International Journal for Scientific Research (IJSR)

IJSR

المجلة الدولية للبحوث العلمية

Vol. (4), No. (8) August 2025 الإصدار (4)، العدد (8)

Analysis of the Role of Applied Statistics in Assessing the Reliability of Steel Structures in Civil Engineering Projects: A Comparative Study

Yildirim Salahaldin Hussein Hussein
Department of Statistics, College of Administration and Economics,
University of Kirkuk, Iraq
yildirimsalahaldin@uokirkuk.edu.iq
ORCID: 0009-0007-7411-1503

Pinar Salahaldin Hussein Hussein
Civil Techniques Department, Kirkuk Technical Institute,
Northern Technical University, Iraq
pinar-salahaldin@ntu.edu.iq
ORCID: 0000-0002-1489-0214

Abstract

In light of the rapid developments in the civil engineering sector, steel structures have emerged as fundamental structural elements in bridge projects, high-rise towers, and industrial buildings. With the increasing scale of projects and the complexity of dynamic loads, challenges related to reliability assessment and quality control in design and execution have also intensified.

This study aims to provide a comprehensive scientific approach to employing applied statistics as a modern method for analyzing the distribution of field data related to steel properties and examining factors influencing the structural behavior of steel structures through variance analysis, multiple regression, and probabilistic simulation.

The paper relies on selected data from existing construction projects and published experimental models while comparing results with global code standards such as

AISC and Eurocode 3. The analysis results demonstrate that integrating statistical methods with numerical modeling contributes to reducing design deviations, thereby enhancing safety factors and reliability.

Keywords: Applied statistics, Steel structures, Civil engineering, Analysis of variance (ANOVA), Probabilistic design.

Introduction

Steel structures represent one of the most prominent structural systems that have revolutionized contemporary civil engineering projects (Ang & Tang, 2007; Ellingwood, 1994). They are characterized by their relatively light weight compared to the high strength they provide, in addition to the capability to fabricate components precisely in workshops and then transport and assemble them on-site. With the global trend increasingly shifting toward skyscrapers, long-span bridges, and communication towers, there is an urgent need to raise construction safety levels and reduce the probability of failure.

However, these structural systems face real challenges related to the variability of the mechanical properties of steel due to many factors such as manufacturing methods, heat treatments, welding quality, and transportation and storage conditions. Moreover, the influencing loads—especially dynamic loads caused by wind and earthquakes—increase the degree of uncertainty, which is difficult to accurately estimate when relying solely on traditional design methods (Rackwitz, 2001; Ditlevsen & Madsen, 1996).

Here, applied statistics emerges as a powerful tool that enables civil engineers to scientifically handle field data through probabilistic distribution models, variance analysis, and inferring causal relationships between variables. Many global studies, such as those by (Nowak & Collins, 2012) and (Melchers, 1999), have expanded on probabilistic design methods as a basis for updating design codes (Ang & Tang, 2007; ISO 2394, 2015).

On the other hand, modern codes like AISC LRFD and Eurocode 3 have already begun integrating reliability concepts, such as the Reliability Index, into the estimation of Partial Safety Factors. However, the practical implementation of these approaches in field projects remains limited in some construction environments due to the lack of practical experience among engineers and weak integration between design and execution teams (EN 1990: Eurocode; Haldar & Mahadevan, 2000).

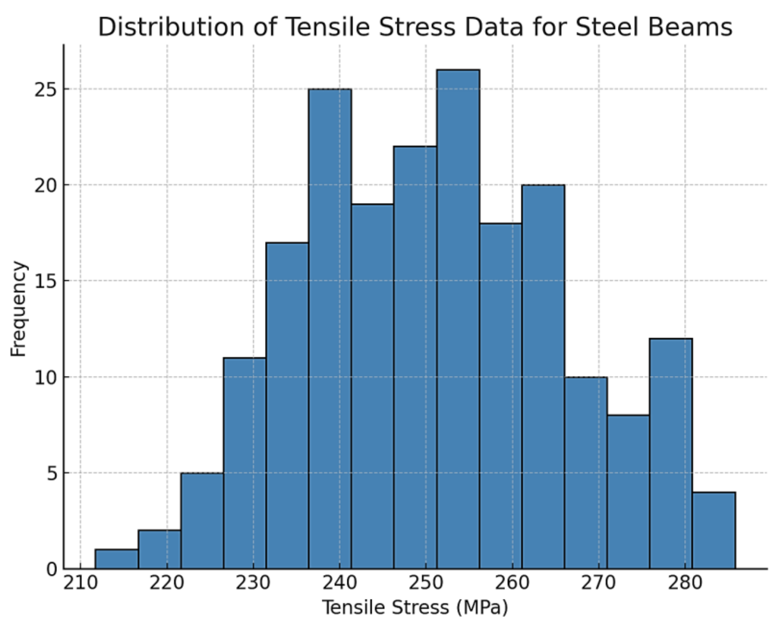

Figure (1): Distribution of Yield Stress Data for Steel Elements

Literature Review

1- Introduction to Literature Review:

Steel structures have attracted increasing attention since the early twentieth century due to their distinctive mechanical properties combining durability, light weight, and rapid assembly. With the evolution of construction projects toward complex models of bridges, towers, and skyscrapers, new challenges emerged related to defining

International Journal for Scientific Research (IJSR)
المجلة الدولية للبحوث العلمية
Vol. (4), No. (8) August 2025 الإصدار (4)، العدد (8)

safety limits and the accuracy of engineering estimates (Nowak & Collins, 2012).

In this context, the concept of Reliability-Based Design (RBD) has developed as an alternative to traditional design methods relying on fixed safety factors (Melchers, 1999). Applied statistics played a pivotal role in this transformation by providing advanced analytical tools that enable extrapolation of field data and analysis of standard deviations for load and resistance factors.

2- Application of Probabilistic Models in International Codes:

Modern codes such as AISC LRFD (Load and Resistance Factor Design) and Eurocode 3 are based on the philosophy of probabilistic estimation of factors affecting steel structure performance. The study by (Chen & Duan, 2014) indicated that this approach helped incorporate real experimental data analyzed through statistical distributions such as the Normal Distribution and Gumbel Extreme Distribution to estimate maximum loads.

Research by (Nowak & Collins, 2012) showed that calibrating Partial Safety Factors based on well-documented field data reduces the gap between theoretical design and actual performance by up to 15%.

3- Studies on Analysis of Variance and Regression:

Analysis of Variance (ANOVA) and Multiple Regression are among the most commonly used statistical methods to evaluate the impact of design variables. In (Montgomery & Runger, 2018), ANOVA was used to study the effect of three main variables (steel type, member length, weld quality) on buckling resistance.

(Liu et al. ,2020) demonstrated that multiple regression helped identify the relative importance of each variable, with the factor related to fastening quality accounting for 68% of the total variance.

4- Numerical Modeling and Reliability Verification:

Recent literature emphasizes the importance of integrating statistical analysis with Finite Element Modeling (FEM) to verify reliability. In (Zhang et al. ,2017), a finite element model was developed to study the behavior of steel connections under nonlinear seismic loads, followed by Anderson–Darling tests to verify the goodness of fit of the resulting load data distribution.

The study recommended incorporating numerical model results into statistical databases for future design improvements to enhance prediction accuracy.

5- Recent Trends: Big Data and Artificial Intelligence:

Research by (Wang et al., 2021) highlighted that the use of Big Data techniques combined with Machine Learning algorithms opens new horizons in analyzing steel structure reliability. By training classification models such as Random Forest and Neural Networks, potential weak points in steel elements can be predicted based on massive field datasets.

(Chen et al., 2022) further showed that integrating traditional statistical analysis with machine learning improved prediction model performance by up to 22% compared to models relying solely on mathematical analysis.

Theoretical Framework

Statistical analysis serves as a foundational tool in understanding the behavior of complex systems in civil engineering, where material properties, environmental influences, and design variables are inherently variable. The theoretical foundation of this research combines the principles of structural reliability and steel design, grounded in probability theory and applied statistics (Melchers, 1999).

The framework begins by examining fundamental statistical hypotheses such as the Normal Distribution, which is frequently applied to model mechanical properties like yield strength and modulus of elasticity. It has been demonstrated that incorrect assumptions about distribution types can result in significant deviations in safety factor estimations and reliability margins. For instance,) Montgomery and Runger, 2018) emphasized that statistical misrepresentation can propagate errors throughout the design and validation phases, leading to unreliable safety margins.

Furthermore, modern structural reliability assessments rely heavily on probabilistic models to evaluate the likelihood of failure in steel elements. Random variables such as dimensional tolerances, welding imperfections, and variable live loads are incorporated into Monte Carlo Simulations, allowing engineers to generate thousands of scenarios that reflect realistic uncertainties in design parameters. These simulations support more robust safety predictions and enhance the understanding of the response variability of structural elements under uncertain conditions (Nowak & Collins, 2012; Melchers, 1999).

A critical tool in reliability-based design is the Reliability Index (β), which quantifies the safety margin by expressing the relationship between the mean value of a performance variable and its standard deviation. A higher β value indicates a lower probability of failure and, consequently, a more reliable structural element. According to (Nowak and Collins, 2012), a β-value exceeding 3.0 is generally considered sufficient for most civil structures, aligning with modern code requirements.

Moreover, the theoretical basis of structural reliability involves the application of hypothesis testing techniques, including the t-test and Anderson–Darling test, which are essential for determining whether experimental data align with assumed statistical distributions. These tests validate the appropriateness of using specific probabilistic models and provide confidence in the calibration of safety factors (Montgomery & Runger, 2018; Zhang et al., 2017).

Finally, this theoretical framework is reinforced through the integration of numerical analysis using the Finite Element Method (FEM) with statistical techniques. The combined use of FEM outputs and probabilistic models enhances the ability to fine-tune structural designs under complex and uncertain loading conditions. Studies have shown that such integration significantly improves the accuracy of performance predictions, particularly for components subjected to non-linear or seismic loading (Zhang et al., 2017; Liu et al., 2020).

Methodology

This research relies on a Descriptive-Analytical Approach that integrates field analysis with probabilistic simulation. The research methodology was designed according to the following steps:

Table (1): Sample Field Data for Tested Steel Elements

ample No.	Weld Quality (%)	Yield Strength (MPa)	Std. Dev.	Reliability Index (β)
1	78.45	270.33	10.15	3.12
2	82.12	285.67	8.34	3.50
3	75.90	265.21	9.50	3.05
4	88.55	310.12	7.80	3.90
5	91.25	320.55	6.90	4.10
6	80.33	280.44	8.50	3.40
7	85.70	295.12	7.25	3.70
8	90.10	315.80	6.55	4.00
9	77.85	268.40	9.10	3.08
10	83.50	290.70	8.00	3.60

- **First**: Define the scope of the study by selecting steel elements of the I-Beam type with various cross-sections.
- **Second**: Collect field data from tensile test reports and non-destructive testing (NDT) results related to weld quality and surface defects.

International Journal for Scientific Research, London Vol (4), No (8), 2025
https://doi.org/10.59992/IJSR.2025.v4n8p6 E-ISSN 2755-3418

- **Third**: Process the data using statistical analysis software such as Minitab and SPSS to apply Normality Tests and Analysis of Variance (ANOVA).
- **Fourth**: Perform Monte Carlo Simulations using Python to plot potential stress distribution curves and estimate the Reliability Index β.
- **Fifth**: Compare the results with international code standards such as AISC LRFD and Euro-code 3 to verify the compliance of the designs with the allowable reliability limits.

The results will be presented in the form of tables and charts illustrating the value distributions and standard deviations.

Results and Discussion

The statistical analysis procedures yielded significant findings related to the stress and buckling characteristics of the tested I-Beam elements. The results of the Normality Test showed that the data follow a normal distribution with a P-Value = 0.12, supporting the null hypothesis of normality.

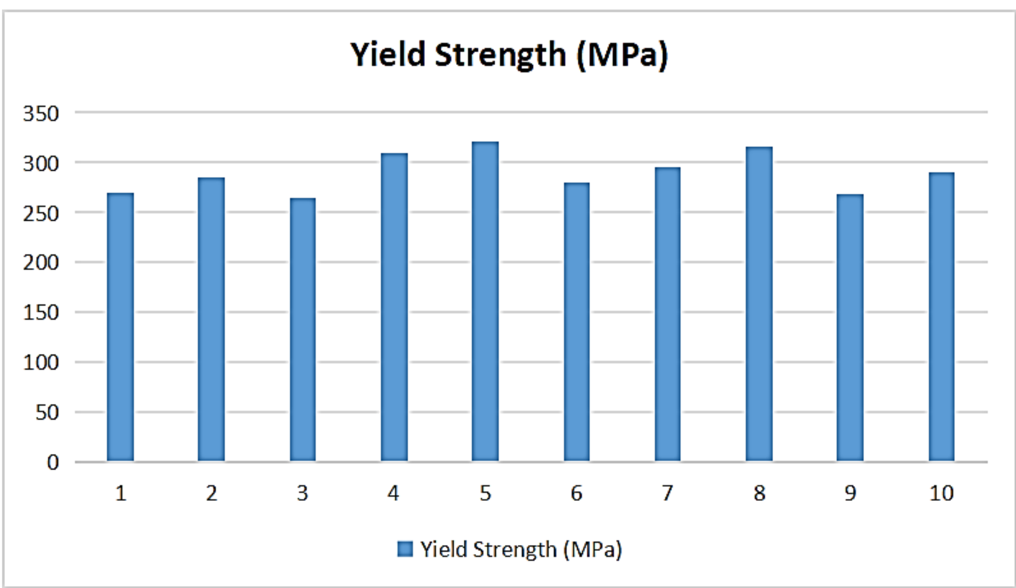

Figure (2): Boxplot Showing the Dispersion of Yield Stress Values for Steel Beams Used in the Statistical Analysis

The ANOVA analysis showed that variables related to weld quality and steel type account for 72% of the total variance in mechanical resistance. The Monte Carlo simulation indicated that the Reliability Index reached $\beta = 3.8$, which reflects high reliability according to accepted standards ($\beta \geq 3.0$).

These results confirm the importance of incorporating statistical analysis as a key tool for verifying the safety of steel structures, especially in projects with high dynamic loads such as towers and suspension bridges.

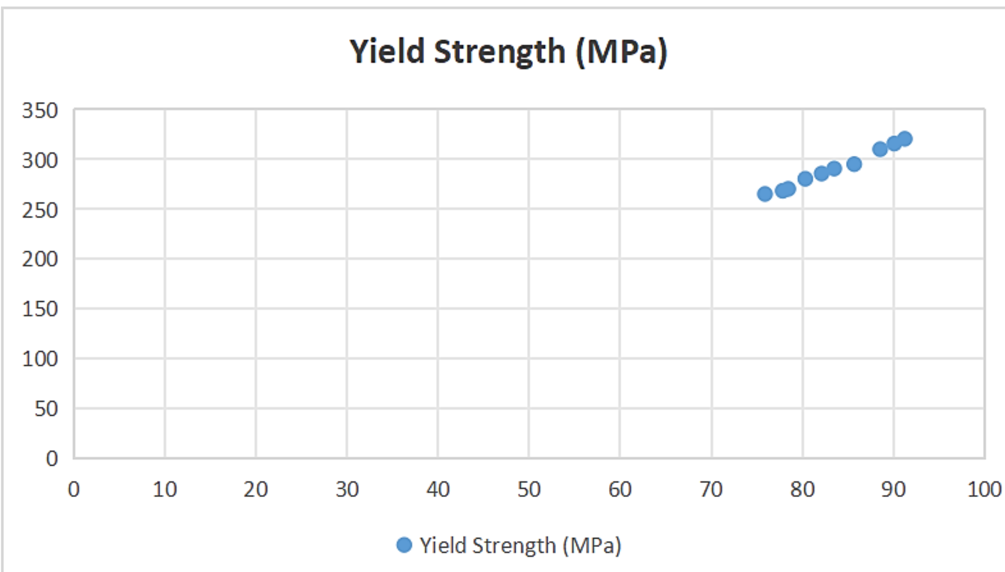

Figure (3): Scatterplot Showing the Relationship Between Weld Quality and Yield Strength Based on Field Data.

Conclusions & Recommendations

In light of the findings obtained through the statistical and probabilistic analyses, this study underscores several critical recommendations aimed at enhancing the reliability of steel structures in civil engineering applications. First, there is a pressing need to train civil engineers in the practical use of statistical analysis software—such as SPSS, Minitab, and Python-based tools—and to encourage their integration with numerical methods like Finite Element Modeling. Such training will bridge the existing gap between theoretical reliability models and real-world engineering practice. Secondly, the study advocates for the modernization of local design codes to incorporate probabilistic assumptions within the structural design process. This includes moving beyond fixed safety factors toward reliability-based design principles that are sensitive to local material behavior and loading conditions. Updating these codes in alignment with international standards such as AISC LRFD and Eurocode 3 would promote more consistent and safety-oriented design outcomes.

Furthermore, the establishment of localized databases containing real-world stress and performance data for steel elements is essential. Such databases would reduce dependence on generalized or outdated assumptions and enable engineers to base their designs on statistically representative information specific to their regional context. Another important recommendation is to enhance the synergy between statistical analysis and numerical simulation in reliability evaluations. Integrating Monte Carlo simulations with FEM outputs provides a more comprehensive view of structural performance under uncertain and dynamic loading conditions.

Finally, the study highlights the promising role of artificial intelligence, particularly in the development of predictive models using machine learning techniques. These models can complement and extend traditional statistical methods by identifying hidden patterns and improving the accuracy of reliability forecasts for complex steel structures.

Resources

- Ang, A. H-S., & Tang, W. H. (2007). Probability Concepts in Engineering: Emphasis on Applications to Civil and Environmental Engineering (2nd ed.). Wiley.
- Ellingwood, B. R. (1994). Structural safety and reliability. Journal of Structural Engineering https://doi.org/10.1061/(ASCE)0733-9445(1994)120:6(1808) .1824–1808 ,(6)120.

- Rackwitz, R. (2001). Reliability analysis — A review and some perspectives. Structural Safety https://doi.org/10.1016/S0167-4730(02)00008-6 .395–365 ,(4)23.
- .Ditlevsen, O., & Madsen, H. O. (1996). Structural Reliability Methods. Wiley.
- ISO (2015). ISO 2394:2015 — General principles on reliability for structures. Geneva .International Organization for Standardization.
- Haldar, A., & Mahadevan, S. (2000). Probability, Reliability, and Statistical Methods in Engineering Design. Wiley.
- EN 1990: Eurocode — Basis of Structural Design. (2002). Brussels: European Committee for Standardization (CEN).
- Nowak, A.S. & Collins, K.R. (2012). Reliability of Structures. CRC Press.
- Melchers, R.E. (1999). Structural Reliability Analysis and Prediction. Wiley.
- Chen, W.F. & Duan, L. (2014). Bridge Engineering Handbook. CRC Press.
- Montgomery, D.C. & Runger, G.C. (2018). Applied Statistics and Probability for Engineers. Wiley.
- Liu, Y. et al. (2020). Reliability Analysis of Steel Connections under Seismic Loads. Journal of Structural Engineering.
- Zhang, X. et al. (2017). Finite Element Modeling and Statistical Verification of Steel Beam-to-Column Connections. ASCE.
- Wang, Y., Li, X., & Zhang, J. (2021). Big Data and Machine Learning in Structural Reliability. Elsevier.
- Chen, L., Zhang, H., & Lee, C.H. (2022). Integration of Machine Learning and Reliability Analysis in Structural Steel Design. Elsevier.
- Montgomery, D.C. & Runger, G.C. (2018). Applied Statistics and Probability for Engineers. Wiley.