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Optical grid Method for Contouring of 1-D Non-Reflective Surfaces

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Abstract. Digital Image Correlation (DIC) is a non-contact optical technique method, based on grey value digital images, that can determine the contour and the displacement of an object under load. This technique is used to measure deformation, displacement, strain. This work aims at finding the slope and curvature contours of the loaded beams (Theory of bending) using a grid method. The spacing between two grid lines is unaltered under no load condition and spacing changes when it is loaded. Thus, the strain of the grid lines is related to slope and curvature. This method is applied to the practical structures where the surfaces (non-reflective) are made into reflective by the use of available coating technique.

1. Introduction
1.1. Principle of Line summation method
The optical strain of uniform grid line spacing reflected by bent beams and plates contain sufficient information to determine the slope and curvature at any point on the surface. The shift in their positions due to deformation can be interpreted in terms of slope and curvature. Since the actual measurements involve the spacings between grid lines, the technique employs thin equally spaced rulings as the grid instead of the conventional gratings.

![Figure 1. Slope and Deflection of cantilever beam](image-url)
According to beam bending equation,
\[ \sigma/y = M/I = E/R \]
where,
\( \sigma \) is the stress in N/mm\(^2\)
\( y \) is the distance from the neutral axis
\( I \) is the Moment of Inertia and
\( E \) is the young’s modulus

Here the \( 1/R \) is the curvature which is proportional to bending moment \( M \) so, whenever there is maximum bending moment the curvature value is also a maximum and vice versa.

![Figure 2. Schematic of Experimental arrangement](image)

From the above figure, it can be observed that when the object is loaded in forward direction the reflected image size in the screen reduces likewise, when the object is loaded in backward direction (away from the laser source) the reflected image size increases. Hence, correlation can be found out with the two states of the object.

2. Relationship Between Slope, Tip slope and Tip Deflection of Cantilever Beam

Tip Slope is given by
\[ \theta_{\text{tip}} = PL^2 / 2EI \]

Tip Deflection is given by
\[ \delta_{\text{tip}} = PL^3 / 3EI \]

Relation between Tip slope and Tip deflection
\[ \theta_{\text{tip}} / \delta_{\text{tip}} = 3 / 2L \]
\[ \theta_{\text{tip}} = 3 / 2L \times \delta_{\text{tip}} \]

Slope at any given length is given by
\[ \theta_{\text{eqn}} = PLx / EI - Px^2 / 2EI \]
\[ \theta_{\text{eqn}} / \theta_{\text{tip}} = 2 \times (x/L) - (x/L^2) \]
\[ \theta_{eqn} / \theta_{tip} = 2 \xi - \xi^2 \]  
where \( \xi = x/L \)

Equation (1) is used to obtain theoretical values of slope and curvature of tip loaded cantilever beam from MATLAB.

3. Analysis of Composite Structure
The composite material comprises of cured epoxy resin thickness of 1mm coated on the sheet made up of Aluminium, Stainless steel, Polycarbonate of 1mm thickness. So, the composite is having a total thickness of 2mm is analysed.

**Beam Specifications:**
- Length (L) = 40 mm
- Width (B) = 10 mm
- Height (H) = 2 mm
- Cross-Section Area = 20 mm²

| Material                  | Young’s Modulus | Poisson’s ratio |
|---------------------------|-----------------|-----------------|
| Cured epoxy resin CY230   | 2.979 Gpa       | 0.348           |
| Stainless steel 316 grade | 190-205 Gpa     | 0.265 -0.275    |
| Aluminium                 | 68.9 Gpa        | 0.33            |
| Polycarbonate             | 2.0 - 2.4 Gpa   | 0.37            |

3.1. Modeling procedure
To analyze the composite structure selected element type is Shell 181. The beam is modeled as per the dimensions, meshing and boundary conditions is applied where the cantilever beam is given a tip-displacement of 0.02 at the free end.

SHELL181 is suitable for analyzing thin to moderately-thick shell structures. It is a four-noded element with six degrees of freedom at each node: translations in the x, y, and z directions, and rotations about the x, y, and z axes namely UX, UY, UZ and ROTX, ROTY, ROTZ.

**Figure 3.** Slope plot of cantilever beam for 0.02 tip displacement

**Figure 4.** Curvature plot of cantilever beam for 0.02 tip displacement
Table 2. Ansys - Slope and Curvature values

| Values   | Stainless steel | Aluminium     |
|----------|-----------------|---------------|
| Slope$_{min}$ | 0.7542E-05      | 0.7439E-05    |
| Slope$_{max}$ | 0.7514E-03      | 0.7507E-03    |
| Curvature$_{min}$ | 0.2850E-06      | 0.2919E-06    |
| Curvature$_{max}$ | 0.37366E-04     | 0.3681E-04    |

4. Reflection coating of Stainless steel and Aluminium

Epoxy resin - Coating process The procedure for coating of epoxy resin on metallic surfaces is listed below. A beaker and a thermometer is used in the process of coating where the temperature of the resin heated in the beaker is measured.

- Take Araldite CY 230 + 20 % weight of black pigment thoroughly mixed at 60°C.
- After cooling the mixture, Add 10% by weight of hardener HY 951 and stir the mixture for 5 minutes.
- Surface of the structure has to be cleaned with Acetone - (CH$_3$)$_2$CO.
- Pour the mixture on to the surface through a fiber glass mat filter (avoiding air bubbles).
- One edge of good quality surface of a transparent perpex sheet is kept on the resin hardener mixture and the other edge lowered squeezing the resin mixture to other edge.
- Apply a pressure of 100gms/cm$^2$ (dead weight) to give coating thickness of 40microns.
- After 24hours of curing at 40°C (or) 72 hours at room temperature , the perpex sheet is stripped off.

5. Experiment Procedure:
Specimen is placed in a fixture as a 1-D cantilever beam in between the screen and laser source. The laser light is focussed through the lens and made it to fall on the specimen. After passing through condensing lens the reflection of the specimen is displayed in the screen, CCD camera is used to capture the image of the reflected specimen.

The camera is mounted at a near normal position to the optical bench where the images of the cantilever beam are captured for the following conditions:
1. Loaded with grid.
2. Unloaded with grid.
6. Results for Non-reflective specimen
The Slope and Curvature values obtained from optical grid method using MATLAB image processing toolbox for non-reflective specimens are compared with the theoretical values. The below graphs show the slope comparison and curvature comparison between Grid method and theoretical values after normalizing for a tip displacement of 0.15 mm.

The data normalization formula is given by:

\[
\text{Normalized data in } X = \frac{(x \text{-} \text{min}(x))}{(\text{max}(x) \text{-} \text{min}(x))}
\]

The figures shown below are the slope and curvature plots obtained for Coated Stainless steel and Aluminium. The distance between the specimen and screen D = 230 mm.

6.1. Coated Stainless steel

![Figure 7](image1.png) Slope comparison - Grid method and theoretical values

![Figure 8](image2.png) Curvature comparison - Grid method and theoretical values
6.2. Coated Aluminium

Figure 9. Slope comparison - Grid method and theoretical values

Figure 10. Curvature comparison - Grid method and theoretical values

7. Conclusion
In this work, the optical grid method is successfully applied to 1-D Stainless steel and Aluminium specimens by giving a epoxy reflection coating and the values of slope and curvature are found out to be close to the theoretical values. The grid line spacings affect the slope and curvature values. So, for obtaining better results more grid lines has to be provided with less spacing between them.

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