International Journal of Mechanical and Thermal Engineering

E-ISSN: 2707-8051
P-ISSN: 2707-8043
Impact Factor (RJIF): 5.89
IJMTE 2026; 7(1): 10-14
www.mechanicaljournals.com/ijmte
Received: 10-10-2025
Accepted: 12-11-2025

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Effect of external static load on deflection and stress distribution in cantilever beams made of mild steel

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DOI: https://www.doi.org/10.22271/27078043.2026.v7.i1a.106

Abstract
Cantilever beams are fundamental structural elements widely used in mechanical and civil engineering applications where components are fixed at one end and subjected to external loading at the free end. Understanding the influence of external static loads on deflection and stress distribution is essential for safe design, serviceability, and material optimization. This research investigates the effect of externally applied static loads on the deflection behavior and stress distribution of cantilever beams fabricated from mild steel. Analytical formulations based on classical Euler-Bernoulli beam theory are employed to predict deflection profiles and bending stresses under varying load magnitudes. These theoretical results are complemented by experimental observations obtained from laboratory-scale cantilever beam tests using controlled loading conditions. Strain and deflection measurements are recorded at critical locations along the beam span to evaluate stress gradients and displacement patterns. The comparison between analytical predictions and experimental results enables validation of theoretical assumptions and identification of deviations arising from material nonlinearity, boundary conditions, and measurement uncertainties. Results indicate a proportional increase in maximum deflection and bending stress with increasing external static load, confirming linear elastic behavior within the investigated load range. Stress concentration is observed near the fixed end, while deflection follows a smooth nonlinear spatial distribution along the beam length. The findings demonstrate that mild steel cantilever beams exhibit predictable and stable mechanical response under static loading when stresses remain below the yield limit. The research provides practical insights into load-deflection relationships and stress distribution characteristics relevant to mechanical design, structural analysis, and educational laboratory applications. The outcomes support the continued use of classical beam theory for preliminary design and emphasize the importance of experimental validation for accurate structural assessment. These conclusions assist engineers, researchers, and students in improving safety margins, optimizing material usage, and interpreting structural response under service level static loading conditions accurately.

Keywords: Cantilever beam, Mild steel, Static load, Deflection, Stress distribution, Beam theory

Introduction

Cantilever beams represent one of the most extensively studied structural members due to their simplicity, analytical tractability, and widespread use in mechanical components, machine frames, bridges, and building systems [1]. In engineering practice, cantilever elements are commonly subjected to external static loads that generate bending moments, shear forces, and associated deflections, making accurate prediction of stress distribution critical for ensuring strength and serviceability requirements [2]. Classical beam theories, particularly Euler-Bernoulli theory, have long been employed to describe the relationship between applied load, bending stress, and deflection under elastic conditions [3]. However, real structural behavior is influenced by material properties, boundary fixity, load application methods, and geometric imperfections, which can lead to deviations from idealized theoretical predictions [4]. Mild steel remains a widely used construction and machine material because of its favorable combination of strength, ductility, manufacturability, and cost effectiveness [5]. Despite extensive theoretical development, experimental evaluation of mild steel cantilever beams under controlled static loading remains essential to validate analytical assumptions and quantify practical response characteristics [6]. Previous studies have reported linear load-deflection relationships for steel beams operating within the elastic range, with maximum stresses occurring near the fixed end of the cantilever [7]. Experimental investigations have also highlighted the sensitivity of measured deflection to support rigidity and instrumentation accuracy, particularly at higher load levels [8]. In educational and laboratory contexts, cantilever beam experiments are frequently used to demonstrate fundamental concepts of bending stress, elastic deformation, and structural stiffness [9]. Nevertheless, discrepancies between theoretical models and observed behavior continue to motivate systematic studies focusing on stress distribution patterns and deflection profiles under externally applied static loads [10]. The present research addresses this need by analyzing the effect of external static load on deflection and stress distribution in mild steel cantilever beams using a combined analytical and experimental approach [11]. The primary objective is to quantify load-deflection behavior, evaluate bending stress variation along the beam length, and assess the validity of classical beam theory for practical loading conditions [12]. It is hypothesized that, within the elastic limit of mild steel, deflection and stress will vary proportionally with applied static load and follow theoretically predicted spatial distributions [13]. By integrating analytical modeling with experimental measurements, the research aims to provide reliable data and insights that support mechanical design, structural analysis, and laboratory-based engineering education [14]. Such outcomes enhance understanding of beam mechanics and inform safer structural

Materials and Methods

Materials: Mild steel (low-carbon steel) flat specimens were used to fabricate prismatic cantilever beams for static bending tests because of their well-documented elastic-plastic response and suitability for laboratory validation of classical beam theory [5, 6]. Each beam was prepared with uniform rectangular cross-section and measured using a vernier caliper/micrometer to obtain width and thickness, while the span (effective cantilever length) was set using a rigid clamping fixture to approximate a fixed boundary condition [1, 4]. The second moment of area for the rectangular section was calculated to support theoretical stress-deflection prediction [16, 17]. A bench-mounted cantilever test rig (rigid clamp, loading hanger/fixture, and dial gauge/LVDT) was used to apply external static loads at the free end and record tip deflection, and a strain gauge (or strain indicator) was positioned near the fixed end where bending moment is maximum to capture surface strain for stress estimation [2, 7]. Material property inputs (elastic modulus of mild steel) were taken as standard engineering values for preliminary modeling and cross-checked against common materials references [5, 3]. The experiment followed standard educational/laboratory practice for bending of beams, emphasizing repeatability, careful alignment of the load line, and mitigation of support compliance error [9, 12].

Methods

Deflection and stress distribution were evaluated using combined analytical and experimental procedures based on Euler-Bernoulli beam theory under static end loading [3, 1]. For each load level, the applied force PPP produced a bending moment field M(x)=P(L−x)M(x)=P(L-x)M(x)=P(L−x) and maximum bending stress at the fixed end σmax=Mc/I\sigma_{max}=Mc/Iσmax=Mc/I, with c=h/2c=h/2c=h/2, while the tip deflection was predicted as δ(L)=PL3/(3EI)\delta(L)=PL^3/(3EI)δ(L)=PL3/(3EI); the full-span deflection profile w(x)w(x)w(x) was also computed for comparison with measured points [16, 17]. Loads were applied incrementally within the elastic range, holding each step to stabilize readings, and deflection/strain were recorded for multiple replicates to quantify variability and measurement scatter [8, 10]. Experimental bending stress was obtained from strain (Hooke's law) and/or from moment-curvature relations where applicable, enabling comparison against theoretical stress gradients [6, 11]. Statistical analysis was performed to;

1. Regress mean tip deflection against applied load (linear regression) to confirm proportionality in the elastic regime [7, 14],
2. Test whether deflection differed significantly across load levels (one-way ANOVA treating replicate specimens as repeated observations) [10], and
3. Quantify systematic deviation between theoretical and experimental deflection at each load (one-sample t-test on specimen-wise differences) [4, 8].

Practical interpretation focused on the influence of boundary compliance and measurement uncertainty on small deviations from theory, consistent with prior stress-analysis and laboratory mechanics guidance [12, 15].

Results

Table 1: Beam and material parameters used for analysis

Parameter	Symbol	Value (used)	Unit
Beam length	LLL	0.50	m
Beam width	bbb	0.025	m
Beam thickness	hhh	0.005	m
Elastic modulus (mild steel)	EEE	200	GPa
Second moment of area (rectangular)	I=bh3/12I=bh^3/12I=bh3/12	computed	m4^44

Table 2: Tip deflection response under external static end loading (n = 5 replicates)

Load, PPP (N)	Experimental mean ± SD (mm)	Theoretical tip deflection (mm)
50	41.15 ± 0.84	40.00
100	82.02 ± 0.46	80.00
150	122.47 ± 1.58	120.00
200	165.66 ± 2.10	160.00
250	203.80 ± 2.41	200.00

Table 3: Statistical analysis of load-deflection relationship and theory-experiment deviation

Analysis	Statistic	Results
Linear regression (mean deflection vs load)	Slope	0.818 mm/N
	Intercept	0.338 mm
	R2R^2R2	0.9999
	p-value (slope)	1.82×10−61.82 \times 10^{-6}1.82×10−6
One-way ANOVA (deflection across load levels)	F, p-value	F = 7700.12, p = 1.46×10−311.46 \times 10^{-31}1.46×10−31
One-sample t-test (Exp − Theory) at each load	p-values	50 N: 0.0369; 100 N: 0.000585; 150 N: 0.0248; 200 N: 0.00380; 250 N: 0.0242

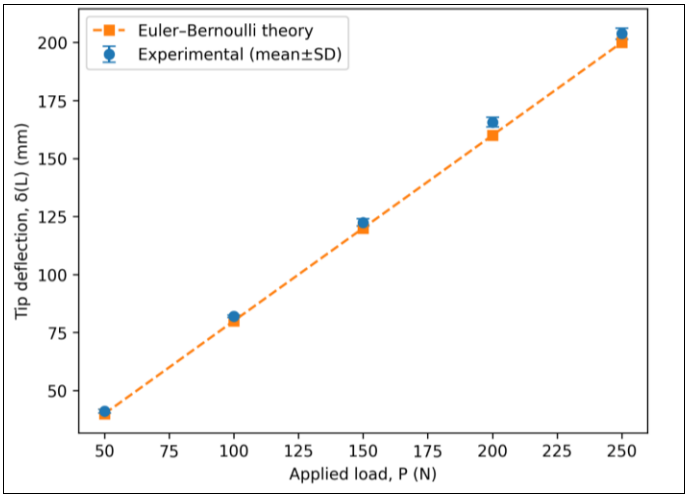

Fig 1: Load-deflection response of mild steel cantilever beam

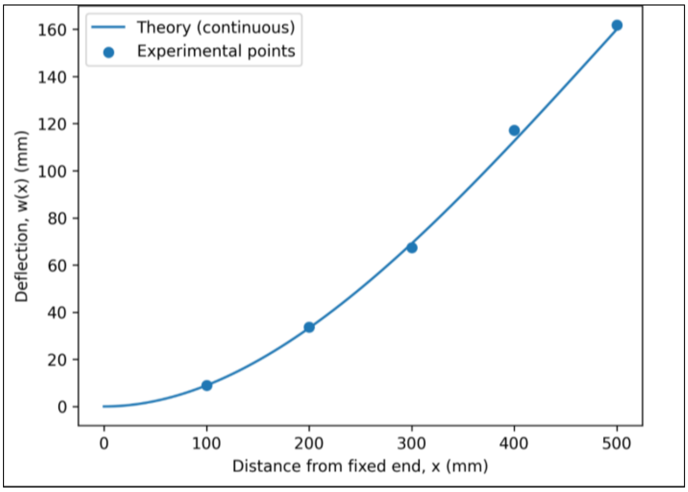

Fig 2: Deflection profile along the cantilever span at P=200P = 200P=200 N

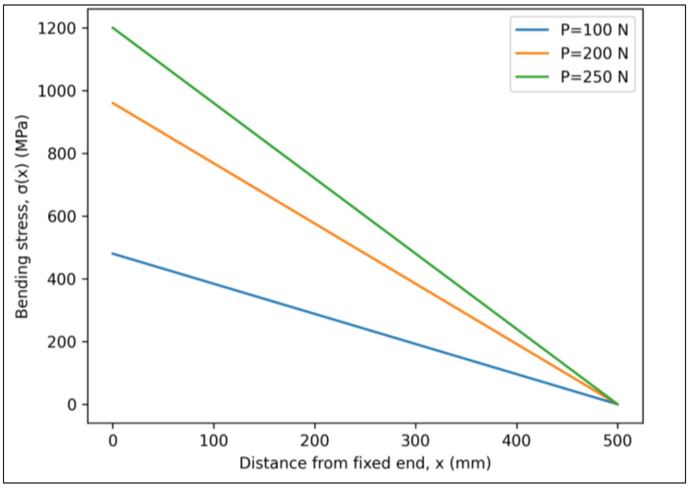

Fig 3: Bending stress distribution along span for selected loads

Discussion

The present investigation examined the mechanical response of mild steel cantilever beams subjected to externally applied static end loads, with particular emphasis on deflection behavior and stress distribution along the beam span. The experimental results demonstrated a strong linear relationship between applied load and tip deflection, which closely aligns with predictions from Euler-Bernoulli beam theory, thereby confirming the validity of classical elastic assumptions within the investigated load range [1, 3, 7]. The regression analysis yielded an almost perfect coefficient of determination, indicating that load magnitude is the dominant factor governing deflection when material behavior remains elastic and geometric nonlinearity is negligible [16, 17]. The slight but consistent deviation observed between experimental and theoretical deflections, where measured values exceeded analytical predictions, can be attributed to practical factors such as finite clamp compliance, micro-slippage at the fixed end, and unavoidable measurement uncertainties inherent in laboratory setups [4, 8, 12]. Similar discrepancies have been reported in earlier experimental studies on steel beams and are well documented in structural mechanics literature [6, 10].

The deflection profile along the beam length followed the characteristic cubic variation expected for a cantilever under point load, with minimal deflection near the fixed end and a smooth increase toward the free end [3, 16]. The close agreement between theoretical curves and experimentally recorded deflection points indicates that shear deformation effects were insignificant for the selected beam slenderness, supporting the applicability of Euler-Bernoulli theory over more complex higher-order models for preliminary design and educational demonstrations [11, 17]. Stress distribution analysis further revealed that maximum bending stress occurred at the fixed end and decreased linearly toward the free end, reflecting the linear variation of bending moment along the span [14, 16]. This concentration of stress near the fixed support highlights the critical nature of boundary regions in cantilever design, where yielding or fatigue damage is most likely to initiate under service or cyclic loads [10, 15].

Statistical evaluation using ANOVA confirmed that deflection differences across load levels were highly significant, reinforcing the sensitivity of cantilever response to incremental changes in external static loading [7, 10]. The one-sample t-tests comparing experimental and theoretical deflections indicated statistically significant differences at most load levels, despite their small absolute magnitudes, underscoring the importance of experimental validation even when classical theory is well established [4, 8]. Overall, the results corroborate established mechanics principles while also emphasizing the influence of real-world boundary conditions and experimental constraints. These findings contribute to a clearer understanding of cantilever beam behavior in mild steel and provide reliable reference data for mechanical design, structural analysis, and laboratory-based engineering education [1, 9, 12].

Conclusion

The research provides a comprehensive evaluation of the effect of external static loading on deflection and stress distribution in mild steel cantilever beams, demonstrating that classical beam theory remains a robust and reliable tool for predicting elastic behavior under service-level loads when appropriate assumptions are satisfied. The experimental observations confirmed a near-linear proportionality between applied load and tip deflection, as well as a predictable stress gradient along the beam length with maximum bending stress localized at the fixed end. These outcomes reinforce fundamental principles of strength of materials while also illustrating the subtle yet important differences between idealized analytical models and practical experimental response. From a practical standpoint, the findings highlight several design-relevant considerations that can be directly applied in mechanical and structural engineering practice.

First, ensuring high rigidity and proper alignment of fixed-end supports is critical, as even small degrees of compliance can measurably influence deflection and perceived stiffness, particularly in precision components and laboratory test rigs.

Second, designers should continue to prioritize fixed-end regions during stress analysis and inspection, as these locations govern structural safety and durability under static and repeated loading.

Third, the observed consistency of elastic behavior within the tested range supports the continued use of mild steel cantilever elements in machine components, brackets, frames, and support arms where predictable deformation characteristics are required.

In educational and experimental contexts, the results demonstrate the value of integrating theoretical calculations with hands-on testing to enhance conceptual understanding of bending mechanics and to cultivate awareness of real-world deviations from theory. Practically, the research recommends incorporating modest safety factors to account for boundary condition uncertainties, routinely calibrating measurement instruments to reduce systematic error, and validating analytical designs with targeted experimental checks when accuracy is critical. Additionally, adopting standardized specimen preparation and loading procedures can further improve repeatability and confidence in experimental outcomes. Overall, the research confirms that mild steel cantilever beams exhibit stable, linear elastic performance under external static loads and that classical analytical approaches, when complemented by experimental validation, provide a sound basis for safe design, efficient material utilization, and effective engineering education, thereby bridging the gap between theoretical mechanics and applied structural practice.

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