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Profiling of Structural Members using Shadow Speckle Metrology

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ABSTRACT

This paper describes the application of a computer-based optical method, shadow speckle metrology, for profiling the surface of large structural members. Artificial speckles are projected onto the surface being studied, and the resulting speckle patterns are digitally recorded as the surface changes shape. The apparent in-plane movement of the projected speckles is computed by numerically correlating small subsets extracted from each pattern. These shifts are related to the profile of the surface with respect to a reference shape. The main advantages of the technique are that it can be applied to any surface, it is non-contact and non-destructive, and the analysis is completely automated. Sensitivity can be varied over a wide range, and tests can be conducted in daylight and under field conditions.

INTRODUCTION

Profiling of large structural members is important in many fields, especially in cases where local buckling of thin structural elements is permitted. Such members are found in earthquake resistant designs and in modern aircraft. Whether these structures are designed for compression, shear, or combined loadings, they all require a thorough, accurate, analytical approach to optimum design. In many cases, experimental tests help to provide the necessary data base to complement or verify the analysis.

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Perhaps the oldest and best known method for profiling structural members is photogrammetry where the basic approach is to photograph an object with one or more precision cameras from different incident angles and then to superimpose these photos to form a three-dimensional image of the object. Out-of-plane displacements which create the three-dimensional image are determined by measuring shifts relative to a known reference point.[1] An alternative approach for measuring out-of-plane displacements is the shadow moiré method in which a reference grating is placed in front of the test surface. When illuminated at an oblique angle, the reference grating casts a shadow on the surface, and the shadow deforms as the surface moves relative to the reference grating. The lines of the reference grating superimpose with those in the shadow to form a moiré which can be analyzed to determine surface deformation.[2]

Improvements have been made in both of these techniques by incorporating optical and image processing equipment for data acquisition and analysis. For example, Kahn-Jetter and Chu recently introduced a technique based on photogrammetry that combines stereoscopic analysis and digital image correlation techniques.[3] Two sets of stereo images are recorded for an undeformed and deformed test surface painted white and splattered with black paint. Digital image correlation techniques are applied to determine displacement. Sang *et al.* developed a simple method based on shadow moiré for measuring local buckling of thin walled members by projecting a pattern of parallel equispaced lines on a test surface.[4] These lines are tracked by a computer and changes in their locations are related to movements in the out-of-plane direction.

Each of these automated methods has its limitations. Problems encountered in the first approach include errors due to movement of one camera simulating two cameras, the camera tilt, limited depth of field, and measuring accurately the geometrical parameters required for subsequent analysis. The second approach is best suited for analysis of test surfaces where curvature is significant only in one direction. Ambiguities can arise in determining the sense of the out-of-plane motion when the apparent movement of the projected grid exceeds its pitch.

In general, the shadow moiré technique is much simpler than photogrammetry; however, the capability of photogrammetry to define buckle geometry far exceeds the capability of shadow moiré. Differences between the two techniques are particularly evident when trying to make peak–valley distinctions on a deformed surface. This is extremely difficult in the case of shadow moiré.

Ideally, a profiling technique should be sophisticated enough to fully characterize the test surface, yet simple enough to allow a technician to make the required measurements easily. To meet these constraints, the authors developed a computer-based technique, called shadow speckle metrology,[5] which combines the simplicity of shadow moiré and the sophistication of photogrammetry. Prior developmental research in this area includes a study of rigid body rotation,[5] contouring of a curved surface,[5] and deflection of a flat plate through a fiber optic system.[6] All of these tests were conducted under laboratory conditions and on relatively small objects (all test surfaces were contained within a 20 cm radius).

In contrast to these laboratory studies, this paper demonstrates that shadow speckle metrology can be applied to contour a relatively large structural component having complex geometry, and the more important feature is that deformations can be measured under field conditions. The following section describes the basis for the approach and gives the fundamental expressions used for analysis.

SHADOW SPECKLE METROLOGY

Numerous investigators have used 'speckles' to measure displacement, deformation, and strain.[7] Speckles can be either laser generated or artificially produced, and are classified as being objective or subjective depending upon the manner in which they are recorded.[8] Objective speckles localize throughout the space surrounding a test surface and can be captured directly on a photographic plate positioned in that region. Subjective speckles, on the other hand, localize on the object and can be photographed through a lens system by focussing on the surface. While this nomenclature is usually applied to laser speckles, both objective and subjective artificial speckles exist. For example, artificial subjective speckles can be generated on an object by splattering paint on its surface. These can be used for profiling as demonstrated in the work of Kahn-Jetter and Chu.[3] Objective speckles, on the other hand, can be produced by projecting a real image of a random pattern into a localized region of space. These artificial objective speckles form the basis for shadow speckle metrology.

Figure 1 shows a light source and camera located at equal distances from a structure. An artificial objective speckle pattern is projected from point S onto the undeformed surface (AB) using a 35 mm slide projector equipped with a clear glass slide splattered with black paint. When the surface deforms or changes its location (to A′B′), speckles

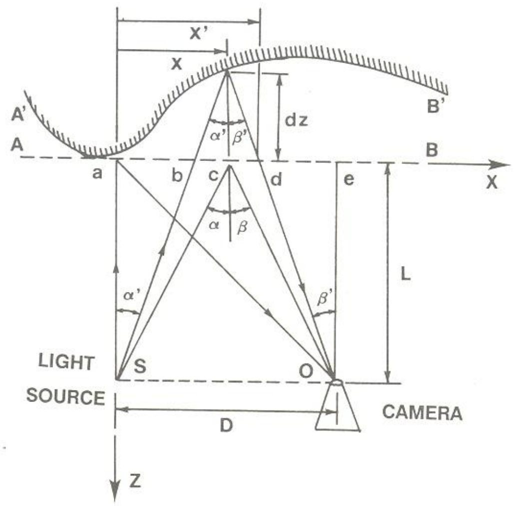

Fig. 1. Set-up for shadow speckle metrology.

appear to shift in the x-direction. The corresponding displacement, u, is related to the out-of-plane displacement, w, by[5]

$$w = \frac{-u}{\tan \alpha + \tan \beta} \tag{1}$$

Although both α and β vary from point to point, the sum of their tangents is constant, and w is linearly proportional to u over the full field.

The perspective effect of the coordinates can be corrected for a large structure since

$$x = x' + (w/L)(D - x') \tag{2}$$

and

$$y = y' + (w/L)(D - y') \tag{3}$$

where x', y' and x, y are the apparent and real coordinates, respectively.

The reader is referred elsewhere[5] for a complete description of the nomenclature on Fig. 1 and a more detailed derivation of eqns. (1)–(3).

In shadow speckle metrology, several speckle patterns can be separately recorded and sorted throughout a load cycle using a photoelectronic-numerical system similar to that shown in Fig. 2. Two of these patterns, corresponding to the deformed surface and a reference condition, are numerically correlated[9,10] to obtain u. Equation (1) is then applied.

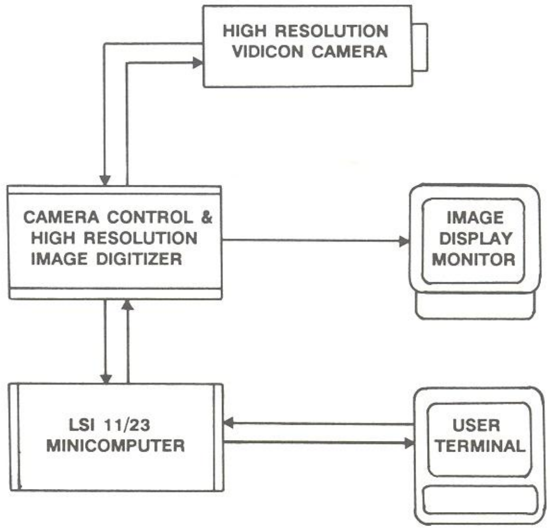

Fig. 2. A typical photoelectronic-numerical processing system.

EXPERIMENTAL

Shadow speckle metrology was used to analyze the deformation/buckling of a 45·7 cm (18 in) diameter pipe with 5·1 cm (2 in) thick plates welded on both ends. The pipe was made of two 304·8 cm (120 in) long steel cans of 0·95 cm (3/8 in) thickness. Before attaching the end plates, 20·3 cm (8 in) was removed from one end of each pipe to provide material for 'as fabricated' test coupons.

Figure 3 shows the key elements of the loading system. Both the specimen and counter used to balance the fixed end moment were 45·7 cm (18 in) in diameter. Therefore the stresses at the end of the specimen were transferred directly through the end plate into the heavy

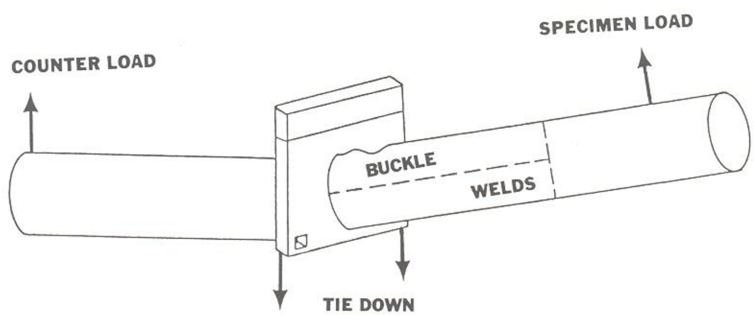

Fig. 3. Schematic of the system for loading the pipe.

counter. This produced a very stiff condition and prevented any warping of the cross section at the fixed end of the specimen. The concentrated load on the cantilever was applied 497·8 cm (196 in) from the end plate with a long threaded rod that passed through an actuator mounted in a gravity load simulator. The pipe was instrumented to measure loads, deflections, vertical diameter changes, and strains. Loads were applied to produce inelastic behavior and buckling occurred near the fixed end.

Shadow speckle measurements of the buckle profile along the length at the top of the pipe were made after the test was terminated (when the deflection capacity of the loading rod was reached or when the load decay curve showed only a slight decrease in load for a significant increase in deflection). The buckle profile describes the appearance of the failure and gives an indication of the structure length affected by the buckle.

A 122 cm (48 in) section of the deformed pipe (including the end plate and the buckle) was cut from the fixed end of the pipe. An undeformed section of equal length was also removed. These were painted flat white so that projected speckles would be clearly visible.

The undeformed section of the pipe was positioned using a laser alignment system so that its longitudinal axis was parallel to the X-direction as shown in Fig. 1. A vidicon camera was positioned at a distance of 222·3 cm (87·5 in) measured perpendicular to the pipe axis ($\beta = 0$). The slide projector was placed at an equal distance from the specimen and at an angle of 34° (α) measured from the viewing direction.

The image of the artificial speckles projected on the pipe was digitized and stored on the LSI 11/23 computer, and then the undeformed pipe was replaced with the deformed section. The deformed pipe was rotated until the buckle faced the vidicon, and the laser alignment system was used to position the end plate normal to the X-axis.

The displaced speckle pattern was recorded and numerical correlations were performed over a rectangular region extending 498 mm (19·6 in) from the base plate and 278 mm (9·0 in) above and below the X–Z plane. A calibration factor of 2·0942 mm/row (column) was used to convert the measured displacements (expressed in terms of rows or columns) to physical quantities (length), and eqn. (1) was used to compute the displacement, measured along Z, of the deformed surface with respect to the undeformed reference surface.

Figure 4 shows the buckling profile along the horizontal center-line. The solid line represents the results of the shadow speckle analysis.

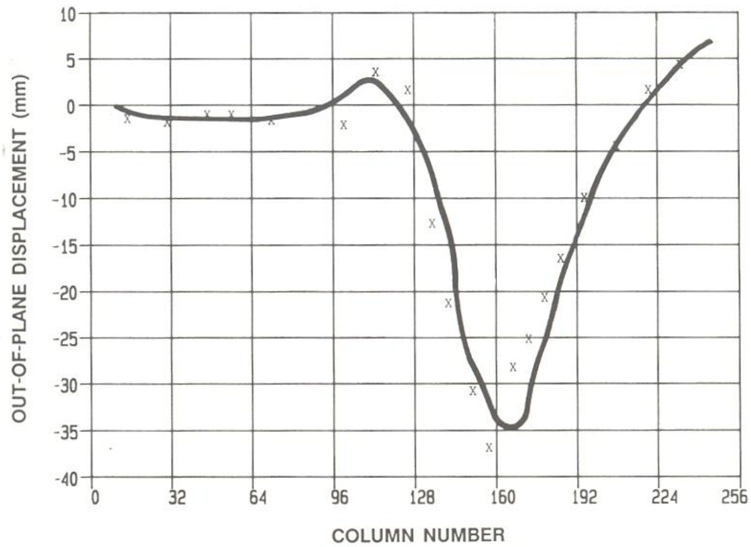

Fig. 4. Buckling profile along the horizontal center-line of the pipe (1 column = 2·0942 mm). The solid line represents measurements from shadow speckle analysis; ×, values recorded using a transit.

These are compared to independently measured values (denoted by ×) obtained using a transit. The maximum displacement determined by application of the shadow speckle occurred 33 cm (13 in) away from the end plate. This agreed to within 3·8% of the location measured using the transit. The discrepancy could be due to perspective effects, errors in the magnification factor, or misalignment between the undeformed and deformed sections. Figure 5 shows the deformed surface in the area of interest with the vertical scale magnified three times in order to emphasize the buckling effect.

The pipe test demonstrates that shadow speckle metrology can be applied to contour the surface of a relatively large structure, but tests were conducted after the structure was removed from the loading frame. To demonstrate that the method could be applied during an actual test under field conditions, the shadow speckle technique was used to monitor deformation in a 6·1 m (240 in) long I-beam with a web width of 40·6 cm (16 in) and a flange depth of 10·2 cm (4 in). The beam was held in a vertical position and braced at quarter points along its length.

The portion of the web located directly above the lower support was spray painted white and speckles were projected onto this region at an angle of 37·6° with respect to the surface normal. A vidicon camera was

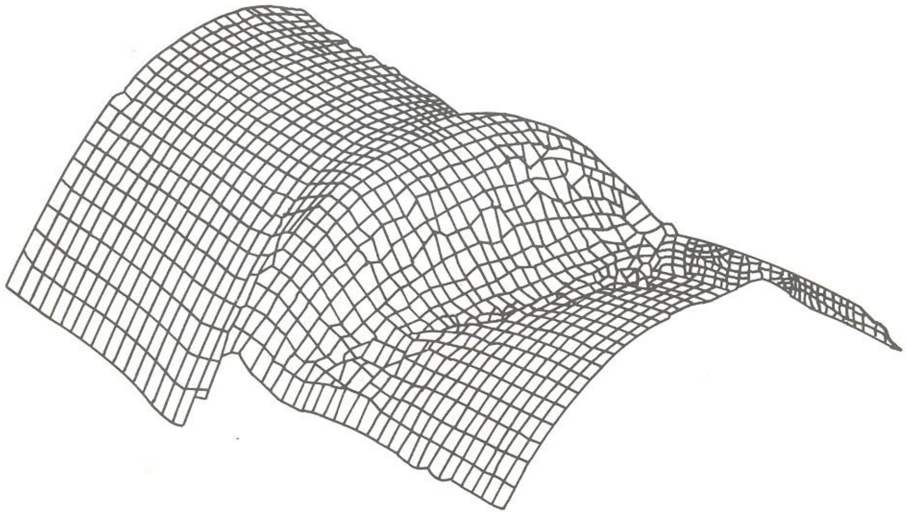

Fig. 5. Contour plot of the deformed surface with a ×3 magnification in the vertical direction.

positioned normal to the web and speckle patterns were recorded for various load increments. Each load increment ranged between 5 and 10 kip until the test was terminated at a 70 kip load.

When the I-beam was removed from the test frame, two significant effects were observed: a ripple along the length of the web and an overall twist in the beam. High points of the ripple were measured at 76·2 cm (30 in) and 142·2 cm (56 in) from the base along the vertical center-line of the web. The ripple seemed to be approximately sinusoidal with an amplitude equal to 1·3 cm (0·5 in).

A shadow speckle analysis was performed along the vertical center-line of the web (column 151) to obtain the out-of-plane displacement with respect to the initial location of the beam for each loading. Figure 6 shows the effect of the first five loading conditions on the region extending from row 30 to row 210. This corresponds to points located between 62 cm (24 in) and 129·5 cm (51 in) measured up from the lower support (based on a calibration factor of 0·381 cm/row).

Figure 7 shows the effect of the next six loadings. A major transition occurs between loadings five and six. At this point, significant distortion occurs on the beam and a rippling effect is observed in the web.

A more detailed study was conducted to understand the overall behavior of the beam. Columns 121 and 181 [located at 11·4 cm (4·5 in) to either side of the central column 151] were analyzed for the last seven loading conditions. As the load increases, displacement plots for

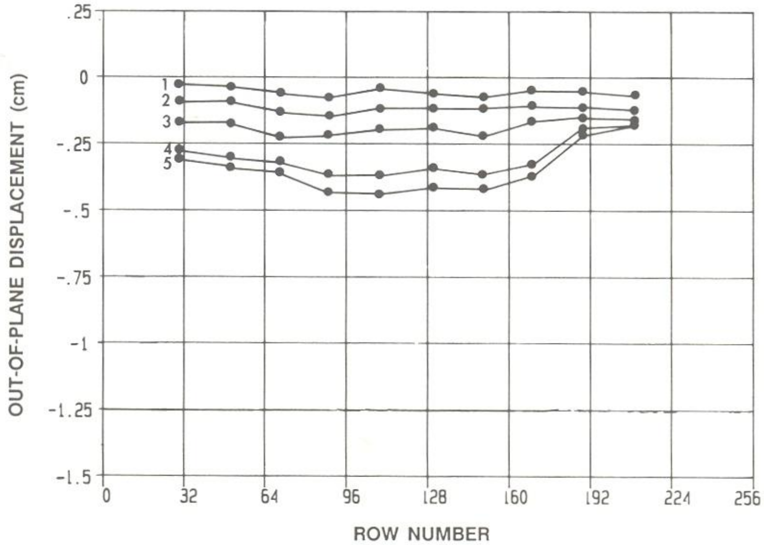

Fig. 6. Deformation along the vertical center-line of the I-beam for the first five load increments (1 row = 0·381 cm).

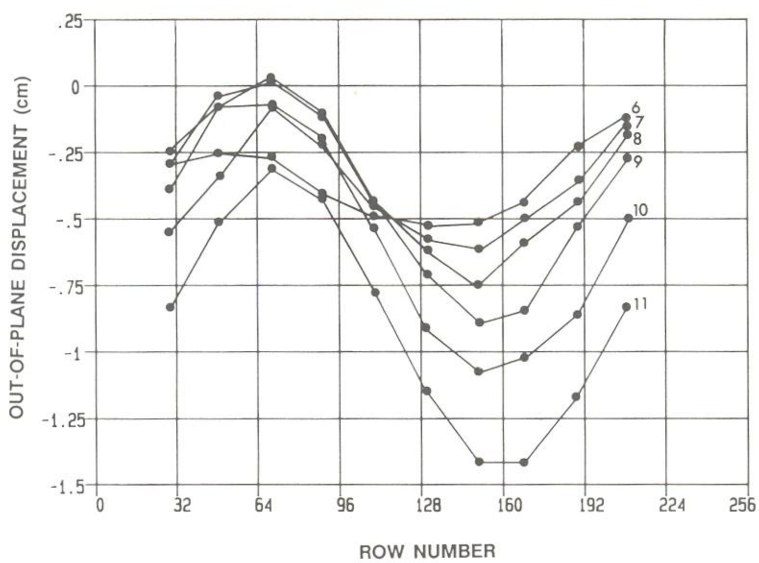

Fig. 7. Deformation along the vertical center-line of the I-beam for the second five load increments (1 row = 0·381 cm).

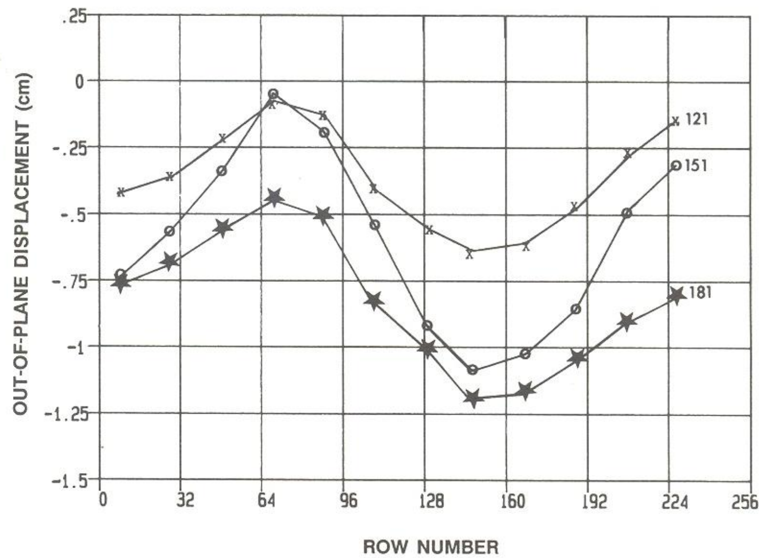

Fig. 8. Deformation along columns 121, 151 and 181 of the I-beam for load increment number 10 (1 row = 0·381 cm).

the outermost columns (i.e. 121 and 181) become approximately sinusoidal. Figure 8, for example, shows the out-of-plane displacements obtained for loading number 10, with values for column 121, column 151 and column 181. The displacement plots for columns 121 and 181 run almost parallel to one another and have nearly equal peak-to-peak amplitudes. They are shifted relative to one another with respect to the reference position, indicating that the I-beam twisted about its vertical axis. The angle of twist is observed to increase with row number.

The central column (151) displays sinusoidal behavior but has a higher peak-to-peak amplitude than determined for columns 121 and 181, indicating that the web experiences a relatively larger displacement at its center. This should be expected, since material on either side is constrained by the more rigid flanges.

CONCLUSION

This work has demonstrated the potential for measuring buckling profiles and surface deformations in relatively large structural components using shadow speckle metrology.

Digital image processing and computer analysis determine both the magnitude and sign for out-of-plane displacements measured relative to a reference, the method relies on a relatively simple set-up, and tests can be conducted under field conditions in ambient light.

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