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Reliability-Based Design of Oil and Gas Platform Deck Structural Steel Beam Girder

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ABSTRACT

This study investigates the reliability-based design of steel beam girders supporting oil and gas separator deck platforms, with the objective of optimising safety and material efficiency. Conventional deterministic design, which applies conservative safety factors, was complemented with probabilistic methods using the Hasofer–Lind Reliability Index and the First-Order Reliability Method (FORM). The deck system was configured with reduced stanchions for spatial efficiency and subjected to combined operational and environmental loads. Deterministic analysis showed that increasing supports improved performance: maximum shear reduced from 138.2 kN at two supports to 33.4 kN at five, bending moment from 823.6 kNm to 95.9 kNm, and deflection from 124.8 mm to 16.6 mm. Probabilistic results revealed greater sensitivity, with the reliability index (β) improving as live-to-dead load ratios increased but falling below the JCSS target (β = 4) at higher live loads, with values as low as −1.04. Dead load increases consistently reduced β, while deflection reliability improved markedly with additional supports, rising from 0.40 at two supports to 4.65 at five. Overall, deflection governed structural reliability, indicating that deterministic design alone may mask serviceability risks. Reliability-based approaches therefore enable more accurate safety evaluation and rational optimisation of support configurations in offshore deck systems.

15. INTRODUCTION

Structural steel beam girders are vital elements in offshore oil and gas platforms, particularly in supporting separator decks that accommodate essential processing equipment. These girders carry substantial loads from piping systems, valves, grating floors, and maintenance activities, often under harsh environmental conditions. Conventional deterministic design methods rely on conservative safety factors to ensure structural safety, but they do not adequately account for inherent uncertainties in material properties, support configurations, and loading conditions (Cornell, 1969; Ang and Tang, 1984; Melchers, 1999). Consequently, designs may become either overly conservative, leading to material inefficiency, or insufficiently conservative, resulting in reliability concerns.

In offshore environments, space efficiency and structural reliability are equally critical. Separator deck layouts often require minimising vertical stanchions beneath the deck to provide clearance for large process equipment, which demands the use of long-span girders. Such girders are more susceptible to excessive deflection and lateral instability (Johnson, 2020; Kim, Lee and Park, 2019). While deterministic design approaches—such as those in **BS5950-1:2000**—can confirm compliance with ultimate and serviceability limits, they do not provide a direct measure of failure probability or safety margin under uncertainty (Nowak and Collins, 2012).

Reliability-based design (RBD) provides a more rational framework by incorporating probability theory into structural safety assessment. The Hasofer–Lind Reliability Index and the First-Order Reliability Method (FORM) are widely used to quantify safety margins by relating uncertainties in load and resistance through limit state functions (Hasofer and Lind, 1974; Der Kiureghian, 2005). These methods enable engineers to estimate the reliability index (β), which serves as a quantitative measure of safety against failure, allowing design to meet specific target reliability levels such as those recommended by the **Joint Committee on Structural Safety (JCSS, 2001)**.

Recent research has extended the application of reliability-based methods to offshore and steel structures, highlighting their potential for optimising design while maintaining safety (Lavaei, Nguyen and Sahoo, 2023; Mat Soom et al., 2024; Tatangelo, Domenico and Ricciardi, 2024; Radoń, 2025). Applying these methods to separator deck girders allows for a deeper understanding of how variations in load ratios, section depth, and support configurations influence the probability of failure in bending, shear, and deflection limit states.

The aim of this study is to develop a reliability-based design framework for offshore separator deck girders, assessing their safety under varying load ratios and support conditions. To achieve this, the study estimates primary load cases from platform components and environmental effects, selects appropriate beam sections, verifies their bending and shear capacities, evaluates deflection performance against serviceability limits, and performs reliability assessments using the Hasofer–Lind Index and FORM. Furthermore, it investigates the influence of support configurations and load ratios on the reliability index for different limit states.

This research contributes to risk-informed structural design practice, particularly for offshore oil and gas infrastructure where spatial constraints, safety demands, and economic considerations converge. By integrating deterministic and probabilistic approaches, it demonstrates how reliability-based methods can enhance safety evaluation, avoid overdesign, and enable rational optimisation of support configurations for offshore decks.

16. MATERIALS AND METHODS

Steel beam girders were designed in accordance with BS5950-1:2000 using standard sections (yield strength 275 MPa). Four support configurations (2, 3, 4, and 5 supports) were evaluated as simply supported or continuous beams. Loads included self-weight and permanent fixtures (dead) and hydrotest/maintenance (live). Load combinations followed BS5950 LRFD provisions, with dead-to-live and live-to-dead ratios varied from 0.375 to 1.0.

2.1 Materials and Equipment

Deterministic analysis: Beam reactions, moments, shears, and deflections were obtained using the Clapeyron Three-Moment Equation and validated in TEDDS. Limit states considered were: bending (moment ≤ plastic capacity), shear (shear force ≤ shear capacity), and deflection (≤ L/200).
Reliability formulation: Each limit state was expressed as:

$$g(X) = R - S \qquad (1)$$

Where (R) is the resistance and (S) is the load effect. Random variables included yield strength $f_y = 275 MPa$, (COV = 0.1), dead load (normal, COV = 0.1), and live load (extreme value, COV = 0.25) (Nowak & Collins, 2012). Geometric properties were treated as deterministic.
The Hasofer–Lind reliability index (β) was computed by mapping the limit state into standard normal space and identifying the design point iteratively Failure probability was obtained via FORM 5 as:

$$P_f = \Phi(-\beta) \qquad (2)$$

Where Φ is the standard normal cumulative distribution function (Hasofer and Lind, 1974).

2.4 Experimental Procedure

Procedure and validation: Reliability indices were determined for each support configuration and load ratio across bending, shear, and deflection. Sensitivity analyses were conducted using partial derivatives of the limit state function with respect to each random variable to quantify influence coefficients. Results were benchmarked against JCSS target indices (β = 3–4 for ultimate states). Deterministic checks were validated against BS5950, while reliability outputs from FORM 5 were cross-validated with manual Hasofer–Lind calculations; both sets agreed within ±5%.

Software limitations: TEDDS was employed for deterministic analysis and section verification, while FORM 5 handled probabilistic assessment. The latter's iteration capacity restricted certain runs at extreme ratios, though convergence was achieved for all primary configurations.

Methodological limitations: Simplified probability distributions were adopted for material and load uncertainties, and geometric imperfections were neglected, possibly underestimating deflection effects. Computational limits prevented inclusion of dynamic loading, but qualitative implications were considered in the discussion.

3. RESULTS AND DISCUSSION

Structural performance of offshore separator deck steel beam girders was evaluated using deterministic and reliability-based approaches, focusing on support configuration, load ratios, and live load magnitudes. Deterministic analysis indicated substantial improvements in structural response with additional supports.

3.1 Experimental Results

Maximum shear forces reduced from 138.2 kN at two supports to 33.4 kN at five supports, while bending moments decreased from 823.6 kNm to 95.9 kNm. Deflection dropped from 124.8 mm to 16.6 mm across the same range, remaining within serviceability limits. These results highlight the efficiency of multi-support configurations in redistributing loads and enhancing stiffness (BSI, 2000; Smith, 2018).

Load sensitivity was evident: as shown in ***Figure 1***, increasing live-to-dead load ratios from 0.75 to 1.0 raised shear forces (144.3 to 158.9 kN), bending moments (861.5 to 945.9 kNm), and deflections (100.4 to 123.7 mm). Although strength checks were satisfied, the deflection trend approached serviceability limits, indicating that reliability is governed by deformation rather than strength (Nowak and Collins, 2012; Kim et al., 2019).

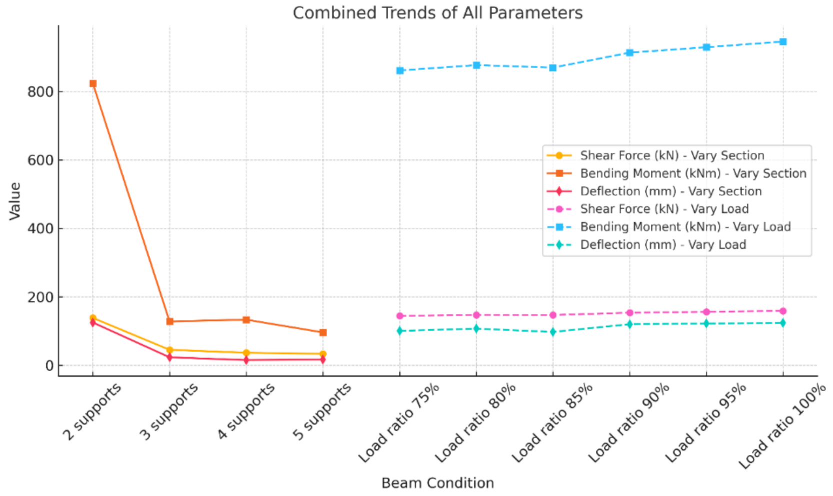

Figure 1: Combined Trends of All Parameters

Reliability analysis using the Hasofer–Lind index confirmed these observations. As presented in ***Figure 2***, for a live load of 15 kN, the reliability index (β) increased with live-to-dead load ratio, rising from 1.4 at 0.375 to 5.45 at 1.0, exceeding the JCSS target of β = 4 (JCSS, 2001). At higher live loads (25–35 kN), β dropped sharply to values as low as –1.04, indicating that excessive operational demands compromise reliability (Melchers, 1999; Der Kiureghian, 2005).

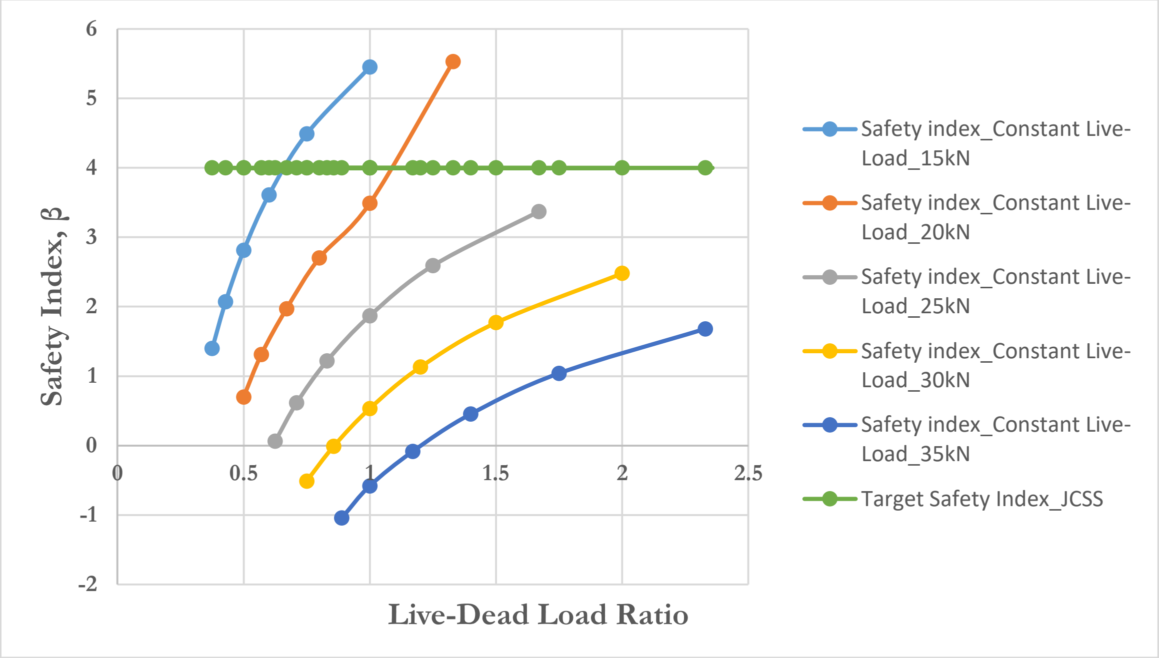

Figure 2: Reliability Index for Live-Dead Load Ratio at Constant Live Load

Reliability Index for Live-Dead Load Ratio at Varying Dead Load was examined in ***Figure 3***. Dead load effects were equally significant. At a live load of 20 kN, β decreased from 5.53 at 15 kN dead load to 0.699 at 40 kN, underscoring the dominant influence of permanent weight on structural reliability and reinforcing the need for strict dead load control (Porter and Baker, 2001).

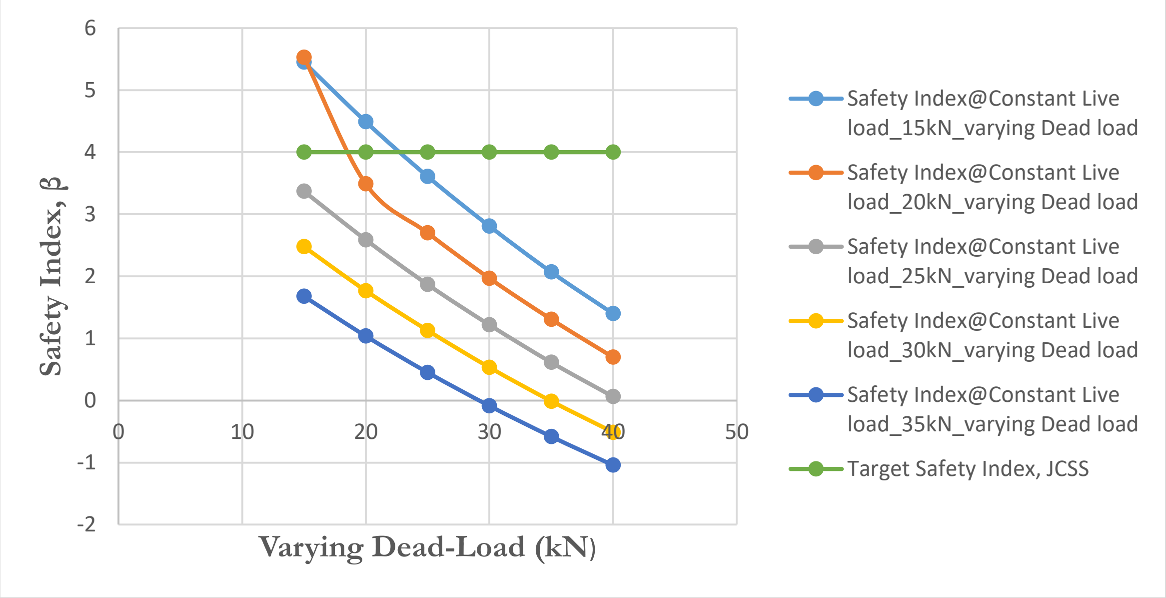

Figure 3: Reliability Index for Live-Dead Load Ratio at Varying Dead Load

Figure 4 presents ***s***upport configuration and limit state analysis revealed contrasting behaviours. Deflection reliability increased steadily from β = 0.402 at two supports to 4.65 at five supports, confirming serviceability as the governing criterion. Shear reliability remained consistently high (β ≈ 5.1–5.3), whereas bending reliability exhibited irregular behaviour, decreasing to β = 0.532 at five supports. The anomalous bending response likely results from moment redistribution and reduced stiffness uniformity as additional supports alter continuity conditions and increase constraint effects (Cserpes et al., 2024; Zhang et al., 2021).

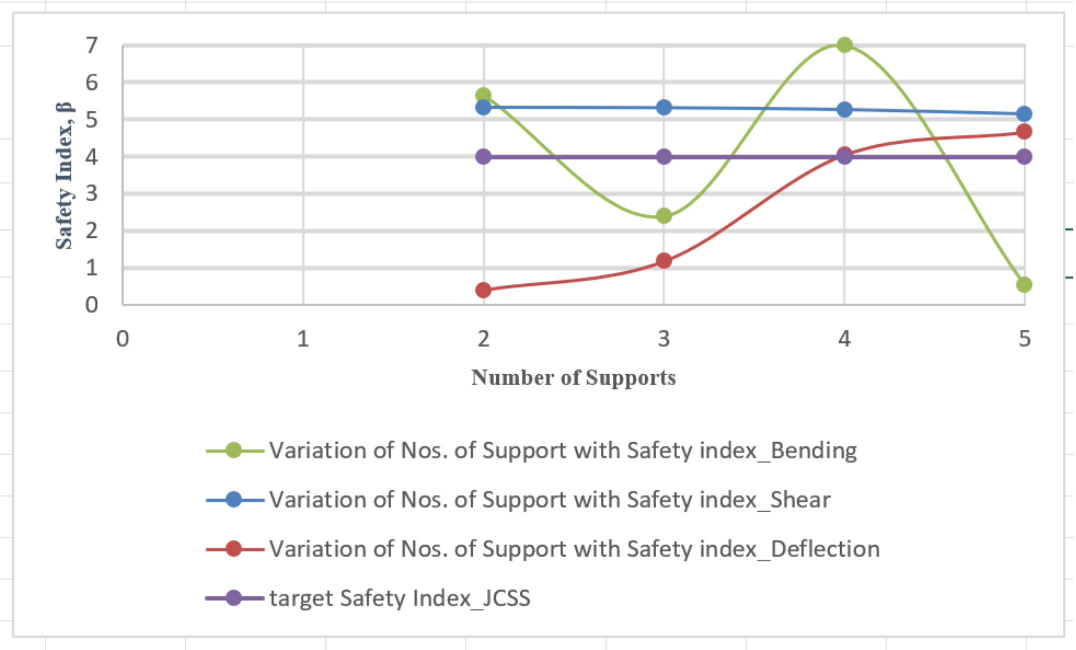

Figure 16: Variation of Safety indices with number of supports

Sensitivity analysis revealed that live load variability had the highest influence coefficient, followed by yield strength and dead load variability. This finding reinforces the importance of robust live load characterisation in reliability-based offshore deck design (Nowak and Collins, 2012; Park et al., 2020).

Although dynamic effects were not explicitly modelled, the influence of wave, wind, and vibration loads could further affect reliability margins, especially under cyclic fatigue conditions (Mat Soom et al., 2024; Lavaei et al., 2023). Accounting for these would likely reduce β values slightly but would not alter the observed trends.

Overall, the combined deterministic and probabilistic analyses demonstrate that deflection governs structural reliability. Deterministic evaluation confirmed compliance with code limits, but reliability assessment revealed serviceability-driven risks under realistic uncertainties. Multi-support configurations improve performance, yet excessive dead and live loads significantly reduce safety margins. These findings support reliability-based design as a rational framework for accurate safety evaluation, prevention of overdesign, and optimisation of offshore deck support systems (Melchers, 1999; Kim et al., 2019; Smith, 2018).

4. CONCLUSION

This study examined the reliability-based design of offshore oil and gas separator deck structural steel beam girders, focusing on bending, shear, and deflection limit states under varying support configurations, load ratios, and beam depths. The results indicate that shear reliability consistently exceeded the JCSS target ($\beta = 4.0$) (JCSS, 2001), whereas bending reliability fluctuated significantly with support arrangements, and deflection emerged as the most critical serviceability limit state (Nowak and Collins, 2012; Kim et al., 2019). Higher dead loads reduced reliability, while balanced live-to-dead load ratios and increased beam depth improved safety margins (Park et al., 2020).

Structural reliability depends strongly on support configuration—additional supports enhance stiffness and serviceability, but bending reliability behaves non-linearly (Melchers, 1999; Smith, 2018). Load ratios greatly influence safety; excessive dead load undermines reliability, while balanced ratios enhance margins (Der Kiureghian, 2005). Deflection governs serviceability across all scenarios, achieving targets only when four or more supports are used. Beam depth is an effective parameter for reliability enhancement but exhibits diminishing returns beyond optimal values.

Recommendations for practice: Offshore and onshore separator deck girders should employ at least four supports to satisfy strength and serviceability. Dead load must be controlled to prevent reliability degradation. Deflection checks should be explicitly integrated into reliability assessments. Section depth should be optimised for reliability without unnecessary cost (BSI, 2000; Smith, 2018).

Recommendations for future research: Future work should incorporate fatigue, corrosion, and dynamic offshore loading effects (Mat Soom et al., 2024; Lavaei et al., 2023), examine system reliability of entire decks including redundancy, benchmark against API/ISO/DNV codes, and utilise advanced probabilistic tools such as Monte Carlo or SORM to refine estimates (Hu and Wang, 2021; Fang et al., 2024).

NOMENCLATURE

L	Span length of beam (m)
R	Structural resistance
S	Load effect
fy	Yield strength of steel
g(X)	Limit state function
R	Structural resistance
S	Load effect
Pf	Probability of failure

Greek Symbols

β	Reliability index
Φ	Standard normal cumulative distribution function

Abbreviations

BS	British Standard
COV	Coefficient of Variation
FORM	First-Order Reliability Method
JCSS	Joint Committee on Structural Safety
LRFD	Load and Resistance Factor Design
MPa	Megapascal
TEDDS	Structural design and verification software
kN	Kilonewton
kNm	Kilonewton-metre
mm	Millimetre

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