Analysis of Strain Measurement Accuracy in WF Steel Beams Using Strain Gauges: An Experimental Study Based on Elastic Theory

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ABSTRACT: This study presents an experimental approach to measure flexural and shear strains in a WF 150.75.5.7 steel beam using strain gauges. The primary objective of this research is to evaluate the accuracy of strain measurements obtained from strain gauges and compare them with theoretical predictions based on elastic theory. The experiment was conducted on a simply supported beam with a span length of 3.7 meters, subjected to a central static load applied through a Universal Testing Machine (UTM). FLA-6-11 strain gauges were installed on the top and bottom flanges to record flexural strain, as well as diagonally on the beam web to capture shear strain. The experimental results showed that flexural strain measurements deviated less than 5% from theoretical predictions, whereas shear strain measurements deviated up to 14%, which is presumed to be caused by inaccuracies in strain gauge installation. This study indicates that strain gauges are highly effective for flexural strain measurement, but require careful installation to ensure reliability in shear strain measurement. The research also highlights the importance of experimental documentation on locally standardized steel profiles, particularly BJ37 grade steel, as a reference for validating laboratory structural testing methods.

KEYWORDS: WF steel beam, flexural strain, shear strain, experimental testing, strain gauge

INTRODUCTION

Understanding the strain distribution in steel structural elements is essential for evaluating structural performance under various loading conditions. In particular, accurate measurement of flexural and shear strains is crucial to validate the assumptions of elastic theory and to ensure the safety and efficiency of structural design. Strain gauges remain one of the most widely used tools in experimental mechanics due to their high sensitivity, ease of installation, and ability to capture local strain responses in structural elements.

Previous studies have employed strain gauges to analyze the mechanical behavior of steel beams under bending, torsion, and shear loads. However, most of these studies assumed ideal installation conditions, with relatively few addressing how installation quality—particularly angular orientation and surface condition—can influence measurement accuracy. This issue becomes especially critical in shear strain measurement, which is highly sensitive to angular misalignment.

Strain gauges are essential instruments for measuring both flexural and shear strains in steel beams. According to Keil (2017), the success of strain measurement highly depends on the precision of strain gauge installation, including surface cleanliness, gauge axis orientation relative to the stress direction, and adhesion quality. This is particularly critical for shear strain measurements, where even slight deviations in angular placement can cause significant errors in readings. Therefore, this study focuses on examining the deviation between flexural and shear strain results in WF steel beams caused by non-ideal strain gauge installation.

Several previous studies have utilized strain gauges in laboratory experiments to validate the elastic behavior of steel elements. For instance, Kaner & Asmaz (2024) investigated the use of strain gauges in tension, torsion, and bending tests, comparing experimental strains with theoretical predictions and numerical simulations. Their results showed that experimental strain data can closely match elastic predictions when strain gauges are properly installed. This highlights that installation accuracy (orientation and location) has a substantial impact on measurement reliability. These findings align with the observations of the present study, where inaccurate gauge orientation proved to cause deviations in shear strain readings.

At the structural component level, Cao et al. (2021) conducted experimental testing on steel truss-reinforced concrete beam–column joints to map shear strain distribution using strain gauges. Although the object of study differs from the focus of this research, their experimental approach and the use of strain gauges for verification are relevant and support the methodology applied here. In a broader scope, Hui et al. (2023) used strain gauge data to validate a seven-degree-of-freedom (7DOF) beam element model for bridge

girders during deck construction. Their study emphasized the importance of actual strain data in validating numerical structural models. However, neither Cao et al. nor Hui et al. addressed the effect of strain gauge installation quality on measurement outcomes, which is one of the key concerns of this research.

In another study, İrsel (2022) combined experimental, theoretical, and numerical approaches to investigate the flexural and fatigue behavior of thin-walled X-section steel beams. Flexural strains were measured using strain gauges, and the results showed good agreement with elastic theory predictions. Nevertheless, İrsel's work did not discuss potential deviations caused by installation errors. Building on this, the present study emphasizes the importance of measurement accuracy for WF steel beams to ensure that both flexural and shear experimental results are valid when compared with elastic theory.

Additionally, Obst et al. (2022) performed four-point bending tests on thin-walled open-section steel beams, where the load was applied through the shear center to generate pure bending without torsion. Their study relied heavily on strain gauge data accuracy in validating elastic beam behavior. Similarly, Pham et al. (2019), in validating the Direct Strength Method (DSM) for thin-walled steel beams with high span-to-depth ratios, stressed the importance of reliable experimental strain data for accurate structural strength predictions. Both findings underline that the integrity of strain data is vital for experimental verification of structural models or theories.

On the other hand, material conditions may also influence strain measurement results. Xiao et al. (2024) observed that corrosion within the shear span of Q550E steel beams significantly altered strain distribution along the beam and reduced its bending capacity. Their study highlighted the effect of material degradation on strain behavior and structural strength. Unlike Xiao et al., who focused on material conditions, this study emphasizes technical aspects of strain gauge application. Specifically, sensor misinstallation is identified as a potential source of deviation in flexural and shear strain data, which requires further investigation to improve the reliability of experimental steel structure data.

From the instrumentation perspective, Gavriushin et al. (2019) reported that strain gauge-based load sensors can respond to bending moments even though they are designed to measure axial forces only. This indicates that stress distribution due to bending can trigger unintended strain readings if the gauge orientation or placement on the sensor is inaccurate. Consistently, Gavrilenkov et al. (2019) highlighted that the design of strain gauge-based force transducers requires multi-criteria considerations to ensure sensitivity and accuracy. They also emphasized that actual field performance of the sensor is strongly influenced by installation conditions, particularly placement and orientation of the gauges. These findings reinforce the urgency of the present study, which evaluates how misorientation and misplacement of strain gauges contribute to deviations in flexural and shear strain measurements in steel beams. This step is crucial for practical validation to ensure the accuracy of laboratory testing data for steel structures.

At the national level, publications documenting actual strain measurements in WF steel beams (e.g., BJ37 grade) are still rarely found. Setiyarto & Abduloh (2025) investigated the local buckling capacity of WF steel beam webs through theoretical analysis based on design guidelines (AISC) and numerical verification. Although that study provided insight into local buckling strength estimates, it did not report direct strain measurement data. Therefore, there remains a knowledge gap regarding experimental strain data on WF steel beams in Indonesia. This study aims to fill this gap by presenting flexural and shear strain data obtained through experimental testing of WF beams under elastic conditions, while also analyzing the factors causing deviations between measurements and elastic theory predictions, particularly related to strain gauge installation accuracy. This contribution is expected to enhance the quality and validity of laboratory testing data for steel beam elements, while also supporting the evaluation and validation of strain-based structural design methods.

In the context of steel structures commonly used in Indonesia, such as hot-rolled WF (Wide Flange) steel sections of BJ37 grade, there is still very limited published experimental data on the actual strain distribution under elastic conditions. Furthermore, the execution of simple laboratory tests using strain gauges is rarely documented systematically, particularly regarding the practical challenges of installation and the analysis of deviations between experimental data and theoretical predictions.

This research aims to experimentally measure flexural and shear strains in WF 150.75.5.7 steel beams using electrical resistance strain gauges. The measured strains are then compared with theoretical predictions based on elasticity theory, followed by an analysis of how installation accuracy (particularly angular orientation on the web) affects the reliability of shear strain data.

The novelty of this study lies in evaluating the influence of strain gauge installation accuracy, particularly in shear strain measurement of structural steel elements. Unlike most previous studies that were conducted under ideal conditions, this research contributes scientific insight by emphasizing potential deviations caused by improper installation, providing experimental data for

WF steel sections of BJ37 grade, and serving as a practical reference for strain measurement techniques in structural laboratories, especially in resource-limited environments.

METHODS

The test specimen in this study was a WF $150.75 \times 5 \times 7$ steel beam with a total length of approximately 3.7 meters, made of BJ37 grade steel. The beam was simply supported and subjected to a centrally applied static load at mid-span. The experimental testing was carried out in the structural laboratory with the following configuration:

a. Testing Machine: A hydraulic-type Universal Testing Machine (UTM) was used to apply incremental vertical loads up to a maximum of 1200 kgf. The testing setup and instrumentation are shown in Figure 1.

b. Strain Gauges: FLA-6-11 strain gauges manufactured by Tokyo Sokki Kenkyujo, Japan, with an effective length of approximately 2 cm and a gauge factor of 2.1.

c. Data Logger: A DC104R data logger, made in Japan, was employed to record resistance changes in the strain gauges and convert them into digital strain data, which could be read through a computer.

d. Laptop: Used for real-time data acquisition and preliminary processing.

Figure 1. Laboratory Testing Setup (units in mm)

- **Strain Gauge Installation**

Strain gauges were installed at critical points along the beam, as illustrated in Figure 2. Two strain gauges (A1, A2) were installed on the top flange, aligned with the beam's longitudinal axis, to capture tensile flexural strain at the top fibers. Two strain gauges (B1, B2) were installed on the bottom flange, aligned with the longitudinal axis, to capture compressive flexural strain at the bottom fibers. Four strain gauges (C1, C2, D1, D2) were installed diagonally in a diamond-shaped configuration on the web, each oriented

at ±45° relative to the neutral axis, to capture principal strains due to shear stress. Prior to testing, electrical resistance of the strain gauges was measured using an AVO meter. The resistance increased from 120 Ω to 120.9 Ω after cable connection. Accordingly, the gauge factor was corrected to 2.0844 and input into the data logger system to minimize reading errors. Axial strain values obtained from the FLA-6-11 strain gauges were converted using the equation proposed by Keil (2017):

$$\varepsilon = \frac{\Delta R}{R} \cdot \frac{1}{k} \tag{1}$$

Where:

- ΔR = change in strain gauge resistance
- R = initial resistance of the strain gauge
- k = gauge factor (commonly between 2.0 – 2.1)

Shear strain in the web was calculated from the difference in diagonal strain relative to the principal axis using Keil's (2017) formula:

$$\gamma_{xy} = 2.(\varepsilon_{45°} - \varepsilon_{0°}) \tag{2}$$
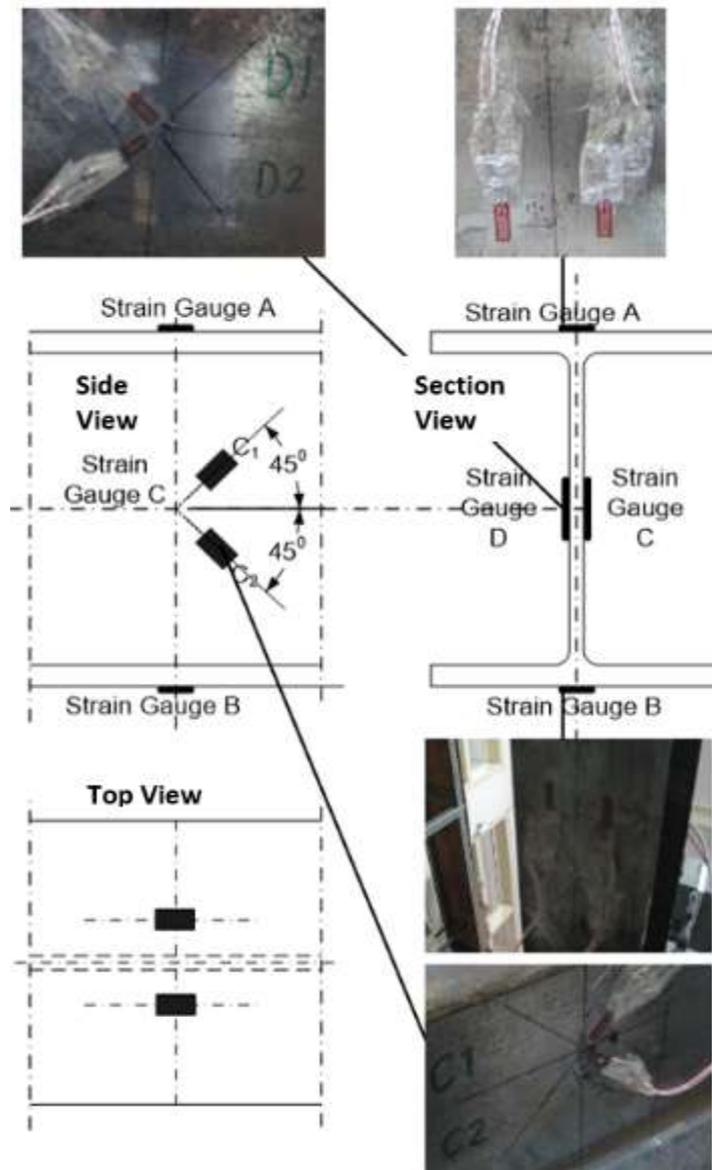

Figure 2. Strain Gauge Placement on the Beam

The beam was placed on simple supports in the UTM, and all strain gauges were connected to the data logger. Static load was applied gradually at intervals of 3 seconds until reaching maximum load (600–1200 kgf). Strain data for both flexural and shear responses were automatically recorded by the data logger and processed into load–strain (P–ε) plots.

Theoretical Calculations

Flexural strain was calculated based on elastic theory and Hooke's Law. The strain at a fiber located a distance yyy from the neutral axis is expressed as (Megson, 2019):

$$\varepsilon = \frac{M.y}{E.I} \qquad (3)$$

where flexural strain at the top and bottom fibers should be equal in magnitude but opposite in sign. Similarly, theoretical shear strain in the web was calculated using the linear elastic formula (Ugural & Fenster, 2020):

$$\gamma_{xy} = \frac{V.S}{G.I_x.t_w} \qquad (3)$$

Where:

- V = shear force
- S = first moment of area
- G = shear modulus
- I_x = moment of inertia about the x-axis
- t_w = web thickness

These theoretical equations provided a basis for validating experimental strain data and identifying potential deviations caused by sensor installation errors.

RESULTS AND DISCUSSION

Flexural Strain

Flexural strain tests were conducted under two load levels: P = 850 kgf and P = 1200 kgf, both of which were below the beam's yield limit capacity of P_{ult} = 1710.47 kgf (as calculated based on SNI 1729:2020). Strain gauges A1 and A2 were installed on the top flange, while B1 and B2 were positioned on the bottom flange.

The results indicated that strain at the top flange was positive (tension), whereas strain at the bottom flange was negative (compression), consistent with the theoretical flexural stress distribution. Experimental strain values were compared with theoretical predictions, as shown in Table 1.

Table 1. Comparison of Flexural Strain (ε) Between Theory and Experiment

Load (kgf)	Theory (με)	Experiment (με)	Difference (%)
850	189	197.5	+4.5%
1200	267	273.5	+3.4%

Note: 1 με = 1 × 10⁻⁶

The strain distribution showed a linear pattern with increasing load, indicating that the beam behaved elastically. However, a discrepancy was observed between the strain values of the top and bottom fibers, which theoretically should be equal in magnitude but opposite in sign. This inconsistency was likely caused by variations in strain gauge placement relative to the neutral axis or surface quality at installation. The complete flexural strain behavior at both load levels is shown in Figures 3.
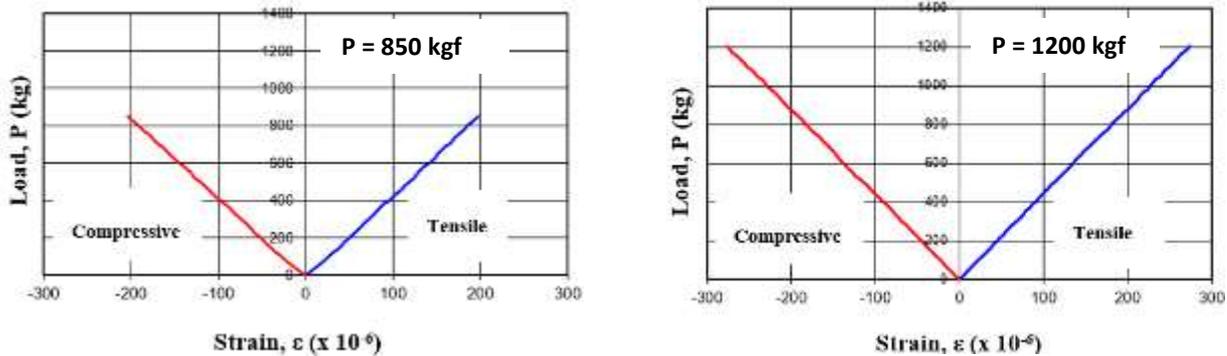
Figure 3. Load–Strain (P–ε) Relationship from Flexural Test at P = 850 kgf and P = 1200 kgf

Shear Strain

For shear strain testing, two load levels were applied: P = 600 kgf and P = 850 kgf. Strain gauges C1–C2 and D1–D2 were mounted diagonally at ±45° on the web to capture principal shear strains. Shear strain was then calculated using Equation (2).

Table 2. Comparison of Shear Strain (γ) Between Theory and Experiment

Load (kgf)	Theory (μγ)	Experiment (μγ)	Difference (%)
600	57	65	+14.04%
850	267	283	+6.1%

Note: 1 μγ = 1 × 10^{-6}

The relationship between load and shear strain (P–γ) appeared approximately linear, as illustrated in Figures 4 and 5. However, differences in strain readings between diagonal gauge pairs were not symmetric ($\varepsilon_1 \neq -\varepsilon_2$), indicating misalignment of strain gauges relative to the neutral axis. This deviation was particularly significant at lower load levels (14.04%), most likely due to:

- Inaccurate installation angle ($\neq 45°$),
- Uneven or insufficiently cleaned steel surface prior to installation,
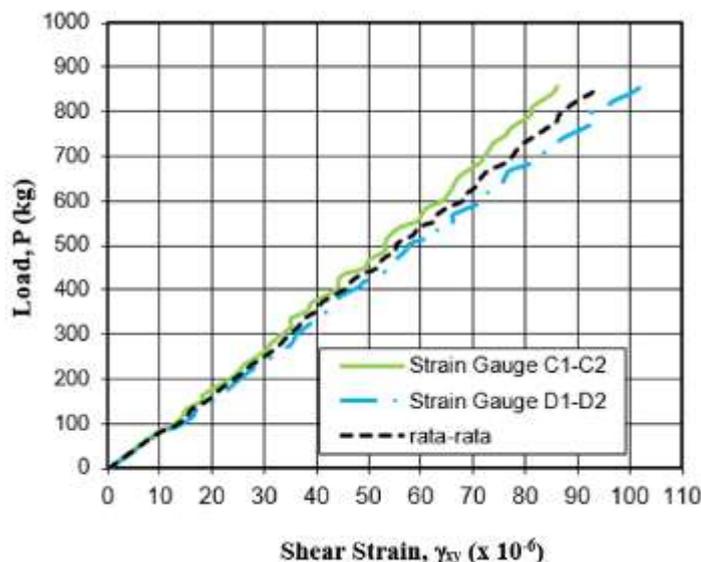- Differences in cable length or soldering joints affecting resistance.

Figure 4. Load–Shear Strain (P–γ$_{xy}$) Relationship from Experimental Test at P = 650 kgf

Overall Analysis

1. Flexural strain measurements yielded accurate results (<5% deviation), demonstrating that strain gauges are effective in capturing axial strain in WF beam flanges.
2. Shear strain measurements showed larger deviations (up to 14%), highlighting that shear strain measurement in webs is more sensitive to gauge orientation and installation quality.
3. Comparison with theory confirmed that the WF steel beam behaved in a linearly elastic manner, consistent with elastic theory predictions.

CONCLUSION

Based on the experimental testing of the WF 150.75.5.7 steel beam using strain gauges, the following conclusions can be drawn:

1. Flexural strain measurement using strain gauges produced accurate results, with deviations from theoretical predictions of less than 5%. This indicates that the beam behaved within the linear elastic range.
2. Shear strain measurement exhibited larger deviations, up to 14%, which were likely caused by inaccuracies in strain gauge installation angles and suboptimal surface conditions at the bonding area.
3. The comparison between experimental results and theoretical pre-analysis suggests that strain gauges are effective tools for experimental studies of steel structures, particularly for flexural testing. However, strict control over installation quality is necessary when measuring shear strains.
4. This research also provides preliminary documentation of strain testing on WF beams made of BJ37 grade steel, which is commonly used in Indonesia, employing a simple yet valid experimental approach.
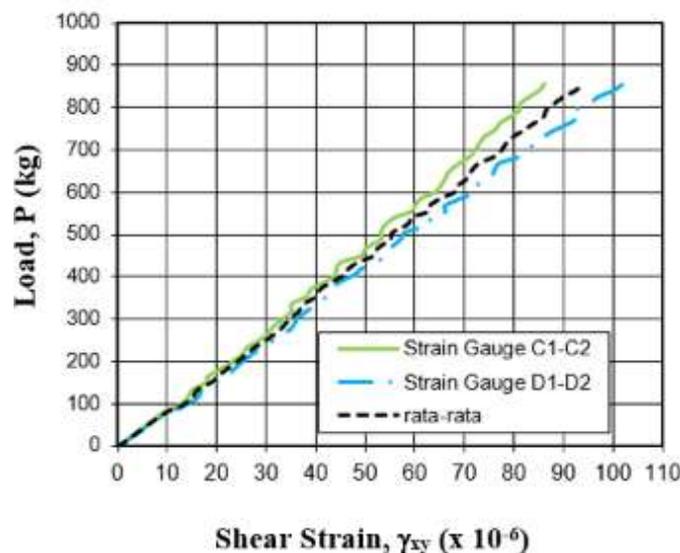

Figure 5. Load–Shear Strain (P–γ_{xy}) Relationship from Experimental Test at P = 850 kgf

SUGGESTIONS

- For shear strain measurements, strain gauges should be installed with precise calibration, ensuring a 45° orientation relative to the neutral axis and a perfectly flat, clean steel surface.
- It is recommended to use modern strain gauges (e.g., type FLAB-6-11) with higher technical specifications, along with specialized connecting cables that minimize resistance changes.
- Further research could explore higher load variations approaching yield point, as well as incorporate optical measurement systems (such as Digital Image Correlation) for validation of actual strain responses.
- This study may serve as a foundation for developing guidelines on experimental strain testing of steel in civil engineering laboratories, particularly within local contexts.

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