PHOTOGRAMMETRIC METHODS OF MEASURING DEFORMATIONS IN ARCHITECTURE

ABSTRACT

A photogrammetric system for the measurement of active displacements in architectural and engineering structure is briefly summarized. The factors which limit the ultimate accuracy of structural deformation measurements also have their influence on the limits of accuracy atteinable in photogrammetric projects for the recording of historic buildings and monuments.

In certain cases, photogrammetry can be the most efficient method for measuring movements of architectural and engineering structure under conditions of use.

PURPOSE OF DEFORMATION MEASUREMENTS

Because of changes of loading, wind, temperature and humidity, architectural and engineering structures are generally in movement within limits which, if properly anticipated in design, are not destructive and may be hardly perceptible. The measure of movement in such structures, by photogrammetric or other methods, can be first a means of examining the adequacy of structural theory in new structures, and second a check of the continued strength and safety of older structures under new conditions of use.

THE PHOTOGRAMMETRIC PROCEDURE

In principle, the measurement of structural movement requires the use of phototheodolites or other precise cameras of fixed interior orientation to take - at intervals of time - series of successive photographs upon flat photographic plates and emulsions from fixed camera stations along fixed camera axes. Pairs of the developed photographic plates from the same camera station are measured together in a stereocomparator. When the axes of viewing are rotated to read the displacements in both coordinate directions successively as horizontal parallaxes, there is identification of movement - even in parts of the structure where it had not been anticipated - through stereoscopic advance or recession in relation to a background of stable elements or to a foreground of survey control within the image.

Two camera stations, with strongly convergent lines of sight, are necessary to measure three-dimensional movement in architectural structure. Relative movement in two image planes, as measured in successive plates from each of the two stations, is then resolved by intersection into movement of the structure in object space. The correspondence between successive pairs of plates which are measured together effectively eliminates systematic error caused by lens defects; and relative measurements of the plates make possible the measurement of structural movements with greater accuracy than measurement of the structure itself.

In practice, the procedure departs from the ideal by small deviations which are measurable in the stereocomparator. The photographic plates are never exactly aligned with each other in the stereocomparator; and there will have been small displacements in re-establishing the camera at the fixed camera station. Even when the camera has remained in position at the station, there will be small rotations from the fixed camera axis caused by loading of photographic plates and realignment. Most seriously, the pairs of plates and emulsions will differ in flatness. The movements to be sought in architectural structure are often so small that they are apparent only after extensive adjustment computation, and they may not draw the attention of the operator of the stereocomparator. Changes of illumination of the measuring points may require compensation for movement of shadow texture or highlights.

The first studies at the Ohio State University in photogrammetric measurement of building movement revealed substantial radial error in the measurements, caused by lack of flatness of the photographic plates and emulsions. The greater reliability of tangential parallax measurements across the fiducial axes of the photogrammetric plates was evident.[1] Subsequent studies established a photographic procedure and an adjustment procedure, which have been published,[2] for isolating and correcting relative radial error in the plates, with no absolute determination of the flatness of any one photographic plate required. With substantial correction of relative radial error, the standard error of measurement in the photographic image has varied from 1/9.000 to 1/50.000 of the width of the image with various photogrammetric cameras.[3]

ADJUSTMENT COMPUTATIONS

For a project of photogrammetric measurement of active displacement in structure, the initial planning of photography and survey control must allow an efficient program of adjustment computations to correct the data and to determine its final accuracy in terms of standard error of measurement in object space. The requirements for accuracy of measurement affect the choice of camera stations. A relatively constant error of measurement in the image plane grows proportionally with distance of projection into object space, and an acute intersection of lines of sight from two camera stations exaggerates the error in one of the coordinate directions of object space. The camera stations and survey control must be permanently established for return to position to record long-term movements. In almost all cases with more than one camera station, simultaneous photography with more than one phototheodolite is desirable to isolate such movements as the slow rebounding of foundations after release from heavy loading. Otherwise such movements become a part of the standard error of measurement.

When two phototheodolites are used, with rotation to divergent axes to isolate radial error, the total mathematical program for adjustment of measured data comprises more than 300 equations for constants, efficient groupings of parallax data, and correction equations to :

Adjust the alignment of pairs of plates in the stereocomparator to each other on the basis of parallax measurements of the fiducial marks and pressure points of the camera frame recorded on each plate.

2. Adjust relative camera displacements and rotations of camera axes within pairs of plates on the basis of parallax measurements of the survey control points within the two images.

3. Adjust the parallax data to correct the relative radial error discovered in pairs of plates.

4. Calculate the propagation of error through the first three stages of the adjustment procedure.

Project rays from the two camera stations through x and y coordinates of measuring points in the images to intersection at the measuring points in object space; and enlarge the scale of the adjusted parallaxes in the images to the scale of object space at each measuring point.

6. Transform image coordinate displacements in object space to displacements on and normal to the epipolar planes through the measuring points, and determine the dimension by which the displacement rays miss intersection as additional evidence of the accuracy of the measurements.

Determine an adjusted intersection of rays on the normal to the epipolar plane according to the magnitude of the image plane errors after projection into object space.

8. Translate the adjusted intersection of displacement rays into structural displacements in the coordinates of object space.

9. Express the standard error at each measuring point in the coordinate system of object space.

MODIFICATIONS OF THE PHOTOGRAMMETRIC PROCEDURE.

When a sufficient number of measuring points may be clearly marked by signals or lights, the measurement of movement during an interval of time can be recorded directly on a single photogrammetric plate by double exposure or by continuous exposure in darkness. This is particularly appropriate for tests under loading. Several of the early stages of the adjustment procedure are no longer necessary in this case, and radial error is practically eliminated.

As surface temperatures are prominent causes of structural movement, an attempt should be made to record these photogrammetrically on infra-red emulsion with a form of thermal survey control through temperature gauges on object surfaces recorded in the photographic image.

APPLICATION TO PHOTOGRAMMETRIC PROCEDURE FOR THE RECORDING OF HISTORIC BUILDINGS AND MONUMENTS.

From the experience of photogrammetric measurement of structural movements the following may be stated for projects of photogrammetric recording of historic buildings and monuments :

First, buildings move. In the case of engineering structures of architectural ruins exposed to extreme temperature changes without the restraint that occupied buildings have from constant interior temperature, the movement may be a significant factor in standard deviations of heights of towers in different elevation plottings. Architectural features such as church steeples must be considered less than ideal as photogrammetric control points because of the bowing of such structures with wind and the travel of sunlight and shadow.

Second, lack of flatness of photographic plates and emulsions must be considered the major factor in the standard error of adjustment upon survey control in architectural photogrammetry. The resulting radial errors are exaggerated by the wide-angle photography appropriate to the subject. Photographic equipment should be examined to assure absence of bending moment in the photogrammetric plate between plateholder springs fiducial marks are recorded by light entering through the lens, for measuring of the distance between fiducial marks will indicate bending of the photographic plate and may suggest a partial compensation of radial error through adjustment of the principal distance of inner orientation in a first order plotting instrument. The orthographic projection of fidudial marks by a separate lighting system does not reveal the bending of the plates.

CHOICE OF METHOD IN THE MEASUREMENT OF STRUCTURAL MOVEMENTS.

There are elaborate provisions for measuring the movements of some structures, such as dams, with first order theodolites and micrometer readings of plumblines with oscillations restrained in oil at the base of shafts through the structure.[5] Photogrammetric measurement is not as accurate as direct measurement when a few well-chosen and prepared measuring points can reveal the essentially uniform movement of a structure.

Photogrammetry is appropriate for measurement of structural movements when there can be good photographic coverage of structure with survey control free from the movement being studied in the structure, when there must be minimum disturbance to normal traffic and use of the buildings, and when there are complex flexures and redistribution of stresses under change of load and dimension, so that hundreds of displacements should be recorded in a single moment, with later discovery of structural movement where it may never have been anticipated. Pioneering works of engineering and architectural structure are among the monuments which deserve this type of photogrammetric investigation.

REFERENCES

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ments in architecture", International Archives of Photogrammetry, 1964.

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