is the most common cause of strain gauge failure in the field. Intrusion of water vapor into the gauge can result in gauge instability and drift since the grid is subject to corrosion. Also, conductive paths in the gauge can result from moisture and cause drift problems.

Since strain gauges only monitor member distress, rigid body type movement cannot be discerned with strain gauges. Another difficulty is mounting the gauges on the structure. This can be a time consuming task, particularly when access to the monitoring points is difficult to obtain.

2.3.2. Dial Gauges

The stability of the dial gauge is good because of its mechanical workings. However, the use of the gauge presents a problem of establishing a rigid foundation on which the gauge must set to maintain a reference position. This problem is magnified for particularly large structures. The mechanical gauge is also susceptible to harsh environmental conditions and is unable to provide continuous data.

2.3.3. Tilt Sensor System

With a tilt sensor system there is little difficulty with obtaining reliable data for situations where the sensor can be mounted directly to the structure. Continuous monitoring also makes the system a desirable alternative. Based upon the literature reviewed, the system is apparently stable and reliable for field use. The mounting procedure is very simple and may be accomplished quickly. The unit is completely sealed, and the environmental effects, such as temperature change, are insignificant.

One difficulty with the tilt sensor system is that of gaining access on certain structures to mount the sensors. Also, since for rigid body rotation the angular change is directly proportional to the calculated deflection, the sensor's range of approximately 20 arc minutes may limit their use in calculating deflections to only very short structures (such as an abutment). Tilt sensors are also unable to monitor structural translation.

Another associated difficulty is that assumptions as to the center of rotation (for rigid body rotation) or end support conditions (for member curvature) must be made in order to calculate deflections from the measured angular information. An additional difficulty for member curvature is that enough sensors must be used to define clearly the deflected structure shape so that integration of the measured data can be performed accurately.

2.3.4. Photogrammetry

Photogrammetry is particularly useful for measurements where the simultaneous recording of a large number of points is desired. The method creates a valuable permanent record of the data (namely, the photograph) and is effective because it reduces the manual labor, scaffolding, and other support equipment needed to make measurements. As is the case for most surveying-related techniques, minimal interruption of traffic occurs during data retrieval.

Disadvantages of the technique include its requirement for good lighting conditions and the inability to do continuous monitoring. Photogrammetry depends on gaining and maintaining vertical and horizontal control of the area to be measured and is therefore directly dependent on the surveying methods used to gain that control. The control is particularly important when the cameras are reset on control locations.

2.3.5. Surveying

According to the literature studies investigated, apparently reliable results have been obtained using surveying techniques. As in photogrammetry, interruption to traffic is minimal, and little support equipment is needed. However, continuous monitoring is possible, and there is a chance of human error occurring in the recording and observing of the data. The time required to make the measurements is relatively large, which certainly may affect the accuracy. The accuracy is also greatly dependent upon gaining and maintaining horizontal and vertical control.

2.3.6. Mechanical Methods

In the literature review some innovative methods were identified that will be defined as mechanical methods. Other variations other than those found could also be possible. These methods may be classified as a combination or variation of surveying and structural instrumentation type techniques that may require construction of a mechanical-type device. The application of the device or method of making measurements most likely employs the surveying and/or structural instrumentation principles. One major advantage of this method is that it is designed for a specific application and therefore is well suited to obtain the data in an effective manner.

One general difficulty with this method is that components making up the device may fail to function properly. The more degrees of freedom associated with the device, the greater the likelihood of error. Subsequently it is difficult to obtain data that are consistent and reliable. Maintaining a stable reference point from which data must be obtained is another problem.

A number of measuring techniques for monitoring long-term structural movement exist, each with advantages and disadvantages. Since the discussions have been kept very general, no one method stands out as the best solution for obtaining accurate data for any condition that may be encountered. In order to select the best method for a field application, the type of information that is needed must be identified. This study is concerned with two applications that have been mentioned earlier: the determination of possible pier movement due to accidental barge impact (Mississippi River Bridge in Lansing, Iowa) and the determination of overall longitudinal movement of integral abutment bridges due to temperature differences. Based on these applications, measurement methods have been selected for further laboratory investigation. These methods are:

- tilt sensing system
- photogrammetry
- surveying

Additional laboratory information regarding accuracy, ease of use, and reliability has been examined to learn more about what to expect in field application. Appendix A discussed specific applications that have been made.

3. DESCRIPTION OF TESTS

3.1. General Testing Program

The laboratory investigation consisted of tests performed on both a vertical column and horizontal beam members. The intent of the tests were to determine the accuracy and reliability of various methods for making typical structural measurements. The column test was devised to create a condition of significant member curvature to allow a number of locations along the member to be monitored. Rigid body rotation was also desired, and the beam tests were designed to allow this.

A number of techniques, including those identified for possible field application, were used to monitor movements of the column. The methods included dial gauges, DCDTs, electrical resistance strain gauges, and tilt sensing devices. In addition, surveying and photogrammetric techniques were employed. The dial gauge data and DCDT data served as the reference by which all other methods were compared.

In the beam tests, rigid body rotation was monitored by the techniques used in the column tests, excluding the strain gauges. The beam was not subjected to any significant external loading (only beam dead load and tilt sensor weight) and member curvature was therefore minimized to the point where only rigid body rotation was assumed to contribute to the deflections. As in the column tests, a displacement gauge served as the reference for the actual beam movement.

Two tests involving both the beam and the column were conducted and will be referred to as Beam Tests 1 and 2 and Column Tests 1 and 2, respectively. These tests were performed at one-week intervals in order to determine the repeatability of the various measuring techniques. Two additional tests, referred to as Beam Tests 3 and 4, were performed to obtain additional information about the capabilities of the tilt sensing system.

A brief description of the methods used for measuring structural movements of the test members is provided below.

Dial gauges Standard laboratory mechanical dial gauges were used that consisted of a spring-loaded sliding arm and dial face. Using these gauges, measurements are accurate to the nearest 0.001 in.

Direct Current Displacement Transducers (DCDT) They operate much like the mechanical dial gauge in that movement is monitored through use of a sliding arm. As the arm is displaced, an electrical resistance signal is sent to and processed by a computerized data acquisition system (DAS). A direct readout is possible to the nearest 0.001 in.

Electrical Resistance Strain Gauges These devices are standard laboratory strain gauges used for steel members. A resistance is measured by a DAS or standard strain indicator box and strains, which are accurate to the nearest 10^{-9} in./in. may be obtained.

These devices were not studied for possible field applications but were used only to obtain additional laboratory data by which other methods could be evaluated. The methods that were determined to have practical field application and were subsequently studied are briefly discussed below.

3.1.1. Tilt Sensing System

The Sperry tilt sensing system is shown in Fig. 2. The system consists of a power source and digital readout unit (Fig. 2a), a strip chart recorder (Fig. 2b), and a tilt sensor and mounting plate (Fig. 2c). Figure 3 shows the sensor attached to a vertical mounting plate, which is used to attach the sensor to a structural member.

The tilt sensor monitors vertical and/or horizontal alignment of the object to which it is mounted. The sensor is an adaptation of an electrolytic gravity sensor commonly used in aircraft and marine gryoscopes. The range of the sensor is ±20 arc minutes with an accuracy of 0.003 arc minutes. However, the measured accuracy decreases as the sensor angle change increases because of a ±5% range of linearity relative to the measured angle.

The tilt sensors are connected to the central console unit, and readings are obtained from the liquid crystal digital readout display. The console can monitor up to four individual sensors. In addition to providing electrical power to the sensors and serving as a data source, the console also processes the electrical signals from the sensors for readout on the connected strip chart recorder. Four channels are available to record up to four tilt sensors. The central console may be battery driven or controlled by a 120 volt current.

Use of the sensor in monitoring structural movement is made by obtaining alignment information at discrete points along the structure. From these data, calculation of deflection may be made by utilizing elementary geometrical and structural analysis principles. In the case of an angle change for rigid body rotation of a horizontal member (see Fig. 4), the movement ΔZ may be calculated using

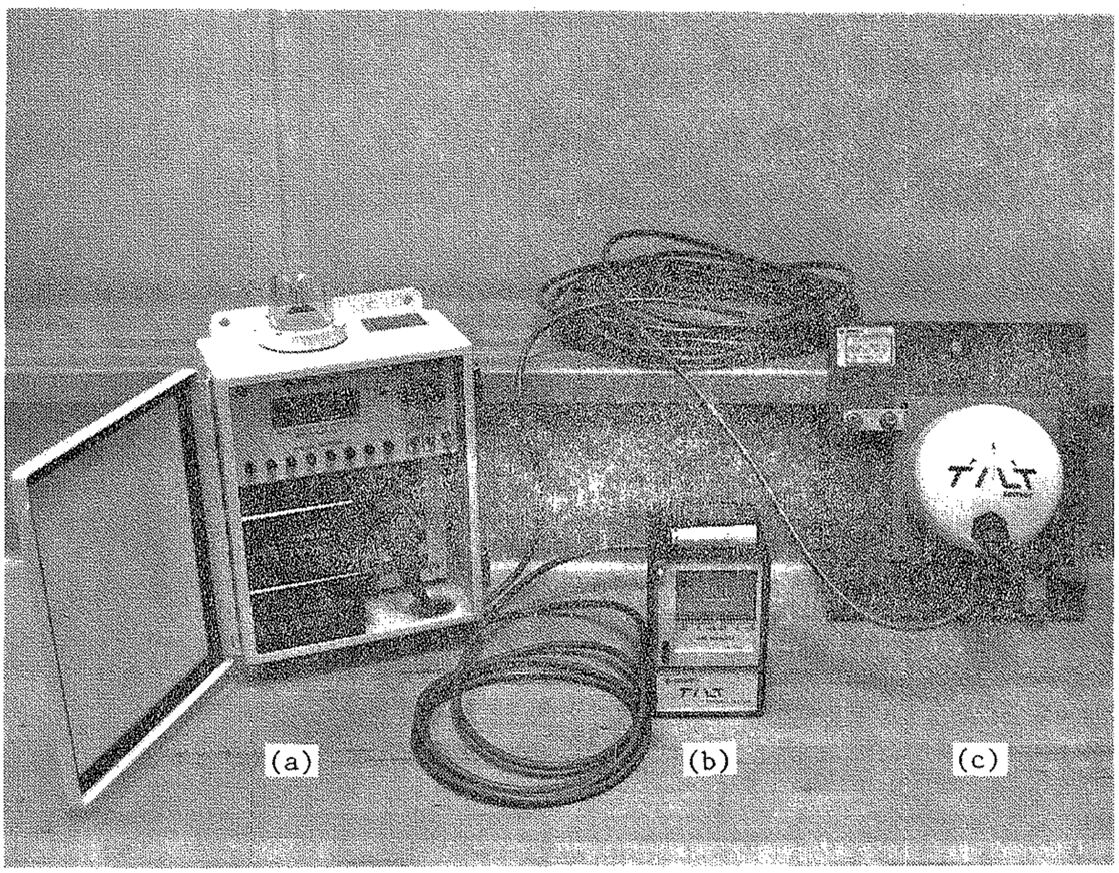


Fig. 2. Tilt sensing equipment: (a) power source, (b) recorder, and (c) tilt sensor and mounting plate.

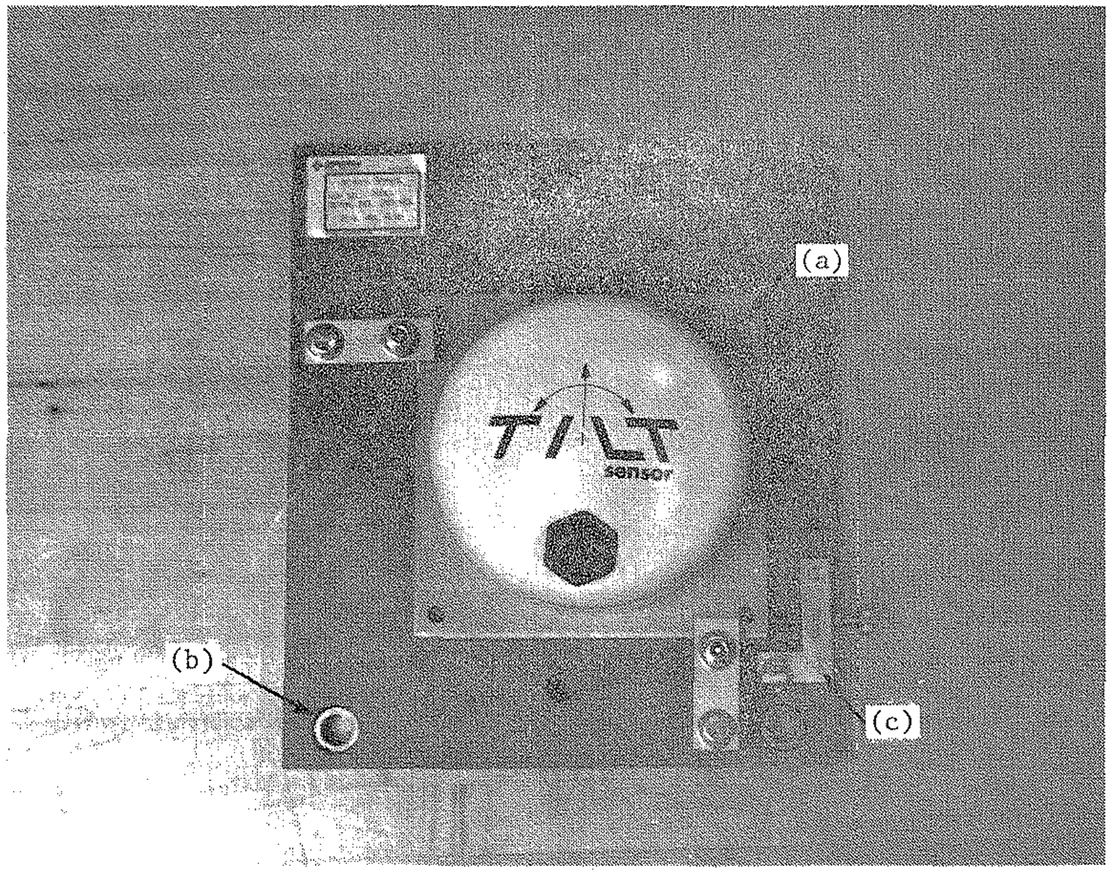


Fig. 3. Details of tilt sensor mounting to the plate: (a) pivot hole, (b) brass mounting pad, and (c) alignment mechanism.

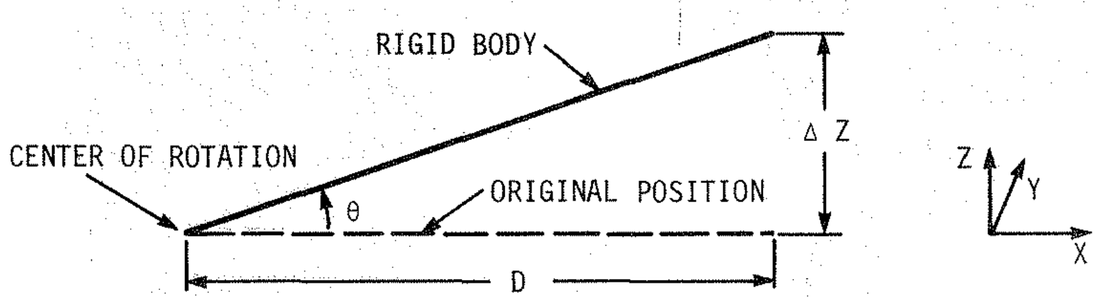


Fig. 4. Description of rigid body rotation for calculating deflections from tilt sensor data.

$$\Delta Z = D\theta \tag{1}$$

where D is the horizontal length of the member and θ is the angle of rotation obtained with the tilt sensor unit.

For determining the deflection of a member bent in curvature with one end restricted against rotation, as illustrated by the deformed column in Fig. 5, if a sensor is mounted at point i, the movement in the x-direction, ΔX, may be determined by integration techniques considering the two equations below.

$$\theta = \int \frac{M}{EI}\, dZ \tag{2a}$$

where

θ = angle measured by the tilt sensor

E,I = member modulus of elasticity and moment of inertia, respectively

M = member moment

From Eq. (2a) the moment in the member may be obtained by substituting the value for the measured angle, θ. Integrating Eq. (2a), the deflection ΔX is obtained from the application of Eq. (2b).

$$\Delta X = \int \frac{M}{EI}\, ZdZ \tag{2b}$$

Appendix B contains a discussion on the expected error and tilt sensor resolution for the tests conducted in this study.

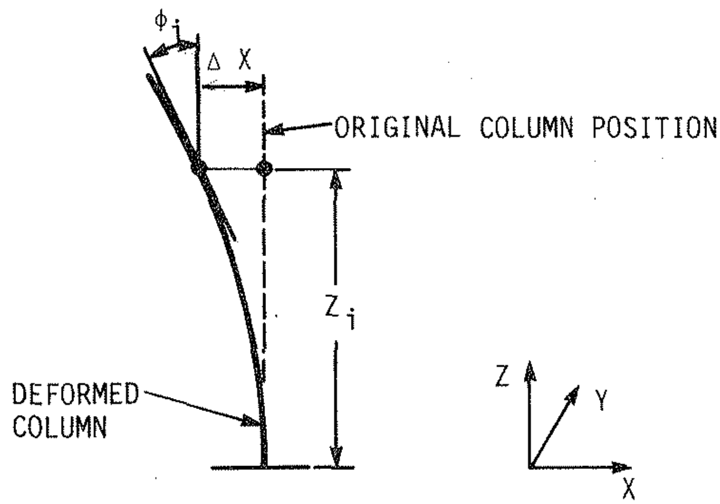


Fig. 5. Description of member curvature for calculating deflection from tilt sensor data.

3.1.2. Analytical Photogrammetry

The photogrammetry technique uses a stereocomparator to take measurements from a photograph. A stereocomparator is shown in Fig. 6. Figure 7 shows a typical stereo camera used to take photographs. The camera produces a negative on a glass plate for image stability, flatness, and enhanced accuracy for making measurements.

The concept for taking measurements using this technique may be illustrated by considering Fig. 8. The photo coordinates of a point (x, y) are related to the ground coordinates (X, Y, Z) by central projection. Thus,

$$x = f \; \frac{A_{11} \, (X - X_o) + A_{12} \, (Y - Y_o) + A_{13} \, (Z - Z_o)}{A_{31} \, (X - X_o) + A_{32} \, (Y - Y_o) + A_{32} \, (Z - Z_o)} \qquad (3)$$

$$y = f \; \frac{A_{21} \, (X - X_o) + A_{22} \, (Y - Y_o) + A_{23} \, (Z - Z_o)}{A_{32} \, (X - X_o) + A_{32} \, (Y - Y_o) + A_{33} \, (Z - Z_o)} \qquad (4)$$

where

f = the camera focal length, and

(X_o, Y_o, Z_o) = the ground coordinates of the camera nodal point,

and

$$\begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} = \begin{bmatrix} \cos k & -\sin k \\ \sin k & \cos k \\ 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & \cos \phi & 0 & \sin \phi \\ 0 & 0 & 1 & 0 \\ 1 & -\sin \phi & 0 & \cos \phi \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos w & \sin w \\ 0 & \sin w & \cos w \end{bmatrix}$$

The terms w, ϕ, and k are rotation angles about the (X, Y, Z) axis that are required to rotate the photo coordinate system (x, y, z) parallel to the ground coordinate system (X, Y, Z).

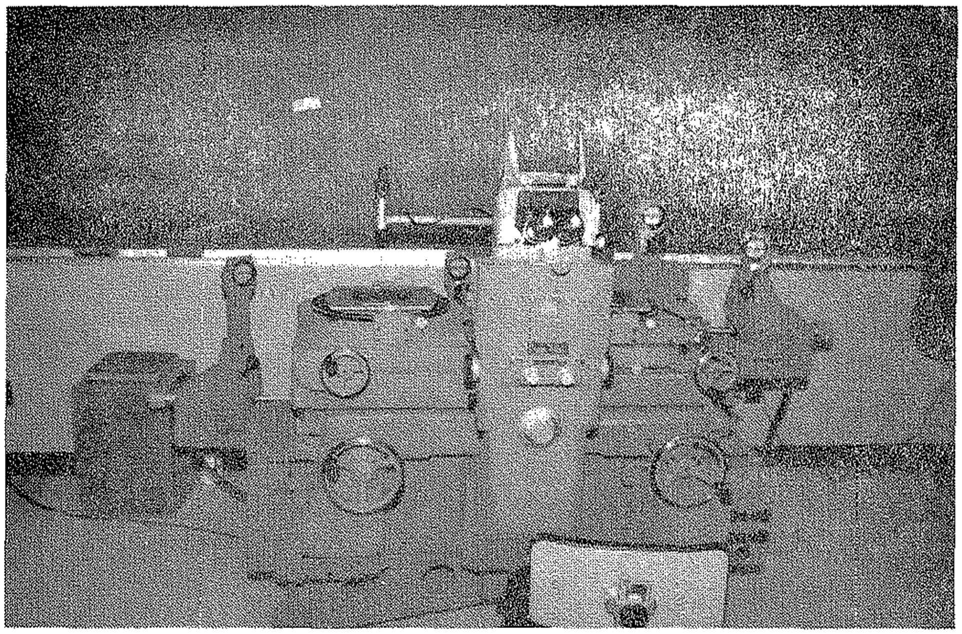


Fig. 6. Wild STK-1 stereocomparator.

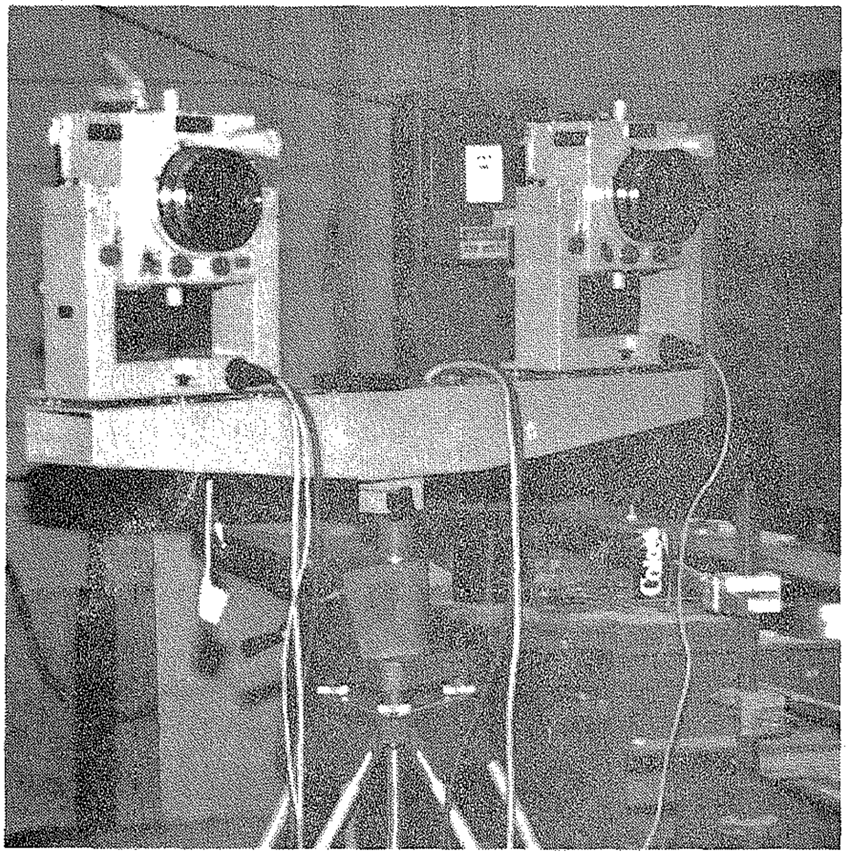


Fig. 7. Zeiss stereometric camera on a tripod.

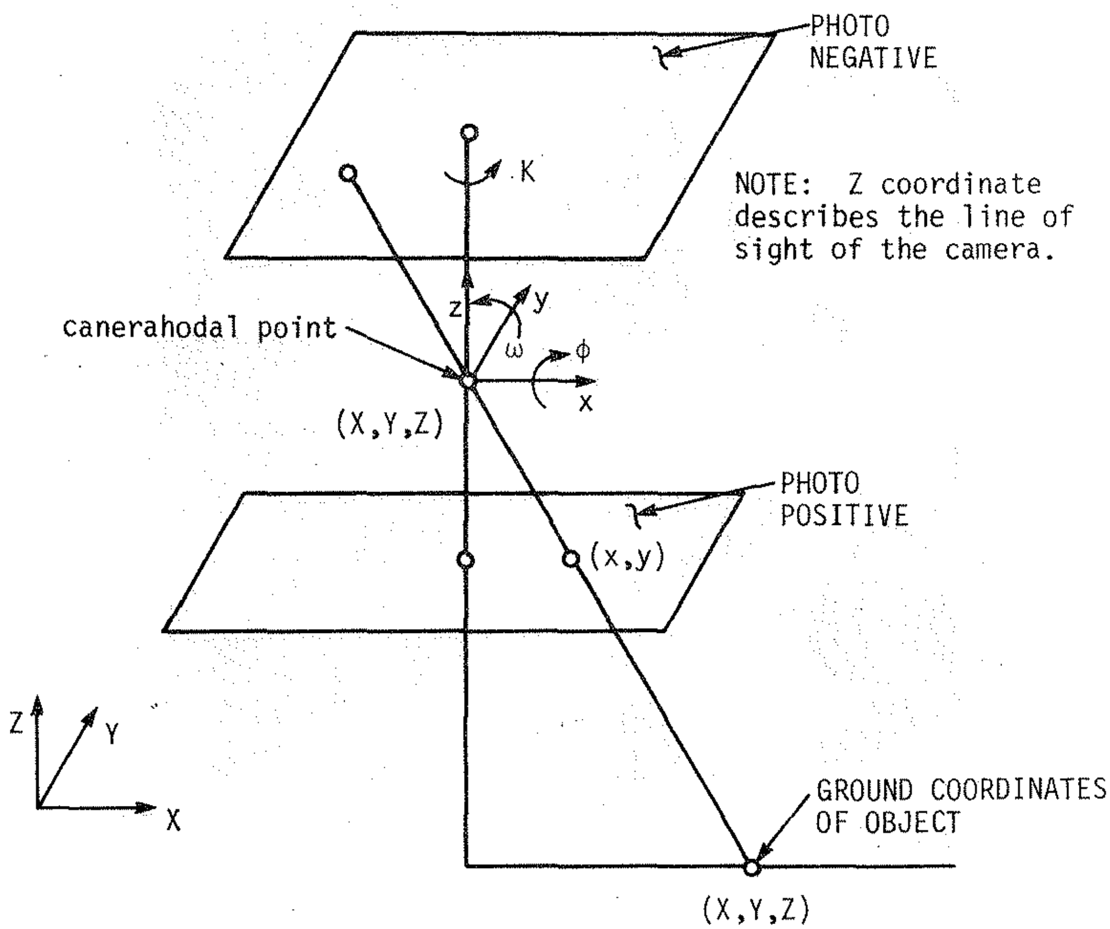


Fig. 8. Photogrammetric resection describing reduction of data for measurements from a photograph.

By measuring the photo coordinates (x, y) of three or more points, for which the ground coordinates (X, Y, Z) are known, the unknown parameters X_o, Y_o, Z_o, k, ϕ, *and* w *can be determined by an iterative least* squares method using six or more equations similar to Eqs. (3) and (4).

If an object, P, is photographed from two points, A and B (see Fig. 9), by measuring the photo coordinates, (x, y) and (x', y'), on both of the photographs, the ground coordinates (X, Y, Z) of P can be obtained from four equations similar to Eqs. (3) and (4): Two equations for each photo, provided the parameters X_o, Y_o, Z_o, k, ϕ, and w are known for each photo.

In practice the unknowns, six parameters per photo and three coordinates for each point, are determined simultaneously by a least squares iterative method using 15 or more equations with *three or more known* control points. Special metric cameras (e.g., Wild P32, Wild C120, and Zeiss), each of which have distortions less than 0.005 min, are required for use. See Appendix B for discussion regarding the expected accuracy of this technique for the tests performed in this study.

3.1.3. Surveying

Application of surveying techniques in the measurement of structural movement requires the use of an instrument for making angular measurements. The measurements are taken for the points on the object being monitored from known reference points. Both Wild T2 and Kern DKM2 Theodolites were used in this study. The surveying method as applied in this study is illustrated in Fig. 10.

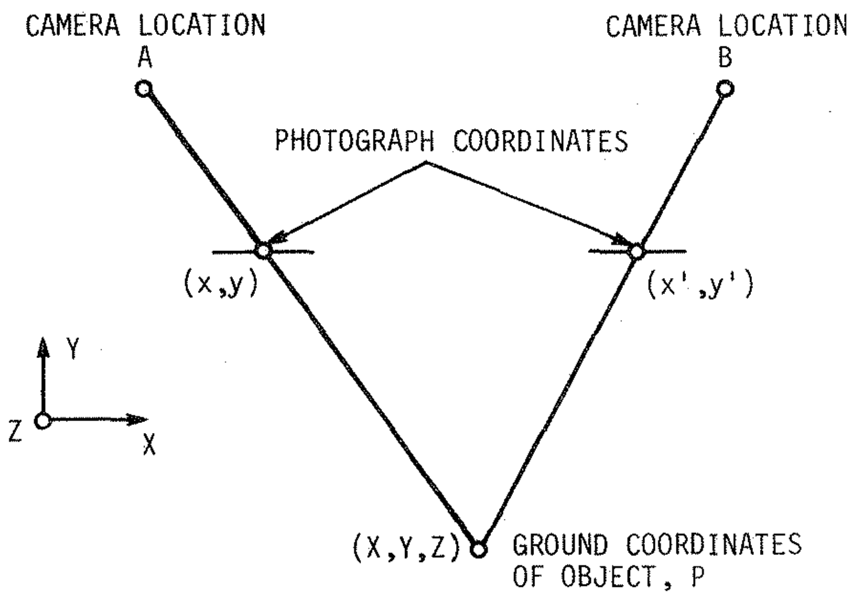


Fig. 9. Plan view of a photogrammetric intersection.

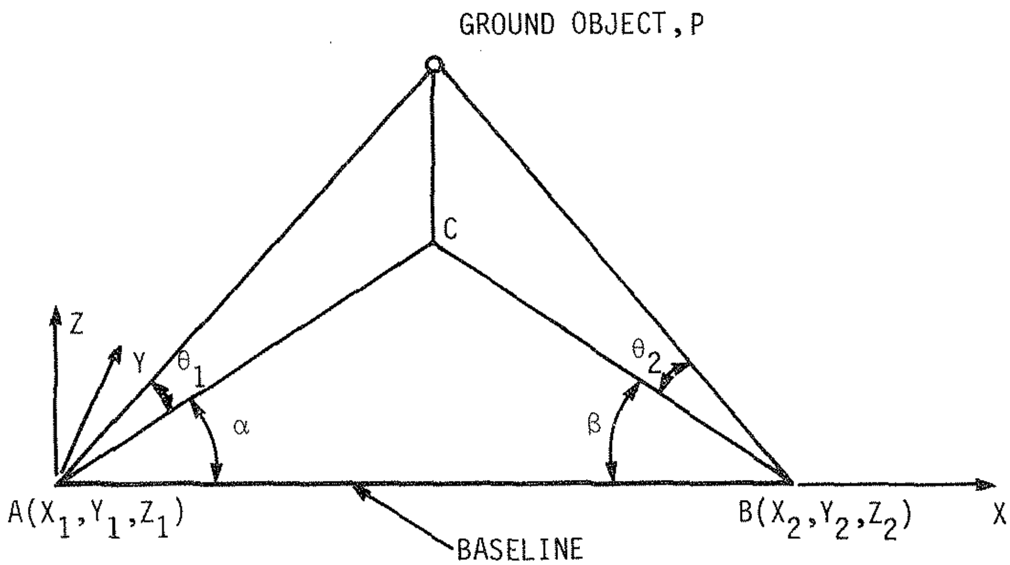


Fig. 10. Three-dimensional view illustrating the concept for making deflection calculations by the surveying method.

The horizontal angles (α, β) and vertical angles (θ_1, θ_2) are measured from two stations, A and B, to a point, P. The coordinates (X, Y, Z) of P are given by

$$X = X_1 + AC \cos \alpha$$
$$= X_2 - BC \sin \beta$$

therefore,

$$X_{mean} = \tfrac{1}{2} (X_1 + AC \cos \alpha + X_2 - BC \sin \beta) \tag{5}$$

Also

$$Y = Y_1 + AC \sin \alpha$$
$$Y = Y_2 + BC \sin \beta$$

therefore,

$$Y_{mean} = \tfrac{1}{2} (Y_1 + AC \sin \alpha + Y_2 + BC \sin \beta) \tag{6}$$

and

$$Z = Z_1 + AC \tan \theta_1$$
$$= Z_2 + BC \tan \theta_2$$

therefore,

$$Z_{mean} = \tfrac{1}{2}(Z_1 + AC \tan \theta_1 + Z_2 + BC \tan \theta_2) \tag{7}$$

where (X_1, Y_1, Z_1) and (X_2, Y_2, Z_2) are the coordinates of A and B, respectively.

Also from triangle ABC we have

$$\frac{AB}{\sin (180 - \alpha - \beta)} = \frac{AC}{\sin \beta} = \frac{BC}{\sin \alpha} \tag{8}$$

If the base length AB is known, the lengths AB and BC can be computed from the above equations.

The accuracy of the coordinates (X, Y, Z) depends on the accuracy of the distance AB and the angles α, β, θ_1, and θ_2. The accuracy of the coordinates may be improved by having three or more stations and using the method of least squares to determine the most probable coordinates. A discussion with regard to expected error for the study in this report is discussed in Appendix B.

3.2. Description of Test Members

The column and beam members used in the laboratory testing program were designed to allow observations of member curvature and rigid body rotation. Dimensions of the members were selected based upon consideration of the magnitude of movements desired and the limitations of the various measuring techniques. The tests were devised to create deformations that would push the limits of these techniques so that an accurate assessment of their precision capability could be made. This would allow an evaluation of their possible field applicability as well as their limitations.

3.2.1. Column Test Configuration

A sketch of an elevation view of the column member is shown in Fig. 11. The column was part of a frame that allowed member curvature and deflection to be developed in the column. A wide flange A-36 steel section (W 6 × 25) served as the column, which was rigidly connected at the base to two steel channel sections (C7 × 12.25). As

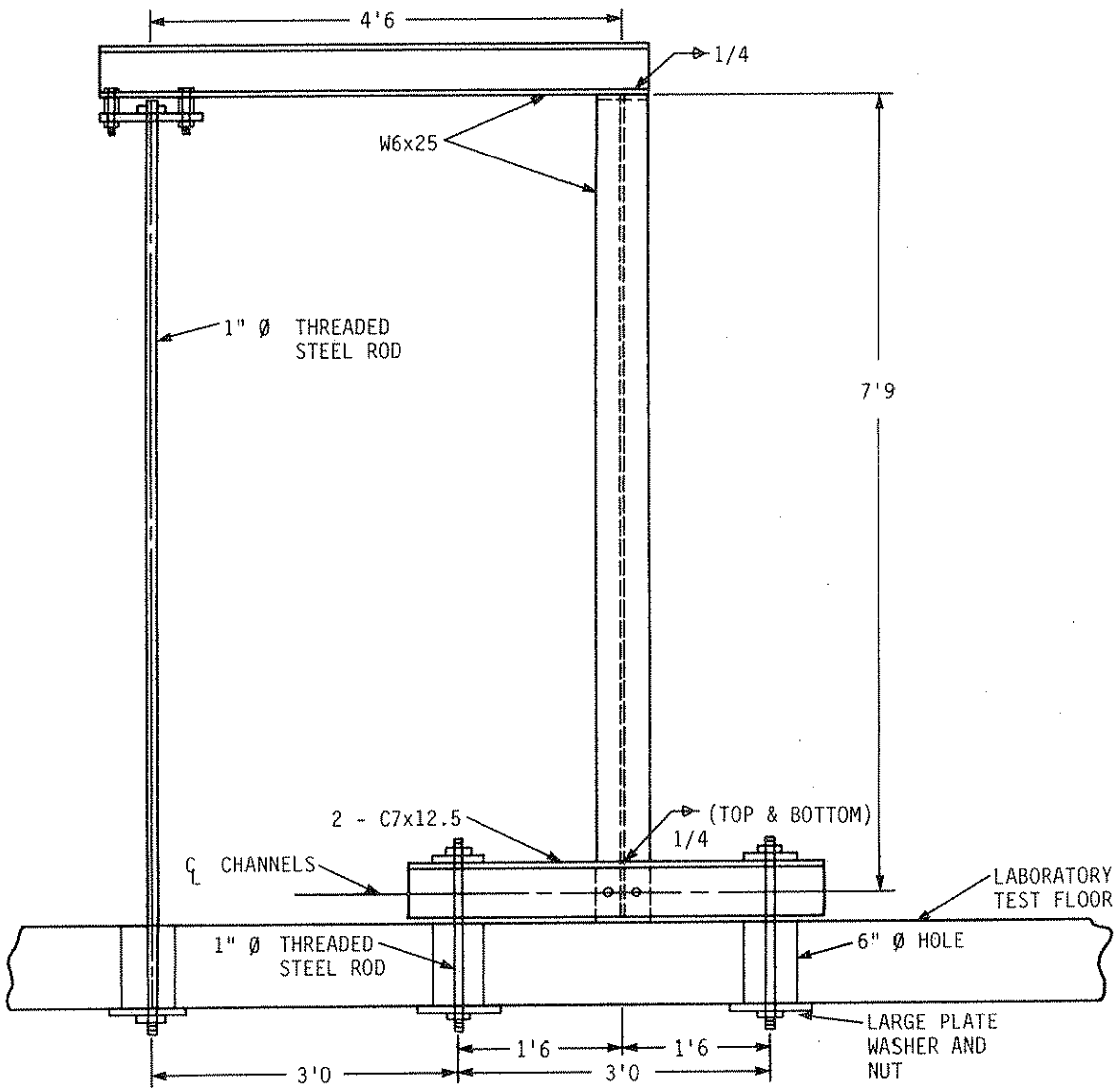


Fig. 11. Frame details for Column Tests 1 and 2.

shown in the sketch, the rigid base connection was created by welding the top and bottom flanges of the channel to the column flanges. In addition, two 1/2-in. diameter bolts were used to complete the connection. The channels were fastened to the laboratory test floor by use of a detail that allowed bearing on a large steel plate washer (attached across the top of the two channel flanges) by a one-inch diameter rod. The rod was secured to the underside of the test floor at a tie down location with a large plate washer and nut. For purposes of deflection calculation, the base of the column was assumed to be fixed.

The beam member of the frame also consisted of a W 6 × 25 section, which was attached through a bottom flange connection to the top of the column. A steel plate welded to the column end at the top acted as a bearing plate for the beam through which the bolted connection was made. The beam-column connection was assumed to create a joint rigid enough so that calculations of member deformations could be made assuming a fully rigid connection.

Loads were applied to the frame through a rod attached to the bottom flange of the beam and secured to the underside of the laboratory test floor at a tie down location. The threaded steel rod was attached to the floor with a large plate washer and nut assembly. By tightening the nut with a wrench, the load was applied to the frame in a manner that provided a very stable condition during the testing.

Selection of the column length was based on measurement limitations of the tilt sensors. The ±20 arc minute range of the sensors allows a maximum column top deflection of approximately 1/4 inch using a column length of 7'9". This deflection was felt to be of such magnitude that an accurate evaluation could be made of the various measuring techniques.

3.2.2. Beam Test Configuration

Figure 12 illustrates the layout for Beam Tests 1, 2, and 3. The tests were designed to achieve rigid body rotation. A 4 × 4 timber served as the beam member that was supported at one end on a rigid base with the freedom to rotate and was supported at the other end by a hydraulic jack, which allowed control of the vertical movement. The configuration allowed a rotation of the whole member in a vertical plane relative to the rigid base end. As shown in Fig. 12, a section of 2 × 4 lumber was carefully grooved and supported on a steel angle member laid on end to form an inverted vee shape. This detail created a hinge-type support that allowed rotation of the member end. At the opposite beam end, a hydraulic jack rigidly connected to the beam was used to raise the member to cause the member rotation. The jack was placed on a steel bearing pad, which rested on top of a concrete abutment.

Selection of the beam length was based upon two considerations. The desire to mount four sensors simultaneously for a portion of the testing dictated the beam length be relatively long. In addition, given the limited angular range of the tilt sensors, the rotation through which the beam could be rotated was limited. For ease in measuring displacements with photogrammetric and surveying methods, a relatively long member was required. Specifications for mounting the sensors for angular measurement require that the sensors be mounted in a plane within 5° of vertical of the planar rotation of the structure. This

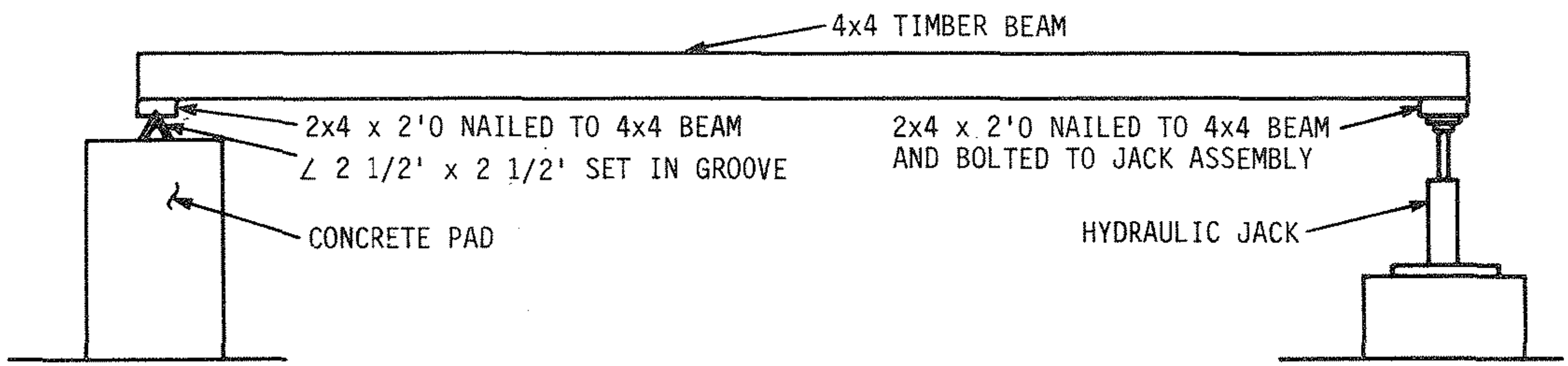


Fig. 12. Member details for Beam Tests 1, 2, and 3.

ensures any difference between the actual structure angular movement and the sensor movement will be insignificant. By using the relatively long beam member, it was also felt that exact planar movement of the beam throughout the range of angular movement would be difficult to achieve and therefore would provide some insight into the adequacy of the sensor mounting specifications.

The beam member used in Beam Test 4 is shown in Fig. 13. As shown, it consisted of a six-inch wide flange steel section that was simply supported. One end was idealized as a hinge support, while the other end was supported on a roller on the hydraulic load ram of the MTS fatigue testing machine. The ram end of the member was displaced to cause rigid body rotation. The MTS machine was used so that a dynamic displacement could be applied and the response time of the sensors could be studied.

The relatively short member length was selected to contrast with the long dimension used in Beam Tests 1, 2, and 3. In these tests possible out-of-plane rotation of the member was more likely to occur; so the short member length was selected for Beam Test 4 to reduce the possibility of the same thing happening again.

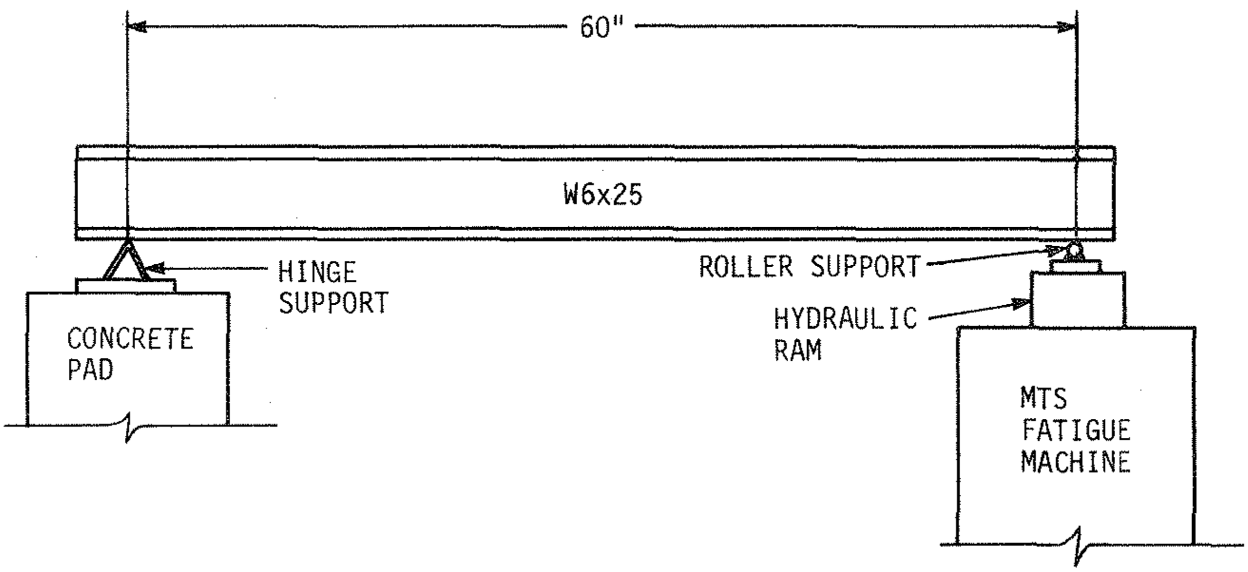


Fig. 13. Member details for Beam Test 4.

4. TESTS AND TEST PROCEDURES

Instrumentation utilized in the laboratory tests consisted of six independent measuring systems: (1) dial gauges, (2) direct current displacement transducers (DCDTs), (3) electrical resistance strain gauges, (4) tilt sensors, (5) surveying instruments, and (6) photogrammetry equipment.

Strain gauges were attached to the steel members with recommended surface preparations and adhesives. Lead wires from the strain gauges were connected to computerized data acquisition system (DAS), which read and stored the strain levels. The DCDTs utilized the DAS in a similar way by monitoring and storing deflection data. The tilt sensor readings were taken from the central console digital display and recorded by hand. Measurements observed using the dial gauges and surveying instruments were read and recorded by hand. The computerized control panel for the MTS fatigue testing equipment was used to monitor the deflections and to control the rate of displacement. Photographs, which were taken during the testing utilizing photogrammetry techniques, were processed and analyzed using a Wild STK-1 Stereocomparator.

4.1. Column Tests 1 and 2

Instrumentation for the steel column consisted of four dial gauges, four tilt sensors, and eight strain gauges as shown in Fig. 14. At each of the locations represented by distances D1, D3, D5, and D7 measured from the center line of the channel base fixture, one dial

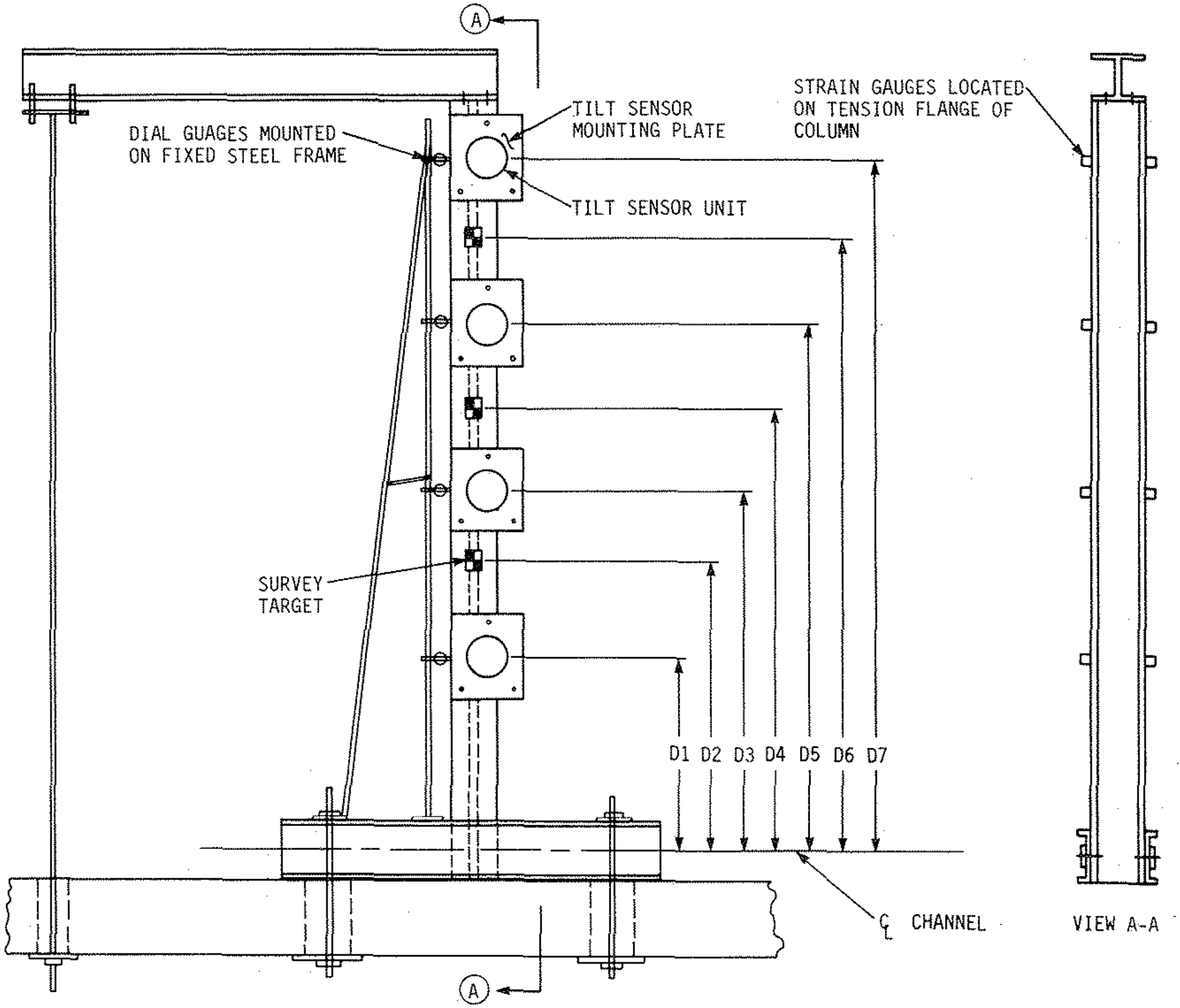


Fig. 14. Test setup and instrumentation for Column Tests 1 and 2.

gauge, one tilt sensor, and two strain gauges were utilized to measure column movements.

As shown in Fig. 14, the dial gauges were mounted on a steel frame, which that was constructed and positioned independent of the test column. The stem of each of the dial gauges was set to bear on the centerline of the column web.

Strain gauges were attached to both flanges of the column on the tension side of the neutral axis. Using two strain gauges at each location provided not only a check on the readings but an indication of any unsymmetrical bending of the column about the axis of bending.

The tilt sensors were mounted on the steel column member with a vertical mounting plate attached to the column by two bolts. Recommended plate installation procedures suggests a three point mounting arrangement using all three mounting holes as shown in Fig. 3 for rough and/or curved surfaces. Brass mounting pads at the bolt hole locations on the plate assembly permit such a mounting. However, the column member flange was not wide enough to accommodate all three fasteners, so the two fastener arrangement was used (see Fig. 15). The two pads that rested on the column were sufficient to stabilize the mounting plate. The narrow column width made it necessary to offset the center line of the tilt sensor relative to the column center line. Since the sensor angular readings are measured relative to a gravitational reference line, this offset did not affect the measurements.

The test layout regarding the photographic and surveying techniques is shown in Fig. 16. The equipment location, as well as the baseline geometry, were the same for all column and beam tests. Three

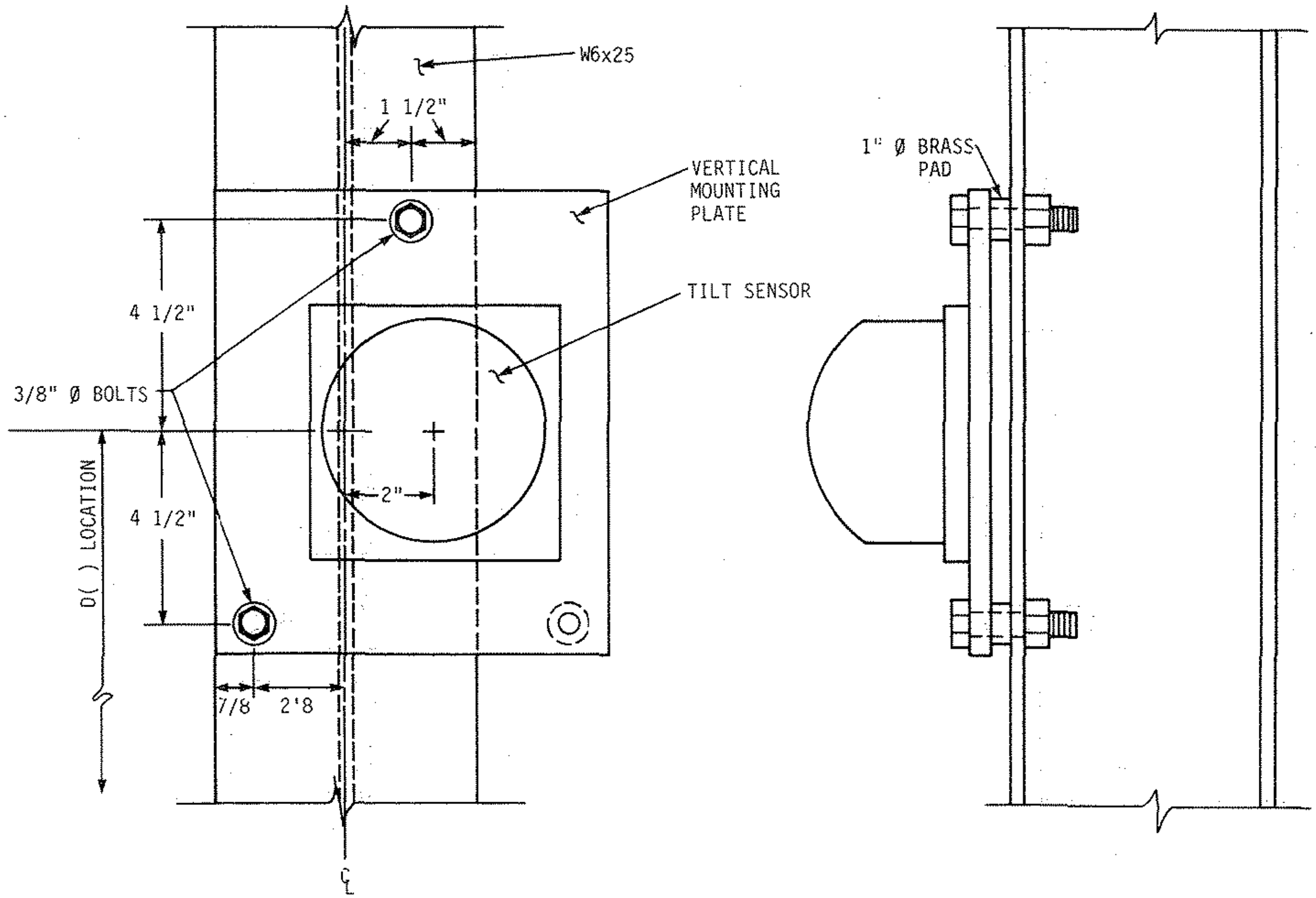
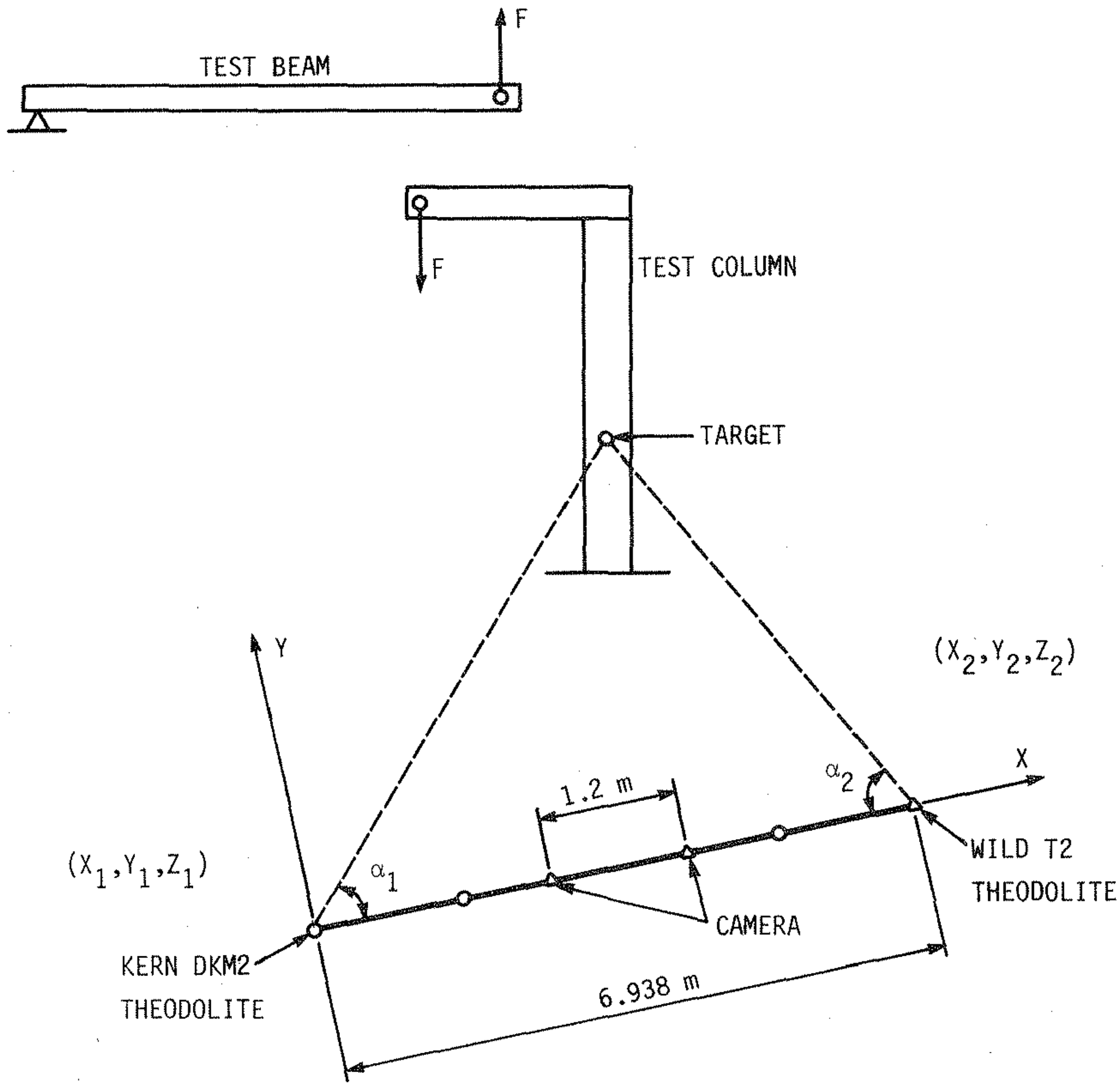


Fig. 15. Details and dimensions of the vertical mounting plate attachment to the column.



α_1, α_2 - measured angles

Fig. 16. Baseline and test setup for photogrammetric and surveying methods.

different cameras were used in this study and their characteristics are shown in Table 1. In addition to the targets that were placed on the column and beam, targets were placed on the wall of the laboratory. These targets were used to determine the position and orientation of the cameras and can be seen in the background in Fig. 17. The coordinates of these control points were determined by surveying methods using the Wild T2 and Kern DKM2 Theodolites.

For this study, the baseline used for the surveying calculations was measured as 5 m (see Fig. 10 for surveying layout). Measurements were made with a Leitz Red EDM (Electronic Distance Meter) with a least count of ±0.001 m. The angles were measured with the theodolites mentioned above, each of which has a least count of ±1 second. In order to eliminate instrument errors, both direct and reverse angular observations were made.

Prior to testing, a slight pre-load was applied to the column to ensure the frame was stabilized and no undesirable column movements recorded. The tilt sensors were initialized (set to zero angular reading) on the column after this pre-load application. This established a gravitational reference tangent or a line from which member rotations were measured.

After initialization, four load increments were systematically placed on the column, and measurements were made at each increment. An exception to this routine was applied to the surveying and photogrammetry techniques. Fewer load increment measurements were taken with these techniques because of the excessive time required to both observe

Table 1. Physical properties of the cameras used in this study.

Camera Type	Focal Length = f (mm)	Format (cm)	Base = B (M)
P32	64.20	6.5 × 9	2.7
C120	63.80	6.5 × 9	1.2
Zeiss	99.10	16 × 11.5	0.84

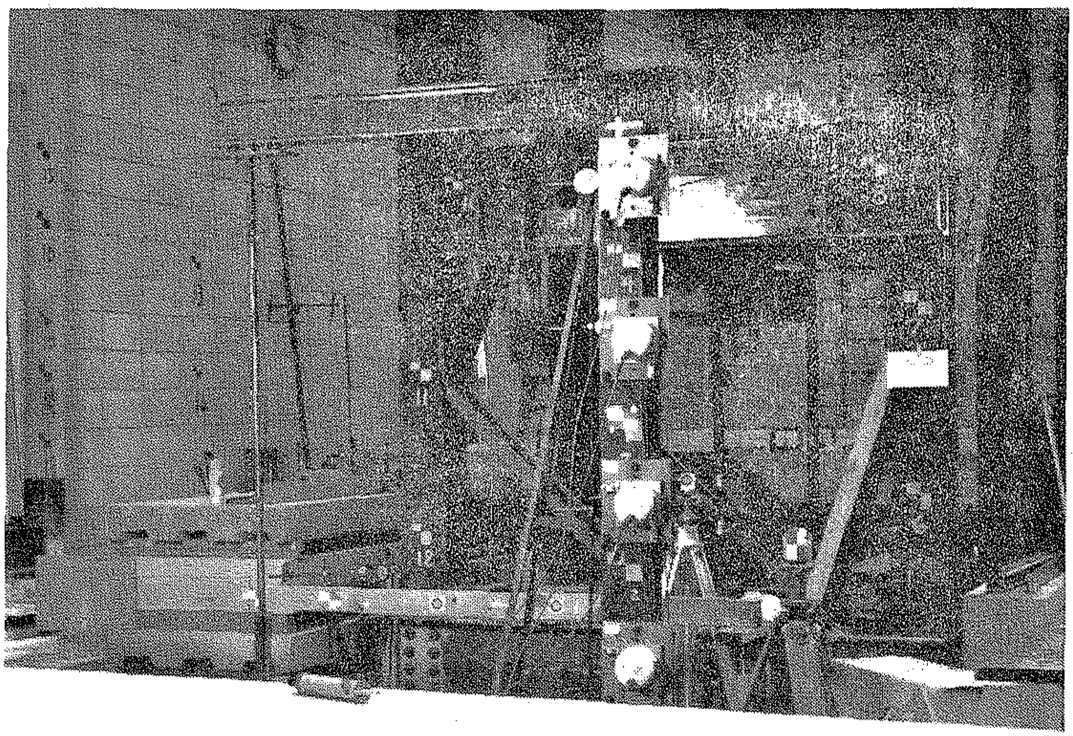


Fig. 17. Test setup illustrating locations of column targets and laboratory wall targets.

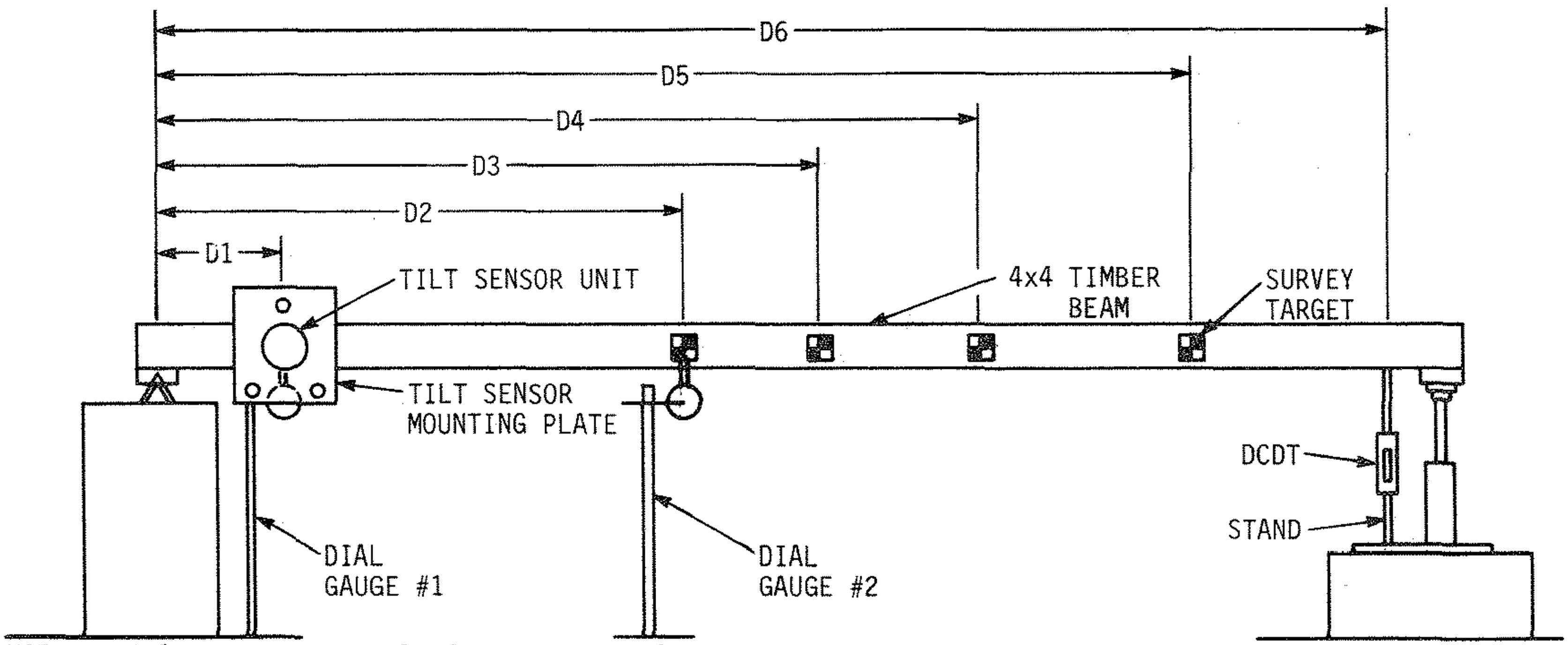
and interpret the data. Load increments were established based upon approximately 5 arc minute readings of the top sensor.

After completion of Column Test 1 and Beam Test 1, the fourth load increment was left on the column. During the one-week period that passed between the performance of Column and Beam Tests 1 and Column and Beam Tests 2, movements of the column were monitored. This included daily observations of the dial gauges, strain gauges, and tilt sensors. The movements were also continuously monitored through the use of the recorder unit for the tilt sensors. A strip chart recording of angular movement versus time was obtained during the interim period. Before the performance of Column and Beam Tests 2 and with the fourth load movement from Tests 1 still applied, data of the column position were recorded by all measurement techniques. The load was then released. A preload was applied, and Tests 2 were performed following the same procedure as in Tests 1.

4.2. Beam Tests 1, 2, and 3

Figure 18 shows the setup used for Beam Tests 1, 2, and 3 and the locations that were monitored for movement. Different arrangements of the instrumentation were utilized for each of the three tests performed on the beam. The instrumentation consisted of dialgauges, DCDTs, tilt sensors, and surveying and photogrammetry techniques.

The dial gauges were located under the beam, and their stems were placed at the beam center line. The DCDT located at one end of the member was positioned beneath the member center line and was placed on a



NOTE: Dial gauges used only for Beam Test 2.

Fig. 18. Instrumentation setup and location for Beam Tests 1 and 2.

steel plate, which rested on a concrete abutment. A plywood gusset plate with holes drilled to match those in the sensor mounting plate was used to mount the tilt sensors. As shown in Fig. 19, the mounting plate and plywood plate were placed on opposite beam faces and connected with studs. This created a clamping action that held the vertical mounting plate in the proper position.

For Beam Test 1, a single tilt sensor was mounted near the hinge supported end of the beam. Since the beam acted primarily as a rigid body member, a single sensor was all that was used to determine the rotation of the member. The DCDT gauge was used to measure the member's actual deflection from which member rotation was calculated. In addition, the deflections at interior points were calculated by proportion based on the DCDT measurement.

The beam tests utilized the same test layout and equipment that were used in the column tests for the surveying and photogrammetry techniques. The tests were designed to cause the tilt sensor to be rotated through a maximum angular range of approximately 40 arc minutes. To do this, the member end at the jack was lowered below the horizontal plane defined by the member center line. In so doing, the tilt sensor reading was near the extreme value of the sensor, which is -20 arc minutes. At this point the member position was observed. The member was then systematically rotated through angular increments of approximately 5 arc minutes by raising the member end with the hydraulic jack. Tilt sensor and DCDT readings were taken at all eight intermediate member positions. As in the column tests, only selected intermediate

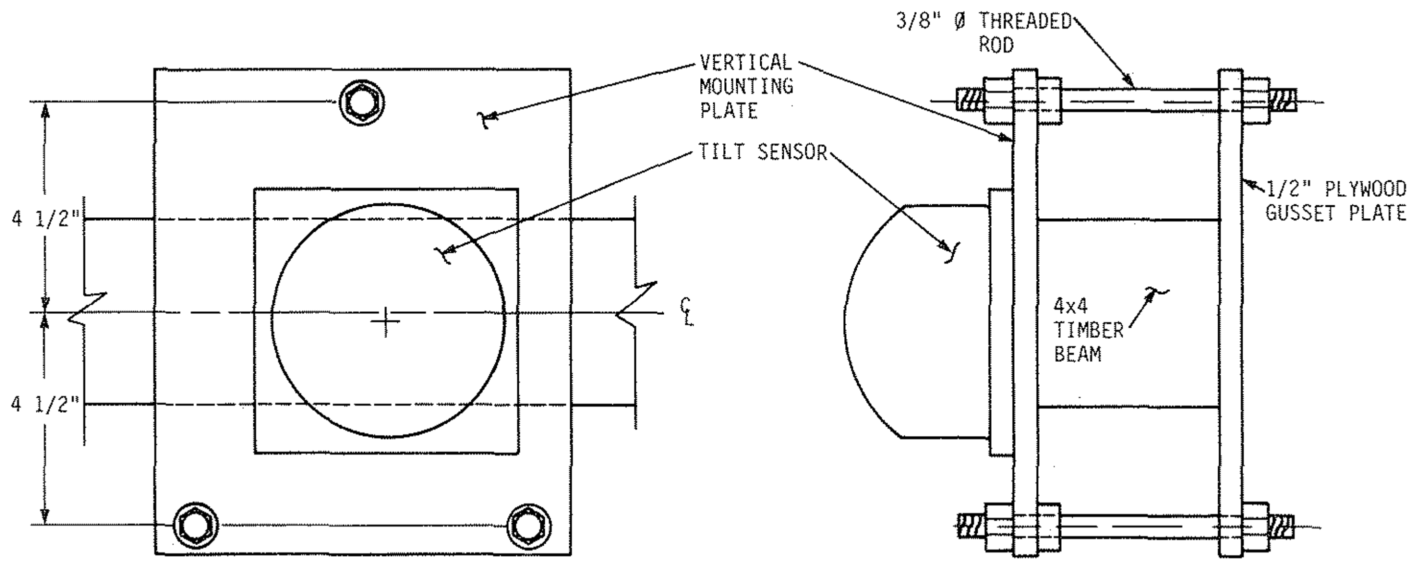


Fig. 19. Details and dimensions of the vertical mounting plate attachment to the beam member.

readings were taken by the surveying technique because of the excessive time required to observe and interpret the data.

Additional deflection data were collected during Beam Test 2 for ease of comparing data obtained from the different measurement techniques. Dial gauges were placed at locations D1 and D3 shown in Fig. 18. These locations correspond to tilt sensor and survey target locations, respectively. These locations were in addition to the instrumentation that was in place for Beam Test 1.

Beam Test 3 was conducted to study both the capabilities of the tilt sensing system and their sensitivity for out-of-plane movement. With the realization that the sensors could not be positioned so that they were able to monitor rotation in exact vertical planes practically (at least not within the high range of precision we were hoping to achieve), the tests were performed and comparisons made of each sensor reading.

Before performing Beam Test 3, the timber member was planed to ensure no unwanted warpage existed. In addition, an improved detail was utilized at the hinge support to eliminate any possible out-of-plane movement of the member. Figure 20 illustrates the test layout. The same procedure used in Beam Tests 1 and 2 for rotating the member through a wide angular range was employed. Neither the surveying or photogrammetry techniques were used during Beam Test 3.

4.3. Beam Test 4

The instrumentation used in Beam Test 4 is shown in Fig. 21, and the test layout is illustrated in Fig. 22. Beam Test 4 used the MTS

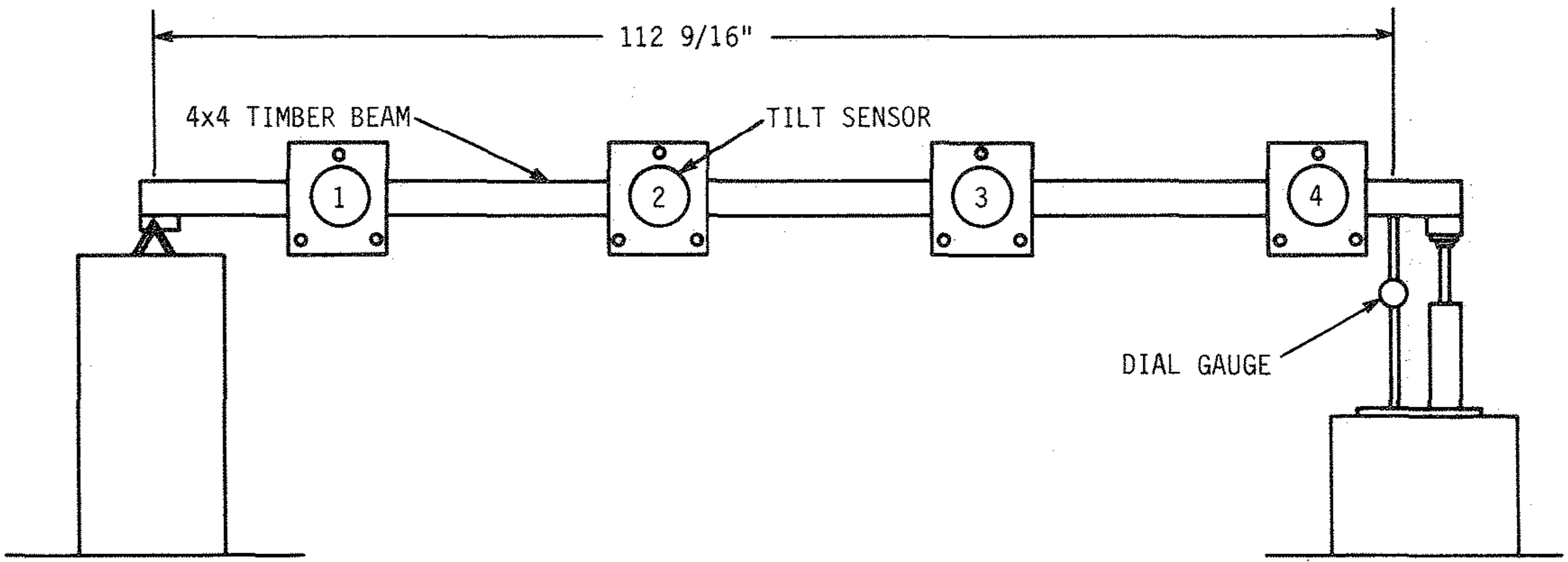


Fig. 20. Test setup for Beam Test 3.

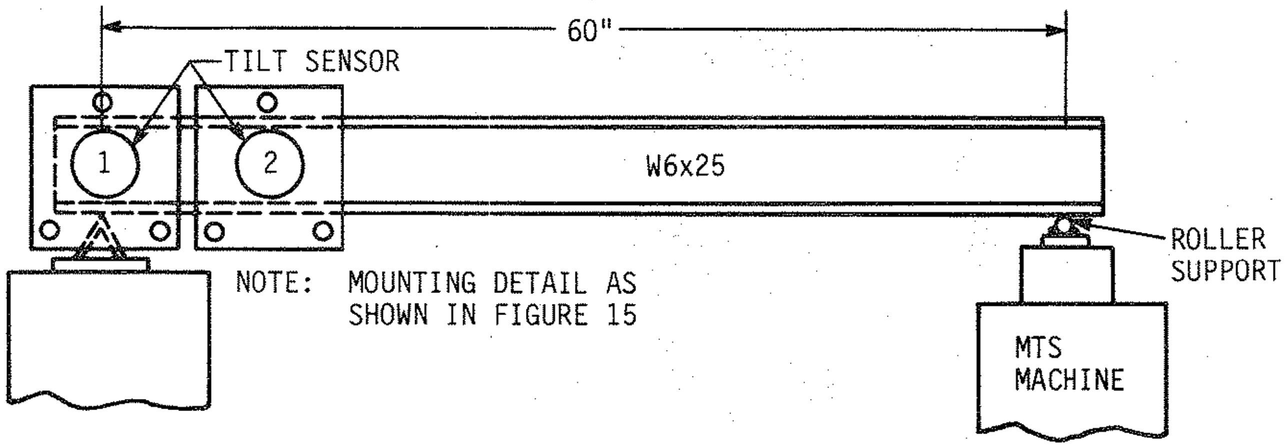


Fig. 21. Test setup for Beam Test 4.

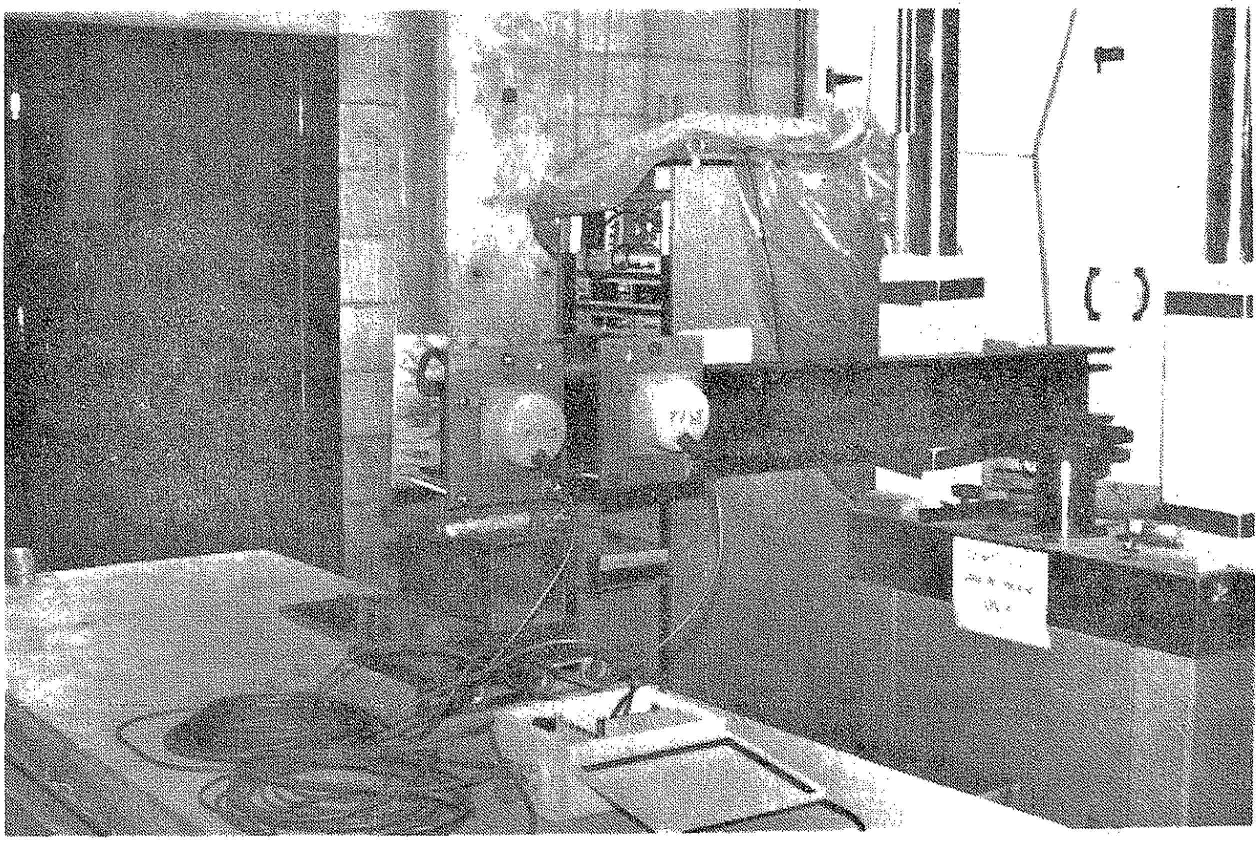


Fig. 22. Test layout for Beam Test 4.

fatigue testing machine to apply displacements to the simply supported member end at selected rates of displacement. The tilt sensors were attached at the hinge-supported end of a W 6 × 25 steel section. The sensors were connected to the member using the same procedure as Beam Tests 1, 2, and 3 and are shown in Fig. 19. The roller-supported end of the member was supported on the load-displacement cylinder of the MTS machine. The displacements and rates of displacement were controlled and monitored by the computerized control console of the machine.

Two objectives of this test were (1) to determine the sensor's ability to respond to nonstatic displacements and (2) to determine the sensor's accuracy and reliability to static displacement. Two tests were conducted: one test representing a relatively large angular motion and the other a relatively small angular motion. The test procedure involved the application of a selected displacement and displacement rate. After a one-second interval, which corresponds to the recording rate of the recorder, the sensor reading was taken manually from the console readout display. At the end of each displacement, the sensor was allowed to settle down completely, and a static reading was taken. The procedure was followed for each of the displacement rates considered.

5. TEST RESULTS AND ANALYSIS

Experimental results of tests performed will be presented in this section. Member deformations, either measured or calculated by the various techniques investigated, will be compared, and a determination will be made as to their accuracy.

5.1. Member Deformation Measurements and Calculation

Member deformation for both the column and beam tests were obtained by using various techniques that included dial gauges, DCDT, strain gauges, tilt sensors, survey instruments, and analytical photogrammetry equipment. A summary of how measurements were made and/or calculated is given below for the various techniques.

Dial Gauges and DCDT

Column deflection observed with the dial gauges and DCDT served to indicate the true position of the members. Dial gauges were read by hand, and the DCDT was read directly from a computerized DAS.

Strain Gauges

Integration techniques were used to calculate column deflections from the strain gauge data. To do this, strain gauges were placed at known distances from the column center line, and columns were assumed to be fixed at the base.

Tilt Sensors

Tilt sensor data were reduced by using direct integration of measured rotations to calculate member deflection.

Analytical Photogrammetry

Data were obtained using various stereometric cameras. The reduction of the data involved determining the coordinates of the targets by analytical photogrammetric techniques using the photocoordinates obtained by observing the photographs with a stereocomparator. Displacements were computed in three, mutually perpendicular directions.

Surveying

Displacements were calculated for the three mutually perpendicular directions used in the analytical photogrammetry technique. A baseline was established from which coordinates for targets on the members could be set by measuring the angles from the baseline to the established reference points. The angular measurements were made by theodolites.

5.2. Column Tests 1 and 2

Data from Column Tests 1 and 2 consisted of measured deflections, strains, and rotations at various locations along the column length. Four load increments were applied in sequence to the column to cause member deformation. These increments will be referred to as Load Cases C1, C2, C3, and C4. Figure 23 indicates the monitoring positions. Positions D1, D3, D5, and D7 correspond to tilt sensor, strain gauge, and dial gauge locations. Because of unavoidable obstructions in the laboratory, location D1 was not monitored by either the photogrammetry or surveying techniques. Targeted locations D2, D4, and D6 were used for use by the cameras and theodolites.

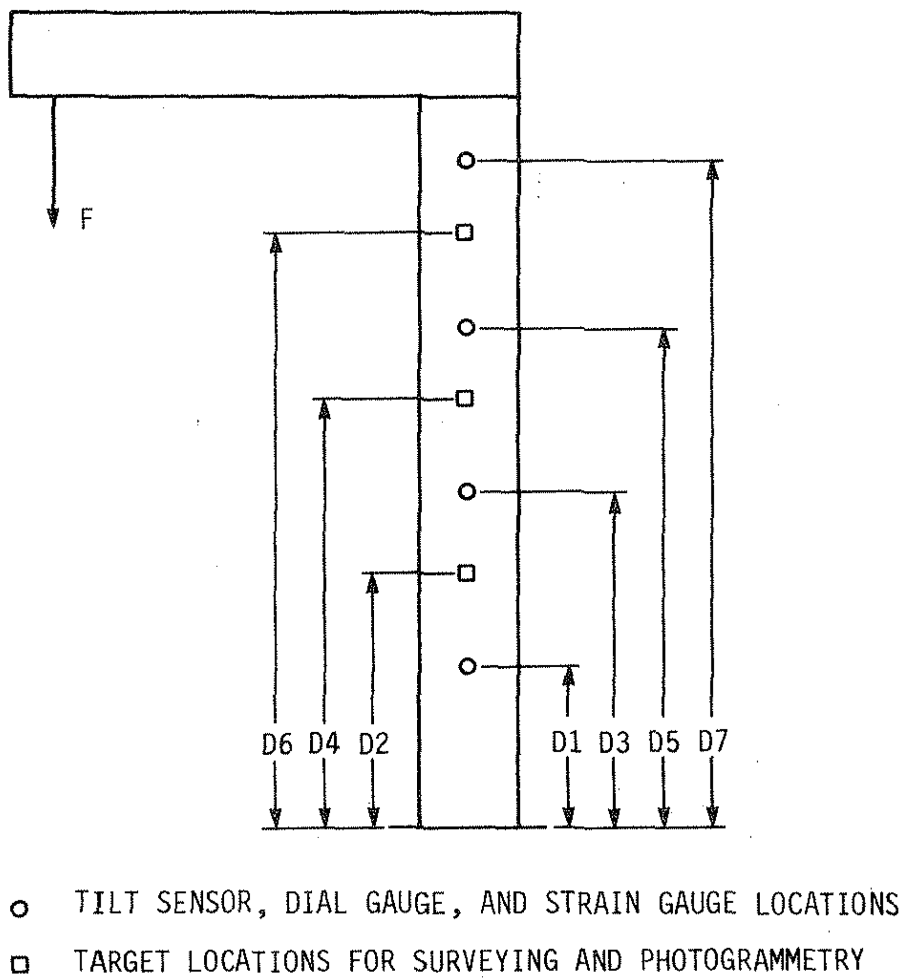


Fig. 23. Locations of monitored positions for Column Tests 1 and 2.

Tables 2 through 5 summarize data from the column tests and indicate comparisons of accuracy between the various techniques. As shown in Tables 3 and 5, camera and theodolite data were excluded. Because of the extensive amount of time required to make measurements and interpret the data, the number of observations by these methods was limited. Observations by these methods were obtained for Load Cases C2 and C4 and one given in Tables 2 and 4. Also note that some interpolation of gauge and sensor data was necessary in order to make comparisons at all deformation locations.

As seen in all four tables, correlation between assumed actual deflections (as obtained from dial gauge data) and the other techniques was quite good. In general, the correlation between strain gauge and tilt sensor data relative to the dial gauge data is better than correlations between surveying and photogrammetry relative to the dial gauges. For Column Test 1, as shown in Table 2, very consistent results were obtained with the strain gauges and tilt sensors at all monitoring locations. The exception to this was the strain gauge data obtained for Load Cases C2 and C4 at location D7 where a relatively large discrepency occurred. The apparent cause of the error was unexpected twisting at the top of the column, most likely because of some small load eccentricity caused by the fabrication of the frame. This is shown by the differences in the strain readings at location D7 on either side of the neutral axis. This twisting would cause the frame to move out of plane, which may not have been recorded by the tilt sensor or dial gauges. A similar result was found in Column Test 2 as shown in Table 4. The same discussions above for Table 2 also apply in general to results in Table 4.

Table 2. Comparison of measured and calculated deflections for load cases C2 and C4 of Column Test 1.

Location of Displacement	Load Case	Surveying	C120 Camera	P32 Camera	Strain Gauge Left	Strain Gauge Right	Dial Gauge	Tilt Sensor	δ = Surveying - Dial Gauge	δ = C120 - Dial Gauge	δ = P32 - Dial Gauge	δ = Tilt Sensor - Dial Gauge
D1	C2	-	-	-	0.010	0.009	0.008	0.010	-	-	-	0.002
D2	C2	-	-	0.067	0.023	0.021	0.023	0.023	-	-	0.044	0.000
D3	C2	0.019	-	-	0.034	0.032	0.032	0.034	-0.013	-	-	0.002
D4	C2	0.042	-	0.033	0.053	0.049	0.053	0.051	-0.011	-	-0.020	-0.002
D5	C2	0.058	-	0.094	0.070	0.069	0.073	0.072	-0.015	-	0.021	-0.001
D6	C2	0.088	-	0.154	0.095	0.095	0.099	0.102	-0.011	-	0.055	0.003
D7	C2	0.116	-	0.209	0.123	0.164	0.120	0.123	-0.004	-	0.089	0.003
D1	C4	-	-	-	0.019	0.017	0.016	0.019	-	-	-	0.003
D2	C4	-	0.017	-	0.045	0.039	0.045	0.045	-	-0.028	-	0.000
D3	C4	0.061	0.059	-	0.064	0.062	0.062	0.067	-0.001	-0.003	-	0.005
D4	C4	0.093	0.105	-	0.099	0.095	0.103	0.100	-0.010	0.002	-	-0.003
D5	C4	0.135	0.138	-	0.134	0.134	0.141	0.141	-0.006	-0.003	-	0.000
D6	C4	0.189	0.174	-	0.184	0.184	0.191	0.199	-0.002	-0.017	-	0.008
D7	C4	0.240	-	-	0.230	0.319	0.232	0.247	0.008	-	-	0.015
									σ_x^* = *0.0069*	*0.0124*	*0.0406*	*0.0046*

*Standard error of differences.

Table 3. Comparison of measured and calculated deflections for load cases C1 and C3 of Column Test 1.

Location of Displacement	Load Case	Surveying	C120 Camera	P32 Camera	Strain Gauge Left	Strain Gauge Right	Dial Gauge	Tilt Sensor	δ = Tilt Sensor - Dial Gauge
D1	C1	-	-	-	0.005	0.004	0.004	0.005	0.001
D3	C1	-	-	-	0.017	0.016	0.015	0.017	0.002
D5	C1	-	-	-	0.034	0.036	0.036	0.037	0.001
D7	C1	-	-	-	0.059	0.085	0.060	0.061	0.001
D1	C3	-	-	-	0.015	0.013	0.012	0.014	0.002
D3	C3	-	-	-	0.050	0.047	0.048	0.051	0.002
D5	C3	-	-	-	0.105	0.104	0.110	0.108	-0.002
D7	C3	-	-	-	0.184	0.244	0.180	0.187	0.007
								$\sigma_x^* =$	0.0025

*Standard error of differences.

Table 4. Comparison of measured and calculated deflections for load cases C2 and C4 of Column Test 2.

Location of Displacement	Load Case	Surveying	Zeiss Camera	Strain Gauge Left	Strain Gauge Right	Dial Gauge	Tilt Sensor	δ = Zeiss - Dial Gauge	δ = Tilt Sensor - Dial Gauge	δ = Surveying - Dial Gauge
D1	C2	-	-	0.010	0.009	0.009	0.009	-	0.000	-
D2	C2	-	-	0.023	0.021	0.023	0.022	-	-0.001	-
D3	C2	0.042	-	0.034	0.033	0.032	0.034	-	0.002	0.010
D4	C2	0.056	-	0.052	0.050	0.053	0.051	-	-0.002	0.003
D5	C2	0.071	-	0.070	0.069	0.073	0.072	-	-0.001	-0.002
D6	C2	0.097	-	0.097	0.095	0.098	0.102	-	0.004	-0.001
D7	C2	0.122	-	0.118	0.164	0.119	0.122	-	0.003	0.003
D1	C4	-	-	0.019	0.017	0.016	0.019	-	0.003	-
D2	C4	-	0.050	0.044	0.039	0.044	0.044	0.006	0.000	-
D3	C4	0.078	0.052	0.064	0.062	0.061	0.066	-0.009	0.005	0.017
D4	C4	0.092	0.086	0.098	0.095	0.101	0.099	-0.015	-0.002	-0.009
D5	C4	0.154	0.157	0.133	0.130	0.139	0.139	0.018	0.000	0.015
D6	C4	0.207	0.243	0.183	0.179	0.187	0.196	0.056	0.009	0.020
D7	C4	0.257	0.245	0.223	0.313	0.227	0.242	0.018	0.015	0.030
								σ_x^* = 0.0258	0.0047	0.0119

*Standard error of differences.

Table 5. Comparison of measured and calculated deflections for load cases C1 and C3 of Column Test 2.

Location of Displacement	Load Case	Surveying	C120 Camera	P32 Camera	Strain Gauge Left	Strain Gauge Right	Dial Gauge	Tilt Sensor	δ = Tilt Sensor - Dial Gauge
D1	C1	-	-	-	0.005	0.005	0.004	0.005	0.001
D3	C1	-	-	-	0.017	0.017	0.016	0.017	0.002
D5	C1	-	-	-	0.036	0.035	0.037	0.037	0.001
D7	C1	-	-	-	0.062	0.085	0.062	0.061	0.001
D1	C3	-	-	-	0.015	0.013	0.013	0.014	0.002
D3	C3	-	-	-	0.049	0.047	0.046	0.050	0.003
D5	C3	-	-	-	0.102	0.099	0.107	0.106	-0.002
D7	C3	-	-	-	0.171	0.240	0.174	0.181	0.007
								σ_x^* =	0.0025

*Standard error of differences.

The tilt sensor data comparisons with the dial gauge data are very good, but as shown in Tables 2 and 4, the comparisons become worse as the column displacements increase. The trend is apparent when the deflection differences from location D1 to location D7 are observed for each load case. The locations nearer the bottom of the column (e.g., location D1) show a better comparison than at points near the top of the column (e.g., location D7). As previously mentioned, the tilt sensors have a linear range (or are accurate) to within ±5% of the measured angle. Since the smaller column deflections correspond to smaller angular readings for the test column, the range of error allowed because of the ±5% linearity range is less than for larger deflections. It is therefore noted that as the measured angle increases, the accuracy of the tilt sensor may decrease for use in measurement of deflections. In all cases, the results obtained by the tilt sensors fell within the tolerance of the sensors.

Deflections obtained by surveying techniques indicated good agreement with dial gauge data on occasion, but the agreement was not consistent. There was no discernible pattern to the errors found; some observations were higher than the actual deflections and others were lower.

The photogrammetry data followed essentially the same pattern as it did for the surveying method: A scattering of observed deflections fell at random points in relation to the dial gauge data. Some observations compared very well with actual column deflections, while others were in error approximately ±10%.

In addition to showing comparison of deflections for various methods, Tables 2 and 4 also show the computed standard error of differences used for evaluating the accuracies of the various methods. The standard error of difference, σ_x, is computed by the equation

$$\sigma_x^2 = \frac{\Sigma(\delta_i - \bar{\delta})^2}{n - 1} \tag{9}$$

where

δ_i = the difference of the ith term

$\bar{\delta}$ = the mean of the differences

n = the number of differences

By computing the standard error of difference in this way, any first order systematic error is eliminated by computing the accuracies between the two methods being compared.

As shown in Tables 2 and 4, standard error of differences were computed for the various methods relative to results obtained by the dial gauges. The accuracy of the tilt sensor method was approximately 0.005 inches. The accuracy of the photogrammetry method varied from approximately 0.01 to 0.04 inches depending on the camera used, with the C120 camera giving the best results and the P32 camera the worst. One possible problem with accuracy of the P32 camera may have been improper lighting arrangements: a glare that made it difficult to aim accurately. The surveying accuracy varied from approximately 0.007 inches to 0.02 inches.

By performing essentially the same tests at a one-week interval, a check of the repeatability of the individual measurement methods was possible. The additional test (Column Test 1) also provided additional data for determining relative accuracies of the methods. Since results from both tests were similar, it may be concluded that the repeatability of the methods is good.

5.3. Interim Test

As previously mentioned, after the completion of Column Test 1 the load from increment C4 was maintained on the column for a one-week period prior to performing Column Test 2. The primary purpose was to check the stability of the tilt sensor and strain gauges. In addition, this test was used to determine the repeatability performance of the surveying and photogrammetry techniques, which would be highly dependent upon relocating the same control points as used in Column Test 1.

During the one-week period the tilt sensors and gauges were continuously monitored. The strip chart recorder was used to monitor the tilt sensor, and in addition periodic readings were taken on the console display. Table 6 shows observed differences between readings taken daily at the end of Column Test 1 and prior to Column Test 2.

As shown, a significant drift occurred in the strain gauge readings at all locations, while the dial gauge and tilt sensor readings were quite stable. The electrical drift of the strain gauges occurred even though the usual problem of "zeroing" the gauge readings was eliminated by keeping the strain indicator box constantly connected during the interim test period.

Table 6. Differences in daily readings for the interim test period between Column Tests 1 and 2.

Time After Column Test 1 (Days)	Dial Gauge Deflections (in.)	Calculated Deflections from the Tilt Sensor (in.)	Calculated Deflections from the Strain Gauge (in.)	
			Left	Right
		Location D1		
1	0.000	+0.0001	-0.015	+0.006
2	0.000	+0.0001	+0.013	-0.029
3	0.000	+0.0001	-0.029	-0.018
4	0.000	+0.0001	+0.013	-0.017
5	0.000	0.0000	+0.011	-0.012
6	0.000	0.0000	+0.006	-0.003
		Location D3		
1	+0.001	0.0000	+0.038	0.000
2	0.000	-0.0001	-0.041	+0.053
3	0.000	-0.0001	-0.008	+0.054
4	0.000	+0.0001	+0.025	+0.058
5	+0.001	+0.0001	+0.032	+0.053
6	+0.001	+0.0001	+0.054	+0.053
		Location D5		
1	-0.001	+0.0001	-0.051	0.000
2	0.000	-0.0001	+0.168	+0.050
3	0.000	-0.0001	+0.140	+0.052
4	-0.001	+0.0001	+0.138	+0.055
5	-0.001	0.0000	+0.144	+0.057
6	-0.001	+0.0001	+0.124	+0.062
		Location D7		
1	0.000	+0.0001	+0.028	-0.280
2	+0.001	-0.0002	+0.049	-0.064
3	+0.001	-0.0004	+0.050	-0.165
4	-0.001	+0.0001	+0.056	-0.210
5	-0.001	-0.0001	+0.038	-0.245
6	0.000	-0.0001	+0.045	-0.291

The changes in the X, Y, and Z coordinates (the X coordinate corresponds to in-plane column movement) from the surveying and photogrammetry techniques are shown in Table 7. Standard error of differences are computed in each coordinate direction and indicate that with the surveying method, repeatability may be obtained with an accuracy of σ_x, σ_y, and σ_z of 0.039 inches, 0.197 inches, and 0.039 inches, respectively. The large error denoted by σ_y is most likely due to a centering error of the theodolite. For the photogrammetry method using the Zeiss camera, the accuracy of repeatability was marked by values of 0.157 inches, 0.079 inches, and 0.079 inches for σ_x, σ_y, and σ_z, respectively. The large error in σ_x is most likely due to a pointing error caused by using an engraved marking on the tilt sensor. The markings were not well defined and caused some difficulty in making photographic measurements.

Although it is not shown in the Table 7, standard error of differences were computed for the other two cameras (P32 and C120) relative to the surveying method. The results for σ_x, σ_y, and σ_z were 0.354 inches, 0.079 inches, and 0.079 inches, respectively, for the P32 camera and 0.394 inches, 0.472 inches, and 0.079 inches, respectively, for the C120 camera. Thus it appears that a large format camera with a long focal length, namely Zeiss, gives better accuracy in the X and Y directions. Thus, for practical application, the Zeiss camera is desirable.

5.4. Beam Tests 1 and 2

Data from Beam Tests 1 and 2 consisted of measured deflections and rotations at various locations along the beam. Eight displacement

Table 7. Interim test data for photogrammetry and surveying collected between Column Tests 1 and 2.

Coordinate	Difference in Coordinates: Surveying (in.)	Difference in Coordinates: Photogrammetry (in.)
	Location D1	
X	0.000	0.039
Y	-0.157	0.157
Z	0.039	-0.079
	Location D3	
X	0.000	0.079
Y	-0.157	0.157
Z	0.039	-0.079
	Location D5	
X	0.000	0.118
Y	-0.157	0.000
Z	0.039	-0.039
	Location D7	
X	-0.039	0.079
Y	-0.157	0.039
Z	0.000	-0.118
	$\sigma_x^* = 0.039$	$\sigma_x^* = 0.157$
	$\sigma_y = 0.197$	$\sigma_y = 0.079$
	$\sigma_z = 0.039$	$\sigma_z = 0.079$

*Standard error of differences.

increments, identified as Load Cases B1 through B8, were applied at the beam end to create a rigid body rotation. The monitoring locations are shown in Fig. 24. Positions D1 and D6 correspond to tilt sensor and DCDT locations, respectively. Additionally, positions D2, D3, D4, and D7 reference the target locations utilized by surveying and photogrammetry equipment.

In making comparisons of the various measuring techniques, angular data from the tilt sensor were reduced to deflections at all monitored positions by assuming the member had rigid body rotation. In a similar manner, deflections at all positions were calculated based upon the DCDT and dial gauge data by a proportion based upon the assumption of rigid body rotation. Tables 8 through 11 summarize the results of the tests and show a comparison of deflection computed by the various techniques. As in Column Tests 1 and 2, a limited number of Load Cases were considered for the surveying and photogrammetry technique. The cases reported in Tables 8 through 11 correspond only to Load Cases B3 and B8. Photo data are excluded in Tables 8 and 10 because of an experimental error in obtaining the initial data. These tables include deflections measured and/or calculated at the end of Load Cases B3 and B8. Tables 9 and 11 include deflections determined by all the measuring techniques and correspond to differences in deflections that result from Load Case B3 to Load Case B8.

The comparisons between surveying, DCDT, and tilt data in Tables 8 and 10 indicate that the methods yield very consistent results. At each location except D1 in Beam Test 2, the surveying results were smaller and the tilt sensor results larger than deflections measured

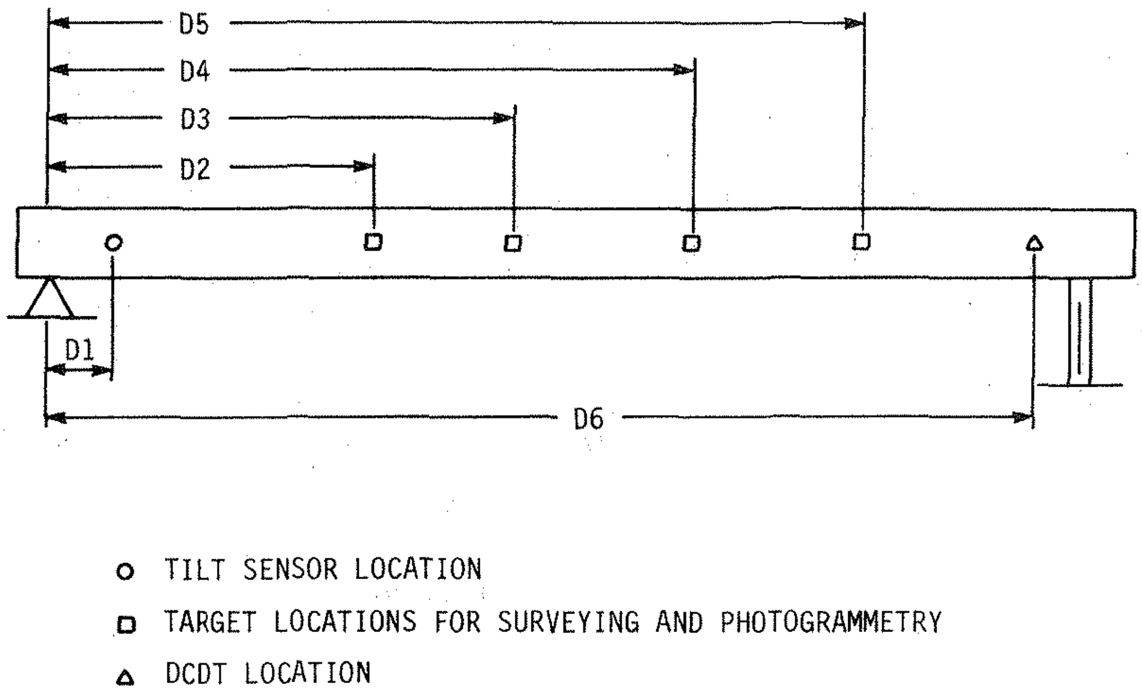


Fig. 24. Locations of monitored positions for Beam Tests 1 and 2.

Table 8. Comparison of deflections for load cases B3 and B8 of Beam Test 1.

Location of Displacement	Load Case	Surveying	DCDT	Tilt Sensor	δ = Surveying - DCDT	δ = Tilt Sensor - DCDT
D1	B3	0.029	0.047	0.048	-0.018[*]	0.001
D2	B3	0.172	0.194	0.196	-0.022[*]	0.002
D3	B3	0.090[†]	0.245	0.248	-0.155[*]	0.003
D4	B3	--[‡]	0.318	0.322	--[‡]	0.004
D5	B3	--[‡]	0.394	0.400	--[‡]	0.006
D6	B3	--[‡]	0.474	0.481	--[‡]	0.007
D1	B8	0.101	0.123	0.128	-0.022	0.005
D2	B8	0.469	0.498	0.523	-0.029	0.025
D3	B8	0.596[§]	0.627	0.660	-0.031	0.033
D4	B8	0.780[§]	0.815	0.857	-0.035	0.042
D5	B8	0.975[§]	1.040	1.068	-0.065	0.028
D6	B8	1.176[§]	1.241	1.283	-0.065	0.042
				σ_x[¶] =	0.0434	0.0162

[*] Not included in σ_x calculation.

[†] Experimental error.

[‡] Could not be determined because of experimental error at location D3.

[§] Extrapolated.

[¶] Standard error of differences.

Table 9. Comparison of deflections occurring from load cases B3 to B8 for Beam Test 1.

Location of Displacement	Load Case	Surveying	C120 Camera	P32 Camera	DCDT	Tilt Sensor	δ = Surveying - DCDT	δ = C120 - DCDT	δ = P32 - DCDT	δ = Tilt Sensor - DCDT
D1	B8-B3	0.072	0.05	0.05	0.076	0.080	-0.004	-0.026	-0.026	0.004
D2	B8-B3	0.297	0.276	0.276	0.304	0.327	-0.007	-0.028	-0.028	0.023
D3	B8-B3	0.506	0.354	0.354	0.382	0.412	-0.124	-0.028	-0.028	0.030
D4	B8-B3	0.808*	0.433	0.472	0.497	0.535	-0.311	-0.064	-0.025	0.038
D5	B8-B3	1.130†	0.63	0.598	0.646	0.668	-0.484	-0.016	-0.048	0.022
							σ_x‡ = 0.2130	0.0184	0.0096	0.0126

*Extrapolate.

†Experimental error.

‡Standard error of differences.

Table 10. Comparison of deflections for load cases B3 and B8 of Beam Test 2.

Location of Displacement	Load Case	Surveying	DCDT	Tilt Sensor	δ = Tilt Sensor - DCDT	δ = Surveying - DCDT
D1	B3	0.060	0.060	0.067	0.007	0.000
D2	B3	0.180	0.179	0.200	0.021	0.001
D3	B3	0.225	0.225	0.252	0.027	0.000
D4	B3	0.290	0.292	0.328	0.036	-0.002
D5	B3	0.359	0.364	0.408	0.044	-0.005
D1	B8	0.226	0.156	0.175	0.019	0.070
D2	B8	0.459	0.460	0.525	0.065	-0.001
D3	B8	0.589	0.592	0.662	0.070	-0.003
D4	B8	0.777	0.768	0.860	0.092	0.009
D5	B8	0.977	0.957	1.071	0.114	0.020
					σ_x^* = 0.0348	0.0227

*Standard error of differences.

Table 11. Comparison of deflections occurring from load cases B3 to B8 for Beam Test 2.

Location of Displacement	Load Case	Surveying	Zeiss Camera	DCDT	Tilt Sensor	δ = Surveying - DCDT	δ = Zeiss - DCDT	δ = Tilt Sensor - DCDT
D1	B8-B3	0.166	-	0.103	0.108	0.063	-	0.005
D2	B8-B3	0.279	-	0.305	0.325	-0.026	-	0.020
D3	B8-B3	0.364	0.354	0.394	0.41	-0.030	-0.040	0.016
D4	B8-B3	0.487	0.470	0.510	0.532	-0.023	-0.040	0.022
D5	B8-B3	0.618	0.630	0.635	0.663	-0.017	-0.005	0.028
						σ_x^* = 0.0392	0.0202	0.0086

*Standard error of differences.

by the DCDTs. The resulting accuracy indicated by the standard error of differences, σ_x, for surveying method was approximately 0.02 to 0.04 inches. Tilt sensor data indicated accuracies from approximately 0.02 inches to 0.03 inches.

Comparisons between all the methods used in Beam Tests 1 and 2 are shown in Tables 9 and 11. These data correspond to differences caused by incremental loading from Load Cases B3 to B8. As shown in Table 9, the data obtained from the two cameras (C120 and P32) and the tilt sensor indicate consistent differences relative to the DCDT data; whereas, the surveying data are erratic at locations D3, D4, and D5. The accuracy of the methods is illustrated by the calculated standard error of differences, σ_x, shown in the table. The large difference of 0.21 for the surveying method was caused by an observation error at location D3 using the theodolite. The differences indicate accuracies of 0.01 to 0.02 inches for photogrammetry.

In order to assess the accuracy of the tilt sensors further, the angular measurement was compared to an angle calculated from DCDT data and is shown in Table 12. Eight load cases and the angle calculated from the DCDT data based upon rigid body rotation are shown. In all cases the tilt sensor recorded angles greater than those calculated for rigid body rotation. However, the discrepency may be accounted for by considering that the values are within the ±5% linearity range associated with the sensors. Similar results were found for Beam Test 2 as shown in Table 13.

Table 12. Angles measured by the tilt sensor for Beam Test 1 compared to angles calculated from DCDT data.

Load Case	Measured Angle Tilt Sensor (arc minutes)	Calculated Angle DCDT (arc minutes)	Tilt Sensor Error (percentage)
B1	4.91	4.57	+6.9
B2	9.52	9.58	+0.6
B3	14.74	14.64	+0.6
B4	19.66	19.50	+0.8
B5	24.85	24.29	+2.3
B6	29.79	28.96	+2.8
B7	34.71	33.39	+3.8
B8	39.32	37.20	+5.4

Table 13. Angles measured by the tilt sensor for Beam Test 2 compared to angles calculated from dial gauge data.

Load Case	Measured Angle Tilt Sensor (arc minutes)	Calculated Angle Dial Gauge* (arc minutes)	Tilt Sensor Error (percentage)
B1	4.71	4.51	+4.2
B2	9.63	9.25	+3.9
B3	15.11	14.43	+4.5
B4	19.60	18.95	+3.3
B5	25.24	24.58	+2.6
B6	29.98	29.09	+3.0
B7	34.70	33.60	+3.2
B8	39.44	37.88	+4.0

*Data from dial gauge #1.

5.5. Beam Test 3

Test 3 involved the simultaneous testing of the tilt sensors by mounting the sensors at different locations along the horizontal member (see Fig. 25). No surveying or photogrammetric data were taken. As was the case in Beam Tests 1 and 2, the member end was systematically raised through an angular range corresponding to the limits of the sensor equipment. The increments of member end displacement are denoted as Load Cases 1 through 7. The member end deflections were recorded by a dial gauge and based on the assumption of rigid body rotation of the member, an angle of rotation was calculated. This angle was compared to the sensor angular readings.

Table 14 summarizes Beam Test 3 results. Each of the four sensor readings were consistently different from each other, with all but Tilt Sensor #4 recording angles larger than those calculated from the dial gauge readings. In all but a few cases, the difference between the tilt sensor and dial gauge readings were within ±5% of the measured angle. The problem with these specific cases could be attributed to experimental error. In some cases during the test, vibrations in the laboratory were apparently detected by the sensors, and these vibrations made it difficult to obtain a stable reading. On these occassions, the reading would fluctuate approximately 0.05 arc minutes, which is great enough to account for the discrepency mentioned above.

Note that in comparing the tilt sensor readings, two different sensors may disagree by as much as 10% of the angular measurement and still work properly because of their linearity range. One reading may

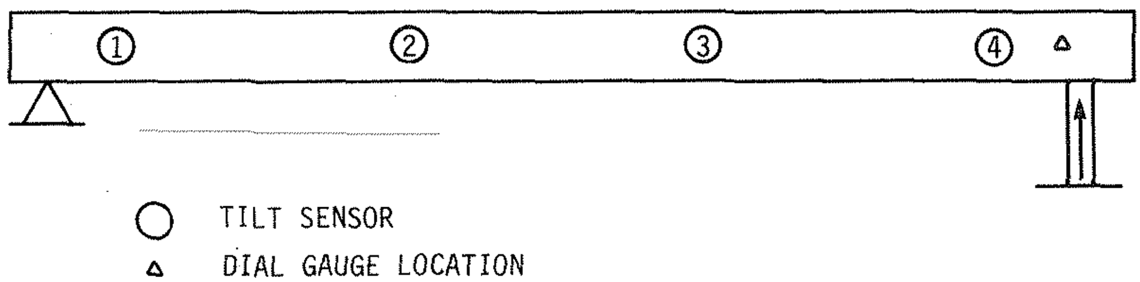


Fig. 25. Location of instrumentation for Beam Test 3.

Table 14. Angles measured by tilt sensors for Beam Test 3 compared to angles calculated from dial gauge data.

Load Case	Measured Angle Tilt Sensor (arc minutes) T.S. #1	T.S. #2	T.S. #3	T.S. #4	Calculated Angle Dial Gauge (arc minutes)
1	5.46	5.43	5.38	4.67	5.04
2	9.03	8.99	8.97	7.92	8.43
3	16.85	16.85	16.66	14.83	15.94
4	22.54	22.47	21.98	19.89	21.38
5	28.61	28.29	27.72	25.14	27.06
6	34.45	33.87	33.18	30.25	32.34
7	38.56	37.62	37.01	33.86	35.92

be 5% lower and the other 5% higher relative to the correct angle. Considering that the angular range in this test was approximately 40 arc minutes, the two sensor readings may differ by as much as 4.0 arc minutes. This explains the wide disparity between Tilt Sensors #1 and #4.

5.6. Beam Test 4

Data from Beam Test 4 consist of angles that were measured and calculated to determine the sensor's reliability and accuracy due to both static and nonstatic loading. Ten different displacement rates were applied to the end of the test member to create rigid body rotation to assess the accuracy relative to the nonstatic loading. Two limiting end displacements were considered (1/8 in. and 1/2 in.), and comparisons were made between the sensor angular measurement and the angle calculated from member end displacements based upon rigid body rotation. Table 15 summarizes the test results and shows the comparisons. Plots of the response data are shown in Fig. 26.

As the data in the plots indicate, and as was expected in the smaller movement cases, the tilt sensor reading was more accurate than the large movement case. The sensors have a settling time of 15 seconds, and it is apparent that the readings will be closer to the actual stabilized values given more time for the full movement to occur. If the load rate and the recorder angular value are known, a qualitative assessment may be made from these data as to the actual member displacement. Table 15 also shows the measured angle after the tilt sensor is stabilized. This angle is compared to the angle calculated for rigid

Table 15. Static and dynamic test results for Beam Test 4.

Maximum displacement 1/8 inch.

Time of Displacement (sec.)	Measured Angle Tilt Sensor #1 After 1 sec. (arc min.)	Measured Angle Tilt Sensor #1 Stabilized (arc min.)	Calculated Angle (arc min.)	Tilt Sensor #1 Error (percentage)
0.5	4.2	7.27	7.10	+2.33
5.0	4.9	7.25	7.10	+2.07
10.0	5.3	7.25	7.10	+2.07
15.0	5.8	7.24	7.10	+1.93
18.0	6.0	7.24	7.10	+1.93
20.0	6.1	7.24	7.10	+1.93
30.0	6.5	7.24	7.10	+1.93
40.0	6.7	7.23	7.10	+1.80
50.0	6.8	7.23	7.10	+1.80
60.0	6.9	7.23	7.10	+1.80

Table 15. (Continued).

Maximum displacement 1/2 inch.

Time of Displacement (sec.)	Measured Angle Tilt Sensor #1		Measured Angle Tilt Sensor #2	Calculated Angle (arc min.)	Tilt Sensor #1 Error (percentage)
	After 1 sec. (arc min.)	Stabilized (arc min.)	Stabilized (arc min.)		
0.5	18.6	29.27	29.27	28.65	+2.12
5.0	20.6	29.14	28.99	28.65	+1.68
10.0	21.8	29.11	28.99	28.65	+1.58
15.0	23.9	29.14	28.95	28.65	+1.68
18.0	25.1	29.15	28.95	28.65	+1.72
20.0	25.1	29.15	28.82	28.65	+1.72
30.0	26.6	29.10	28.95	28.65	+1.55
40.0	27.2	29.10	28.77	28.65	+1.55
50.0	27.7	29.22	29.10	28.65	+1.95
60.0	27.9	29.14	28.95	28.65	+1.68

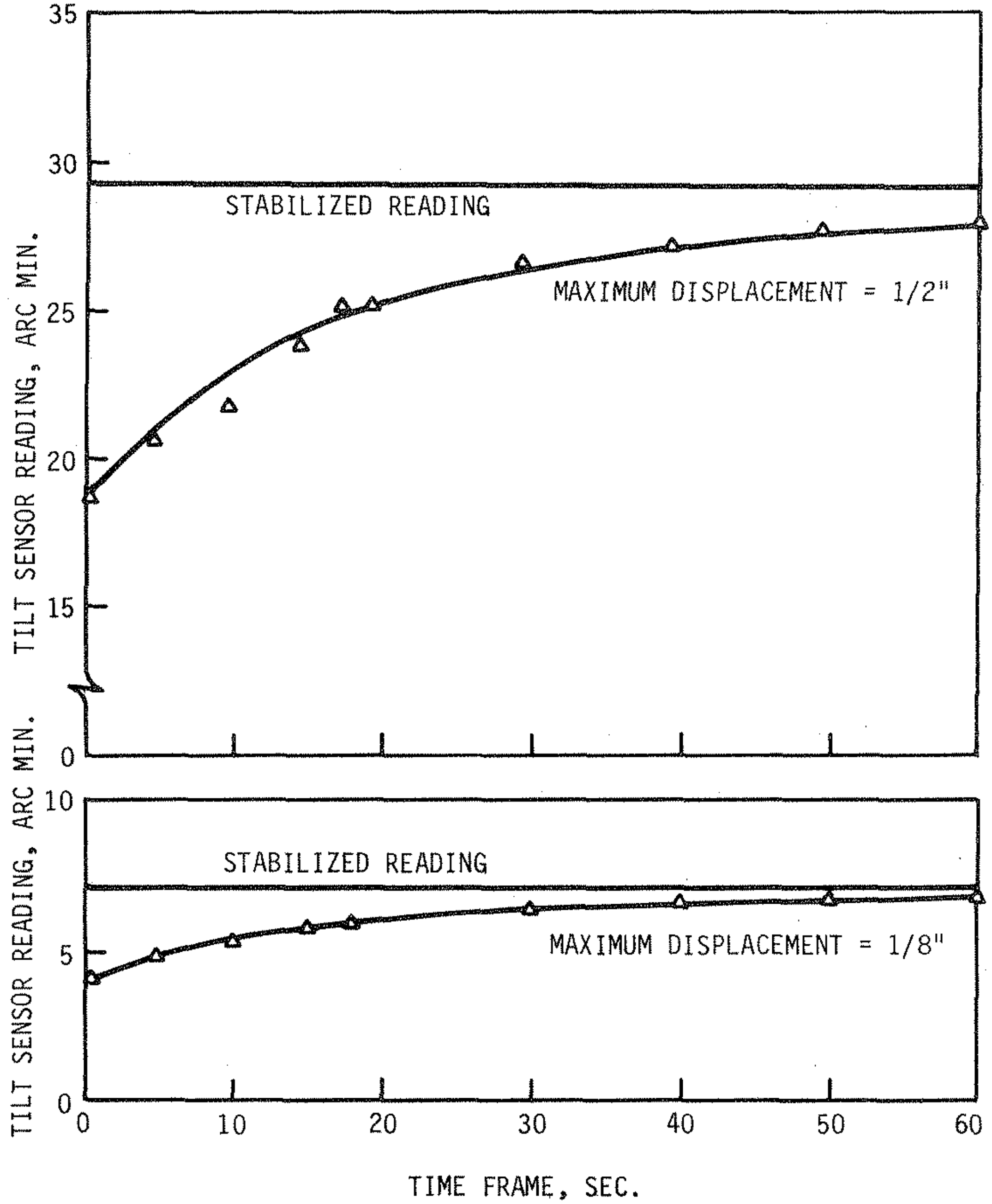


Fig. 26. Plot of response data for the tilt sensor.

body motion using the displacement data obtained from the MTS transducers. As shown for all cases, the difference in the angular readings is quite small and is well within the ±5% range associated with the sensors. The data from these tests further illustrate the excellent repeatability of the sensors' performance.

When the tests in this study were being set up, a concern was expressed that a possible error might exist in measurement if the tilt sensors and the member rotate through different vertical planes. When the sensor results were compared for all the beam tests, Beam Test 4 results were the best. This may be because Beam Test 4 conditions were the most favorable for eliminating possible out-of-plane movement.

6. SUMMARY AND CONCLUSIONS

6.1. Summary

The accurate measurement of long-term movement is very difficult to achieve in the field. Environmental conditions can create problems with instrumentation, and maintaining fixed reference points from which to make measurements is extremely difficult. Instrumentation and techniques that are used successfully in the laboratory are inadequate in many cases for field use.

Two specific applications have been identified in Iowa where long-term movement data are needed. One example involves the Mississippi River Bridge in Lansing, Iowa. Accidental barge impacts have occurred with the main span pier over the past few years, and concern exists as to whether any permanent pier misalignment has occurred. In another case, the magnitude of stresses induced in an abutment piling of integral abutment bridges is the concern. In prior studies sponsored by the Iowa DOT, analytical models have been developed to predict pile stress behavior that is due to bridge longitudinal movement. Field information on actual overall bridge movement is needed in order to validate the model.

The literature study identified a number of methods and types of instrumentation for monitoring field movements. Techniques related to surveying, dial gauges, strain gauges, tilt sensors, and methods that could be classified as mechanical in nature were included in the study. These mechanical methods are best described as involving combinations of the previously mentioned methods and instruments. An assessment was made of these methods as to their feasibility in making measurements for the applications identified earlier.

The laboratory testing program, which was set up to study the applicability of photogrammetry and tilt sensor instrumentation and techniques in the field, was effective. Tests were devised to evaluate these methods' reliability, accuracy, and ease of use. Tests also determined shortcomings regarding possible use of the various methods. Vertical column and horizontal beam members served as the test members and allowed member curvature and rigid body rotation to be simulated. Laboratory dial gauges and strain gauges provided reference data to verify deflection determined by various methods.

The tilt sensors were found to be very precise and sensitive instruments. They were simple to operate, and their repeatability performance was excellent. The entire sensing system has the capability of continuously monitoring, which, along with its excellent stability over time, makes it very useful for making long-term measurements. However, an important limitation of the system is its inability to monitor direct translations. The sensor monitors tilt or angular change and, therefore, requires knowledge of the center of rotation or the type of member end conditions. Because of the tilt sensors' inherent tolerance in angular measurement, which is directly proportional to the measured angle, more accurate measurements of deflections are possible if small angles are involved. The effect of the structure's out-of-plane movement to the in-plane movement as measured by the sensors is minimal and may be neglected. The sensors are intended for measurement of static movement and will yield inaccurate results if applied in a nonstatic environment.

Analytical photogrammetry proved to be a feasible method for making accurate measurements provided that a sensitive camera was used. Three cameras were used in the study, two of which were stereo cameras. The Zeiss stereo camera was shown to be the most accurate. The photographs from this camera were of the highest quality and made data reduction with a comparator easier to perform. The camera's accuracy for long-term movement will be greatly dependent upon being able to reestablish the camera control point. Also, the method is very dependent upon accurately establishing and maintaining additional control points. The type of target used is important to the accuracy attained with this method. Background lighting is also an important parameter for making accurate measurement.

The surveying method provided accuracies similar to the photogrammetry method, except for a few cases where human error caused significant errors. Many of the problems associated with photogrammetry also apply to surveying methods, since gaining and maintaining control and using proper targets for accurate sighting are common concerns. The method's accuracy may be improved by establishing a larger baseline for horizontal control. Obtaining data by surveying is much more time consuming compared to the photogrammetry method.

Recommendations for field application procedures have been made for the methods considered in this study. It is clear from this study that no one method of obtaining long-term movement data would provide the best results for every application. The problems associated with obtaining movements for a typical integral abutment bridge are obviously different than those associated with a major river crossing structure, such as the Mississippi River bridge in Lansing, Iowa. However, using the recommended field application procedures, a proposal could be written and detailed procedures could be designed to obtain data in the field.

6.2. Conclusions

The following conclusions were developed as a result of this study:

1. Tilt sensors are very stable, precise, and sensitive instruments.

2. Tilt sensors will provide better accuracy if angular movements are small when measuring deflection.

3. Tilt sensors are unable to monitor nonstatic movement accurately.

4. Tilt sensors should provide accuracy within approximately 0.02 inches when measuring deflections, provided that reasonably accurate assumptions are made regarding the member's center of rotation.

5. Analytical photogrammetry accuracy is related to lighting, the type of target, and the ability to gain control of the camera setup point and background reference points.

6. Photogrammetry data indicated that the camera orientation changed slightly for each exposure. Care must be taken to restrict the camera's orientation.

7. A large format stereo camera with large focal length provides the best accuracy.

8. Photogrammetry should provide accuracy within 0.02 inches in measured deflections. Accuracy attainable in the field will be dependent upon the distance the camera is located from structure.

9. Since photogrammetry accuracy may be determined within 0.02 inches when the camera is located approximately 10 meters from the member, it is expected that movement may be detected within an accuracy of 0.02 inches when the camera is 100 meters from the member.

10. The most probable error in the surveying method was centering the theodolite. This could be improved by using well-defined survey stations.

11. The accuracy of the surveying method was about 0.03 inches. This may be improved by using a least squares adjustment method using three or more stations, as well as using first order triangulation procedures with theodolites that make measurements to an accuracy of 0.2 seconds of arc.

12. The most probable error in the photogrammetry method was due to a pointing error on the target. This could be improved by using targets with better defined reference lines.

7. RECOMMENDED STUDIES

This study has shown that tilt sensor and analytical photogrammetry techniques can be used accurately in the measurement of long-term structural movements. In view of the results of this study, the following is recommended:

- One or more bridges should be monitored for long-term movement utilizing the tilt sensing system and analytical photogrammetry methods. Monitoring should occur over a time frame of 1 1/2 to 2 years.
- Additional laboratory testing should be performed to determine the feasibility of using tilt sensors as displacement transducers to measure deflections directly for certain applications. This recommendation also applies to other possible transducers, such as a linear variable displacement transducer (LVDT) or any mechanical-type method.

8. ACKNOWLEDGMENTS

The study presented in this report was conducted by the Engineering Research Institute of Iowa State University and was sponsored by the Highway Division, Iowa Department of Transportation, through the Iowa Highway Research Board under Research Project HR-275.

The authors wish to extend appreciation to the engineers of the Iowa DOT for their support and cooperation. Sincere appreciation is extended to Vernon J. Marks, Research Engineer, Iowa DOT; and Lowell F. Greimann, F. Wayne Klaiber, and Wallace W. Sanders, Jr., Professors of Civil Engineering at Iowa State University. Appreciation is also extended to the following firms who provided services in the laboratory investigation: Dennett, Muessig, Ryan and Associates of Cedar Rapids, Iowa, and Aerometric Engineering of Sheboygan, Wisconsin.

Special thanks are given to the following students for their assistance in various tasks of the project: Douglas L. Wood, Paul Free, Marlee Morse, Edward Kasper, and Supachi Sirayanone.

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10. APPENDIX A:

RECOMMENDATIONS AND PROCEDURES FOR FIELD APPLICATION OF BRIDGE MEASUREMENT

This section briefly describes the procedures used to make field measurements using the instrumentation investigated in this study. The recommendations are based on the literature review and the laboratory testing.

It is anticipated that any direct translations of the pier on the Lansing Bridge are small. Therefore, the primary cause of deflection will come from the pier's rotation because of the barge's impact. While the magnitude and direction of the applied force is uncertain as is the resulting pier displacement, the pier's movement may be resolved in directions parallel and perpendicular to the center line of the bridge. It is suggested that the tilt sensor system be used to monitor these movements. Proposed instrumentation of the pier is shown in Fig. A.1. Two tilt sensor units, one attached on the pier's side face and another on the pier's front face, could monitor anticipated pier movements.

Because of the massive size of the pier, little if any member curvature can be assumed to occur. Pier displacement may be probably best described as rigid body rotation. Therefore only one tilt sensor unit is necessary to monitor pier movement in each direction as suggested. In this case the pier's base is assumed to be stationary with rotation occurring about this location. Movement of the pier foundation is not considered probable given the relative size of the structure and the assumed foundation support.

In considering movements of the integral abutment bridges, both the abutment's translation and rotation must be considered. Temperature effects causing expansion and contraction of the bridge superstructure can displace the entire abutment horizontally along the bridge's center

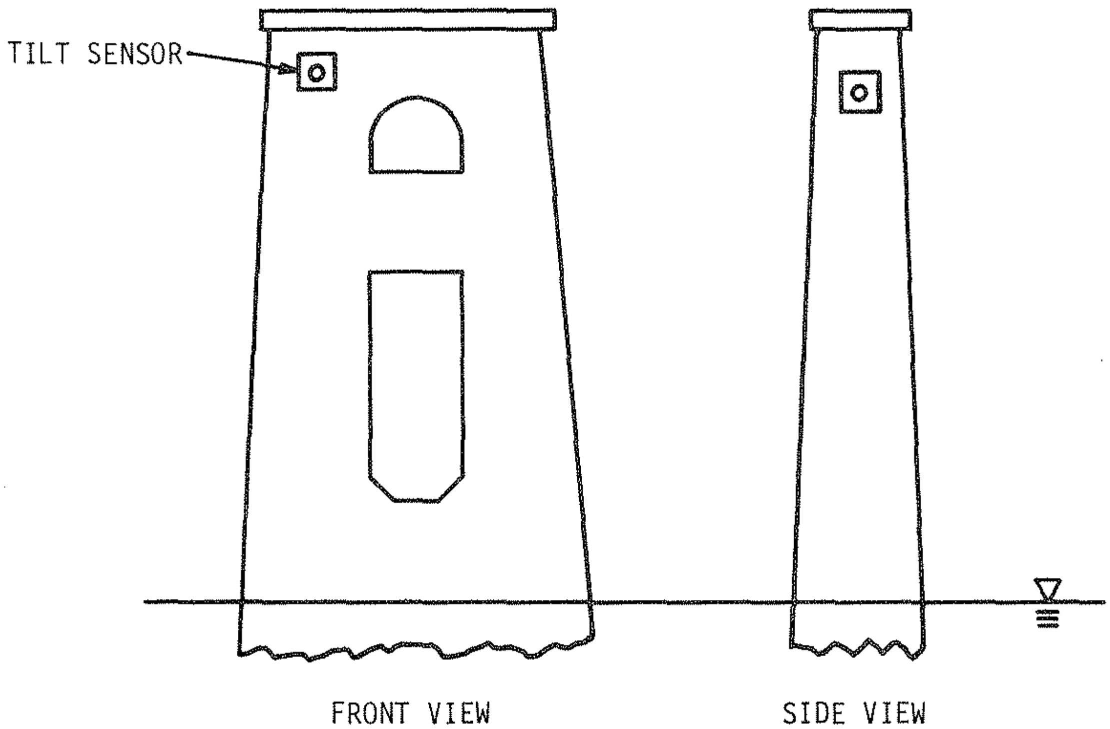

Fig. A.1. Tilt sensor arrangement for monitoring pier movement.

line as well as cause abutment rotation. Monitoring abutment rotation may be performed using the tilt sensor system, which may involve mounting a single tilt sensor unit at a convenient location on the side face of the abutment's diaphragm. Rotation of the abutment is essentially that of a rigid body because of a large width-to-depth ratio of the abutment, so again a single tilt sensor unit is sufficient to monitor rotational movement. In order to monitor abutment translation, a mechanical device in combination with another tilt sensor unit may be used to record abutment motion continuously. Because the tilt sensor can only measure the angular rotation of an object, it is necessary to convert abutment translation into a rotation. To accomplish this task, a fixed reference point must be provided about which a rotation may be measured. Once a reference point is established, connections may be made tothe tilt sensor unit that is allowed to rotate as translations occur. The tilt sensor unit could be mounted on the abutment itself or on a simple frame connected to the abutment. Figures A.2 and A.3 show these two possible setups. Possible problems exist in locating a reference point near the abutment where the reference point could be subject to movement by earth pressures from abutment movement. While the advantage in using the tilt sensor system (that of making use of a gravity reference thereby eliminating the need to maintain some fixed reference point) is lost in having to establish another reference location, making use of other tilt sensory system components required for monitoring of abutment rotation is feasible.

The use of analytical photogrammetry is recommended for monitoring movement of both the integral abutment and the Lansing bridge. Applica-

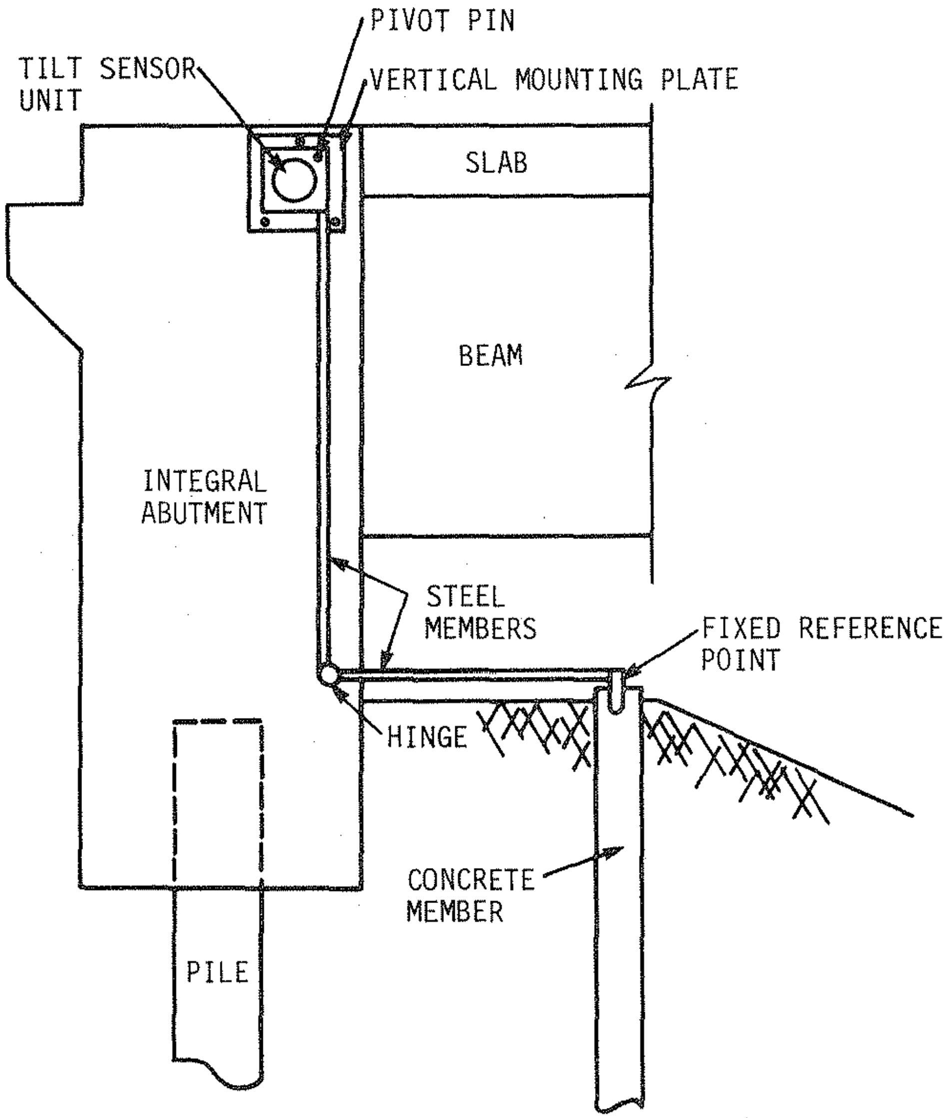

Fig. A.2. Tilt sensor arrangement for monitoring abutment translation (alternative 1).

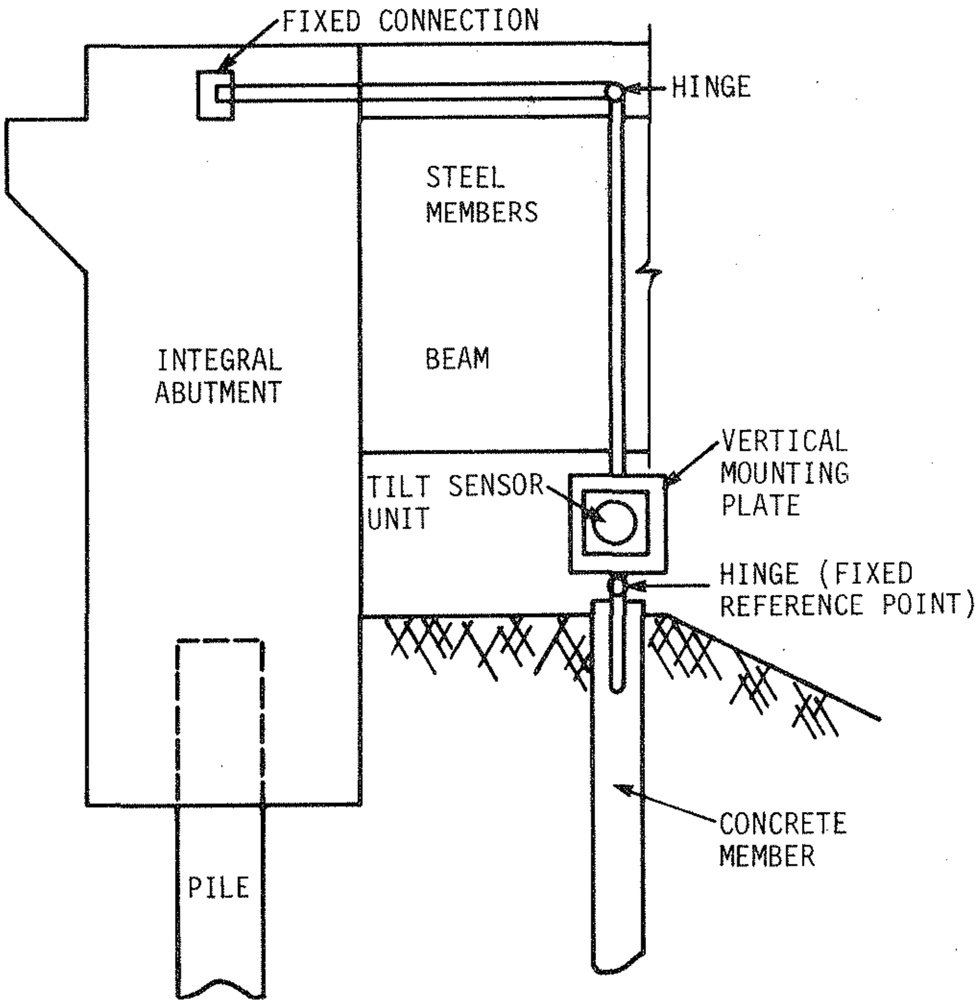

Fig. A.3. Tilt sensor arrangement for monitoring abutment translation (alternative 2).

tion of the method would require the establishment of a minimum of six permanent survey control markers on one side of the bridge. In addition, two camera stations would be required on the opposite side of the bridge. The control markers will need to be monitored to ensure no unknown movement occurs.

The Zeiss stereocameras should be used, and the coordinates of the camera stations should be determined by three-dimensional triangulation. Distances as large as possible should be maintained between camera stations. Coordinates of all other control points should be determined by using first-order triangulation, trilateration, and precise leveling.

The collected data should be processed by an analytical dynamic calibration mode, which would give the X, Y, and Z coordinates of the points that are monitored on the pier together with their standard errors. Using periodic measurement it will be possible to determine their three-dimensional displacements and their statistical confidence level.

11. APPENDIX B:

DISCUSSION OF EXPECTED ACCURACY FOR MEASUREMENT METHODS USED IN COLUMN AND BEAM TESTS

This section briefly describes the accuracy that could be expected for the tests conducted in this study. Discussion follows for the various methods considered.

11.1. Tilt Sensing System

Using Eq. (2) in the text of this report, it may be stated that the deflection ΔX is related to the measured angle θ by the relationship

$$\Delta X = \frac{\theta Z}{2}$$

If the error in the measured angle θ is approximately 0.01 arc minutes (0.000003 radians) and Z = 10 ft, the error is the calculated deflection, $\delta(\Delta X)$, is given by

$$\delta(\Delta X) = \frac{\theta Z}{2} \qquad \text{(B1)}$$

$$= 10/2 \times 12 \text{ in.} \times 0.000003 \text{ radians}$$

$$= 0.0002 \text{ in.}$$

For this specific case, the resulting sensor resolution would be less than the desired accuracy of 0.001 in.

11.2. Analytical Photogrammetry

This discussion relies on equations and figures from Section 3. Referring to Figs. 8 and 9, the accuracy of the ground coordinates, X and Y, or a point, P, depends on the accuracy of the photo coordinates.

If $k \cong \phi \cong w \cong X_o \cong Y_o \cong Z_o = 0$ (thereby implying that no error exists in camera nodal points resulting in a perfect camera setup), we have from Eqs. (3) and (4)

$$x = f \frac{X}{Z} \quad \text{or} \quad X = \frac{Z}{f} x$$

therefore,

$$\delta X = \frac{Z}{f} \delta x \tag{B2}$$

Assuming that the measurement of the photo coordinate is performed with a comparator having an accuracy of 0.005 mm, the error in the X-ground coordinate, δX, for a focal length of f = 60 mm and a distance from the object P to the camera of Z = 6 m is

$$\begin{aligned} \delta X &= \frac{Z}{f} (0.005) \\ &= \frac{6}{60} (0.005) \\ &= 0.0005 \text{ m} \\ &= 0.02 \text{ in.} \end{aligned}$$

Thus, the accuracy obtained by analytical photogrammetry of the X and Y coordinates is about 0.0005 m. This is less than the desired accuracy of approximately 1 mm or 0.039 in.

The accuracy of the Z coordinate can also be determined from Eq. (B2), although it is not of great interest since this coordinate refers to out-of-plane movement. As before, if $X_o = Y_o = Z_o = k = \phi = w = 0$ for photo #1, then

$$x = \frac{f}{Z} X$$

and if $X_o = B$ (the distance between the lenses on the stereo cameras), $Y_o = Z_o = k = \phi = w = 0$ for photo #2, then

$$x' = \frac{f}{Z} (X - B)$$

Taking the difference between x and x', we obtain

$$x - x' = \frac{f}{Z} B \quad \text{or } Z = \frac{fB}{x - x'} \tag{B3}$$

Calling $p = x - x'$, Eq. (B3) can be written as

$$Z = \frac{fB}{p} \tag{B4}$$

Then the error in the Z coordinate, δZ, is given by

$$\delta Z = \frac{fB}{p^2} dp \tag{B5}$$

Selecting Z = 6 m, f = 60 mm, and B = 2 m, we obtain

$$p = 20 \text{ mm}$$

and if $dp = \sqrt{dx'^2 + dx^2} = 0.005$ m, then from Eq. (B5)

$$\delta Z = \frac{fB}{p^2} dp$$

$$= \frac{60 \times 2}{400} (0.005) = 0.0015 \text{ m}$$

For B = 1 m, we obtain

$$\delta Z = \frac{35}{60} \times (0.005) = 0.003 \text{ m}$$

Thus the obtainable accuracy in the Z coordinate is about 1 mm to 3 mm depending on the distance B, which is a stereo camera variable. By substituting Eq. (B4) into Eq. (B5), we obtain

$$\delta Z = \frac{Z^2}{fB}\, dp \tag{B6}$$

Note that the accuracy in the Z direction increases with increasing Z and decreases with increasing f.

11.3. Surveying

As mentioned in the description of the test setup in Section 4, the baseline for calculations by this method was measured as 5 m. Also, the angles were measured with instruments with least counts of ±1 second (0.000005 radians) and distance measurements were made with an instrument with a least count of ±0.001 m. It may be concluded that since the distances AC and BC are approximately 6 m (see Fig. 10), the accuracy of distances AC and BC is likewise correct to within ±0.001 m. The accuracy of the X coordinate of the object P, based upon the location defined by the coordinates (X_1, Y_1, Z_1), is given by

$$\delta X = \delta X_1 = AC(\cos\alpha)\delta\alpha + (\sin\alpha)\delta(AC) \tag{B7}$$

If $\alpha \cong 60°$ (as in the tests conducted in this study, $\alpha_1 \cong \alpha_2 \cong 60°$) and the other actual test values are considered for the parameters in Eq. (B7) i.e., $\delta\alpha = 0.000005$ *radians*

$AC = \cong 6$ m

$\delta(AC) = 0.001$ units

we obtain

$\delta X = 0.0005$ m (assuming $\delta X_1 = 0$)

Thus for α and B approximately equal to 60°, the errors in the X and Y coordinates is less than a desired value of 1 mm or 0.039 in.

For the tests performed in this study, the vertical angle, θ, is less than 30°, and hence the error in the Z coordinate (because of instrumental error) is also less than 1 mm. However, the vertical angle is affected by refraction. The *maximum error due to refraction* is known to be about 20 seconds (0.0001 radians). The error in the Z coordinate, δZ, is given by

$$\delta Z = AC \sec^2 \theta \, d\theta$$
$$\cong AC \, d\theta \qquad (B8)$$

for $AC \cong 6$ m and $d\theta = 0.0001$ radians, we obtain

$\delta Z = 0.0006$ m

This is also less than the desired maximum of 1 mm. In conclusion, the error in the measured coordinates X, Y, Z *are less than 1 mm* (0.039 in.) for the given test conditions.

The baseline for making surveying measurements was not parallel to the axes in which the member deflections were taken (see Fig. B.1). The relation that was used to correct this misalignment was

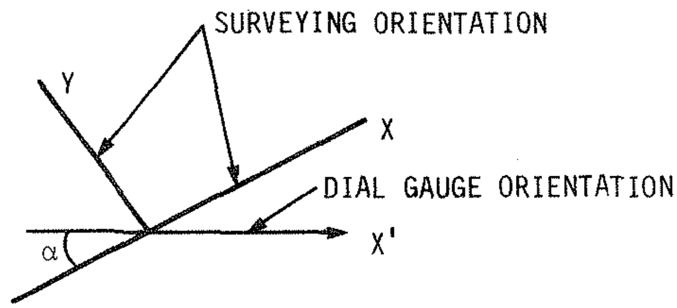

Fig. B.1. Axes' orientation for surveying calculations and movement's orientation as measured by dial gauges.

$$\Delta X' = \Delta X \cos\alpha - \Delta Y \sin\alpha \tag{B9}$$

where

$\Delta X, \Delta Y$ = survey coordinate deflections

$\Delta X'$ = deflection along dial gauge axes, X

α = angle between surveying and dial gauge axes