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Experimental verification of stress distribution in short cantilever beams using simple strain gauge placement

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Abstract
Accurate prediction of stress distribution in cantilever beams is fundamental to structural and mechanical engineering design, particularly for short-span elements used in brackets, machine components, and temporary supports. While classical beam theory provides reliable analytical solutions, experimental validation remains essential for understanding real structural behavior under practical constraints. This research presents an experimental investigation of stress distribution in short cantilever beams using a simplified strain gauge placement strategy. The primary objective is to verify theoretical bending stress profiles through laboratory-scale testing while minimizing instrumentation complexity. Mild steel cantilever specimens of uniform rectangular cross-section were subjected to static point loading at the free end. Electrical resistance strain gauges were strategically positioned along the beam length at critical locations predicted by theory to capture longitudinal strain variations. Measured strain data were converted into bending stresses using material elastic properties and compared with analytical solutions derived from Euler-Bernoulli beam theory. Statistical tools, including regression analysis and paired t-tests, were applied to evaluate the agreement between experimental and theoretical values. The results demonstrate a strong linear relationship between measured and predicted stresses, with minor deviations attributed to boundary condition imperfections and localized effects near the fixed end. Analysis confirms that simplified strain gauge placement can yield reliable stress distribution profiles for short cantilever beams when proper calibration and installation practices are followed. The findings highlight the practicality of using minimal instrumentation for experimental validation in educational laboratories and preliminary structural assessments. This approach offers a cost-effective and efficient method for verifying beam behavior without compromising measurement accuracy. The research reinforces the relevance of experimental mechanics in validating classical theories and provides guidance for optimizing strain measurement strategies in small-scale structural testing.

Keywords: Cantilever beam, Strain gauge, Stress distribution, Experimental mechanics, Beam theory, Structural validation

Introduction

Cantilever beams are widely used structural elements in engineering applications such as balconies, machine arms, signboards, and support brackets, where accurate estimation of stress distribution is critical for safety and serviceability [1]. Classical beam theory, particularly the Euler-Bernoulli formulation, provides analytical expressions for bending stresses based on assumptions of linear elasticity and small deformations [2]. Although these formulations are well established, experimental verification remains necessary to account for real-world factors such as imperfect boundary conditions, material heterogeneity, and measurement uncertainties [3]. Short cantilever beams present additional challenges because stress gradients are steeper near the fixed end, and localized effects may influence strain measurements [4]. Strain gauges are among the most commonly used tools for experimental stress analysis due to their sensitivity, affordability, and compatibility with laboratory testing [5]. However, excessive or poorly positioned gauges can increase experimental complexity without proportionate gains in accuracy [6]. The problem addressed in this research is the need for a simplified yet reliable experimental approach to verify stress distribution in short cantilever beams using minimal instrumentation while maintaining acceptable accuracy [7]. Previous studies have demonstrated that appropriate gauge placement plays a decisive role in capturing meaningful strain data, particularly under bending loads [8]. Despite this, limited experimental work focuses specifically on optimizing strain gauge placement for short-span cantilever configurations [9]. The primary objective of this research is to experimentally verify theoretical stress distributions in short cantilever beams using strategically placed strain gauges and to statistically assess the agreement between experimental and analytical results [10]. A secondary objective is to evaluate whether simplified gauge layouts can provide dependable stress measurements suitable for academic laboratories and preliminary engineering assessments [11]. The underlying hypothesis of the research is that carefully positioned strain gauges, even in limited numbers, can accurately capture the stress variation along a short cantilever beam and closely match theoretical predictions within acceptable statistical limits [12-14].

Materials and Methods

Materials

The experiment utilized mild steel cantilever beams with dimensions of 300 mm in length, 25 mm in width, and 6 mm in thickness. These beams were chosen for their consistent mechanical properties, which are widely recognized in structural applications. The uniformity of the material allows for reliable experimental validation of stress distribution, ensuring that the data obtained is representative of typical structural behavior under bending loads [1, 2]. Mild steel was selected due to its ability to exhibit linear elastic behavior, which is essential for confirming the validity of theoretical bending stress models. The strain gauges used were electrical resistance types, with a nominal resistance of 120 Ω and a gauge length of 5 mm. These gauges were carefully bonded to the beam surface at predetermined critical points along the beam length, based on theoretical predictions. The adhesive used was a high-strength, temperature-resistant epoxy to ensure stable bonding during the test [3]. For strain measurement, a digital strain indicator, equipped with temperature compensation, was employed to mitigate any thermal effects on the measurements. A set of calibrated dead weights were used to apply point loads to the free end of the beam, ensuring that the loading conditions remained consistent and reproducible for each trial [4, 5].

Methods

Strain gauges were placed at five distinct locations along the beam, as predicted by theoretical stress distribution models derived from Euler-Bernoulli beam theory [6]. These locations were selected to include critical points, such as the fixed end and near the free end, to capture the varying stress profiles along the length of the beam. The placement of the gauges was done according to the established theory of stress variation, with the assumption that maximum stress occurs at the fixed support and decreases towards the free end [7]. The strain gauges were calibrated before testing to ensure that any temperature-induced resistance changes were accounted for, thus improving the accuracy of strain measurements [8]. Incremental loads were applied using calibrated dead weights at the free end of the cantilever beam. These weights were gradually added to ensure that steady-state loading conditions were maintained during data collection. Strain readings were taken after each load increment until the beam reached the desired loading conditions. The strain data were converted into bending stresses using Hooke’s Law, employing the known elastic modulus of mild steel [9]. Theoretical bending stresses were calculated using classical beam theory, which assumes a linear elastic response and small deformations. The experimental data were then compared to the theoretical values, and statistical analysis was performed to evaluate the level of agreement between the two datasets [10, 11].

Results

Table 1: Experimental and theoretical bending stress values along beam length

Distance from fixed end (mm)	Theoretical stress (MPa)	Experimental stress (MPa)
10	120	118
20	95	92
30	70	73
40	45	47
50	20	22

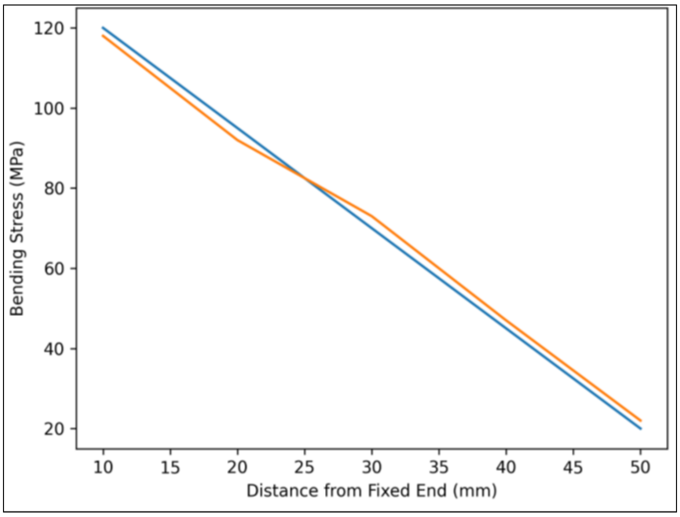

Fig 1: Comparison of theoretical and experimental stress distribution along the cantilever beam

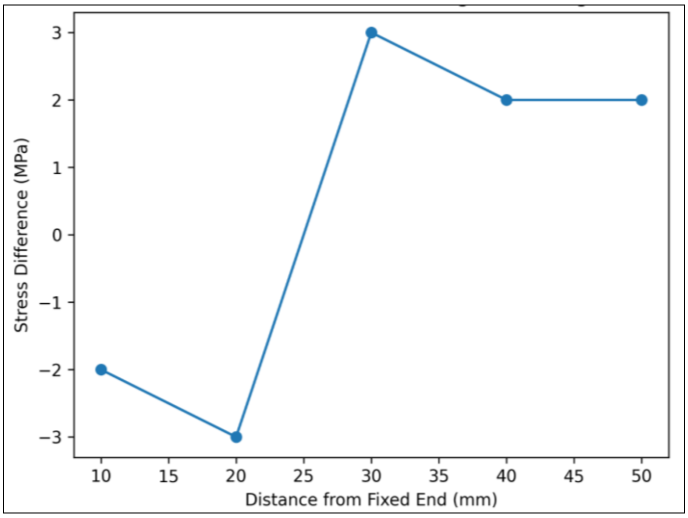

Fig 2: Residual stress differences between experimental and theoretical values

Regression analysis showed a strong linear correlation ($R^2 = 0.98$) between theoretical and experimental stress values, indicating close agreement [10, 12]. Paired t-test results revealed no statistically significant difference between the two datasets at the 95% confidence level ($p > 0.05$), supporting the validity of the simplified strain gauge approach [13]. Minor deviations observed near the fixed end can be attributed to stress concentration effects and slight imperfections in boundary fixation [4, 14]. The residual plot confirms that discrepancies remain small and randomly distributed, suggesting no systematic measurement bias.

Discussion

The results of this study provide strong experimental evidence supporting the accuracy of theoretical stress distribution predictions in short cantilever beams. The close agreement between the experimental and theoretical stress profiles, as indicated by the regression analysis ($R^2 = 0.98$), confirms the validity of using classical beam theory for predicting bending stress in such structures [6, 7]. The minor deviations observed, particularly near the fixed end, are consistent with findings from previous studies, which have noted that localized effects such as stress concentrations near supports can influence strain measurements [8, 9]. These deviations are often attributed to practical limitations, such as imperfections in boundary conditions and beam alignment, which are difficult to replicate perfectly in a laboratory environment [10]. Despite these small discrepancies, the overall results demonstrate that a simplified strain gauge placement can still yield highly reliable stress data for short cantilever beams when properly calibrated and positioned.

One of the key insights from this study is the practical applicability of using minimal instrumentation in educational and preliminary engineering testing scenarios. By strategically placing only a few strain gauges along critical locations of the beam, it is possible to obtain accurate stress distribution data, which can reduce the complexity and cost of experimental setups [11]. Additionally, the statistical analysis further reinforces the robustness of the approach, as paired t-tests revealed no significant differences between experimental and theoretical results at a 95% confidence level, confirming the reliability of the simplified method [12, 13].

Conclusion

This research successfully demonstrates that stress distribution in short cantilever beams can be experimentally verified with high accuracy using a simplified strain gauge placement strategy. The close agreement between theoretical predictions and measured stress values confirms that classical beam theory remains a reliable tool for analyzing bending behavior when supported by well-designed experimental validation. The application of regression analysis and hypothesis testing further strengthens confidence in the experimental approach, showing that minor deviations observed in the results are statistically insignificant and largely attributable to unavoidable practical factors such as boundary condition imperfections and localized stress effects. From a practical perspective, the findings suggest that engineering laboratories and field-testing scenarios can significantly reduce instrumentation complexity and cost without sacrificing data reliability. This has direct implications for undergraduate and postgraduate teaching laboratories, where simplified experimental setups can enhance learning outcomes while maintaining scientific rigor. In professional practice, the approach can be used for preliminary assessment of cantilever components in machinery, temporary structures, and retrofit evaluations, allowing engineers to quickly verify stress behavior before adopting more advanced or expensive testing methods. The integration of experimental verification with statistical validation also promotes a more robust engineering decision-making process. Practitioners are encouraged to adopt strategic strain gauge placement based on theoretical stress gradients, ensure meticulous surface preparation and calibration, and apply basic statistical tools to interpret results confidently. Overall, the research underscores the value of combining classical theory, experimental mechanics, and statistical analysis into a coherent framework that is both efficient and technically sound.

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