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VALIDATION FOR FINITE ELEMENT ANALYSIS OF FREE-SPANNING SUBSEA PIPELINE USING THEORETICAL FORMULA

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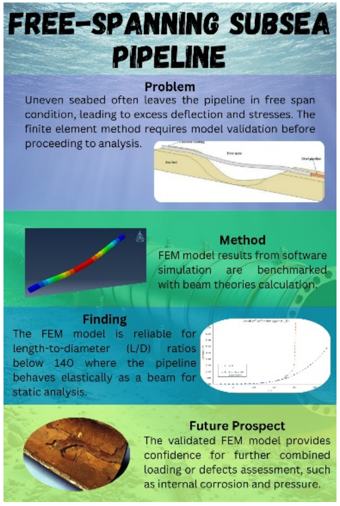
Graphical abstract



Problem
Uneven seabed often leaves the pipeline in free span condition, leading to excess deflection and stresses. The finite element method requires model validation before proceeding to analysis.

Method
FEM model results from software simulation are benchmarked with beam theories calculation.

Finding
The FEM model is reliable for length-to-diameter (L/D) ratios below 140 where the pipeline behaves elastically as a beam for static analysis.

Future Prospect
The validated FEM model provides confidence for further combined loading or defects assessment, such as internal corrosion and pressure.

Abstract

Hydrocarbon products from offshore sources are primarily transported to onshore facilities using subsea pipelines, which typically rest on the seabed. To ensure safe operation and prevent failure, engineers must assess the reliability of these free-spanning pipelines, which are prone to structural risks due to uneven seabed conditions. The finite element method (FEM) is widely used for structural analysis due to its flexibility in modelling complex structures. Validation of FEM is essential for verifying its accuracy, typically against physical experiments or reliable theoretical data. This study validates a finite element (FE) model for the static analysis of free-spanning subsea pipelines by comparing FEM predictions with Euler-Bernoulli and Timoshenko beam theories. The pipeline model, developed in Abaqus, was evaluated across various length-to-diameter (L/D) ratios. Results show that for L/D < 140, FEM predictions align with beam theory, exhibiting errors below 2%. However, for L/D > 160, FEM deviations exceed 30%, indicating nonlinear effects beyond the range of beam models. These findings refine the applicability of DNV-RP-F105 guidelines, enhancing pipeline integrity assessment methodologies in offshore engineering. The validated FEM model offers confidence for further evaluation of pipeline integrity under combined loading or defects.

Keywords: Free-spanning pipeline, Finite Element Method (FEM), FEM validation, beam theory, static analysis, deflection.

Abstract

Produk hidrokarbon dari sumber luar pesisir utamanya diangkut ke kemudahan darat menggunakan saluran paip bawah laut, yang biasanya terletak di dasar laut. Untuk memastikan operasi yang selamat dan mengelakkan kegagalan, jurutera mesti menilai kebolehpercayaan saluran paip rentang bebas ini, yang terdedah kepada risiko struktur akibat keadaan dasar laut yang tidak rata. Kaedah elemen terhingga (FEM) digunakan secara meluas untuk analisis struktur kerana fleksibilitinya dalam memodelkan struktur yang kompleks. Pengesahan FEM adalah penting untuk mengesahkan ketepatannya, biasanya terhadap eksperimen fizikal atau data teori yang boleh dipercayai. Kajian ini mengesahkan model elemen terhingga (FE) untuk analisis statik saluran paip bawah laut bebas dengan membandingkan ramalan FEM dengan teori rasuk Euler-Bernoulli dan Timoshenko. Model saluran paip, yang dibangunkan di Abaqus, telah dinilai merentasi pelbagai nisbah panjang-ke-diameter (L/D). Keputusan menunjukkan bahawa untuk L/D < 140, ramalan FEM sejajar dengan teori rasuk, menunjukkan ralat di bawah 2%. Walau bagaimanapun, untuk L/D > 160, sisihan FEM melebihi 30%, menunjukkan kesan tak linear melebihi julat model rasuk. Penemuan ini memperhalusi kebolehgunaan garis panduan DNV-RP-F105, meningkatkan metodologi penilaian integriti saluran paip dalam kejuruteraan luar pesisir. Model FEM yang disahkan memberikan keyakinan untuk penilaian lanjut integriti saluran paip di bawah pemuatan gabungan atau kecacatan.

1.0 INTRODUCTION

Subsea pipelines are essential for transporting oil and gas from deep-water fields to processing facilities. They have been widely applied due to the cost-effectiveness and efficiency of this transport method compared to others (Rui et al., 2024). However, the subsea pipeline installation, which includes the laying process, presents some challenges in placing the pipeline precisely on an even seabed along the entire route Subsea pipelines often experience free spans due to seabed irregularities, which induce localised bending stresses that may compromise structural integrity. While DNV-RP-F105 recommends beam models for L/D ratios between 30 and 100, their applicability to longer spans remains unverified. This study investigates FEM accuracy for extended L/D ratios, addressing this gap and improving the understanding of pipeline behaviour in deep-water conditions (Monacchi et al., 2023). Consequently, pipeline failure can occur due to static loads, thus causing environmental damage, financial loss and operation disruptions.

Furthermore, seabed conditions can change over time due to erosion, seismic activity, and subsidence, which can significantly impact the length of free spans. The free spans that arise from these uncontrollable factors require engineers to assess the reliability of the pipeline regularly. Mitigation measures must be meticulously planned, as the pipeline lies deep underwater, making the process extremely dangerous and expensive. Hasty decisions without thorough analysis can cause financial loss to the oil and gas company for the maintenance action (Chee et al., 2018). Therefore, accurate structural analysis is essential to predict the remaining strength of the pipeline when subjected to free spans.

In pipeline analysis, there are common methods that have been used to calculate deformation and stress distribution, such as analytical methods and finite element methods (FEM) (Phuor et al., 2023). With advancements in computational power, software like Abaqus has been widely utilised to conduct finite element analysis for various structures. This software provides convenience to engineers and enhances the accuracy of analyses, regardless of the complexity of the structural model, unlike traditional analytical calculations that are restricted to certain specific structural conditions. Nevertheless, prior to the application of the finite element model for structural analysis, its accuracy needs to be validated. This validation is usually performed by comparing the FEM results with experimental data or theoretical calculations (Hwang & Lee, 2019).

However, the enormous size of subsea pipelines and the long spans required to simulate real seabed conditions make experimental studies on free-spanning pipelines challenging and costly (Shittu et al., 2019). As a result, limited research has conducted experimental studies on free-spanning pipelines. Therefore, theoretical calculations are necessary to validate the finite element model. According to recommended practice DNV-RP-F105, free-spanning subsea pipelines can be assumed to exhibit beam-like behaviour when responding to loads. Based on well-established theories, the Euler-Bernoulli and Timoshenko beam theories are commonly used to analyse the beam behaviour of the pipeline (Khiem, 2017).

Thus, this paper aims to validate the finite element (FE) model for static analysis of a free-spanning pipeline using theoretical calculations before conducting parametric and stress studies. The Euler-Bernoulli and Timoshenko beam theories will be studied to determine which is the most suitable for the model validation. The lack of experimental data on the deflection effects in free-spanning pipelines highlights the importance of those theoretical formulas in the preliminary step of finite element analysis. This step ensures model precision and avoids inaccuracies in subsequent parametric studies.

2.0 THEORETICAL BACKGROUND

Structural analysis requires an understanding of the fundamental theories that describe the behaviour of structures under load. In the case of free-spanning pipelines, beam theories are applied to describe the stresses and deflection in the pipeline, as recommended in DNV-RP-F105. This chapter discusses two widely used beam theories, the Euler-Bernoulli and Timoshenko beam theories, for their suitability for free-spanning pipeline static analysis. Both theories provide insight into the mechanical behaviour of pipelines under static loading from free span conditions and help facilitate the validation of the finite element model (FEM).

2.1 Euler-Bernoulli Beam Theory

The Euler-Bernoulli beam theory, also known as the classical beam theory, is one of the oldest and most widely applied theories in structural mechanics. The deformation of a beam structure subjected to loadings can be analysed based on the Euler-Bernoulli beam theory. This theory assumes that there is no distortion or warping of the beam's cross-section, neglecting the shear deformation and rotational inertia effects. According to the theory, plane sections perpendicular to the beam's neutral axis will remain plane and perpendicular after bending or deformation.

There are few studies that applied the Euler-Bernoulli beam theory to structural analysis. Firstly, a study by Yıldırım (2018) has presented closed-form solutions using the transfer matrix method based on the theory for the bending analysis. This study's method is an alternative to the finite element method. This study's closed-form solutions, which utilise Euler-Bernoulli beam theory, provide a benchmark for validating finite element computational solutions. Next, a research study by Gee (2021) formulated dynamic finite element (DFE) for Euler-Bernoulli beams under various conditions. The new DFE formulation was validated against the classical finite element method (FEM) to ensure its accuracy in structural analysis. Then, the DFE formulation can be extended to more complex beam models. The studies conducted by Yıldırım (2018) and Gee (2021) have demonstrated that the Euler-Bernoulli beam theory is well-known for flexural or bending deformation of structural analysis while neglecting the shear effects. The theory can be used to validate a new finite element model or as the base of new formulations for specific structural conditions.

In the context of free-spanning subsea pipeline analysis, the Euler-Bernoulli beam theory is applied to estimate the pipeline's deflection when subjected to relatively long span lengths compared to the pipeline's diameter (Hwang & Lee, 2019). The governed equation of the Euler-Bernoulli beam theory is expressed as:

$$EI\frac{d^4y(x)}{dx^4} = \omega(x) \tag{1}$$

This theory assumes linear approximations, simplifying the calculations by only considering small deflection and neglecting shear deformation in the structure. As the span length decreases or the pipeline diameter increases, shear deformation effects may become more significant, requiring a more advanced approach to predict the structural response accurately.

2.2 Timoshenko Beam Theory

To overcome the limitations of the Euler-Bernoulli beam theory, the Timoshenko beam theory was developed to incorporate shear deformation and rotational inertia effects. This theory is particularly useful for shorter, large-diameter beams or structures experiencing high-loading conditions, where shear deformation significantly influences the structural response.

For the example of the Timoshenko beam theory applications, a study by Thang (2021) has enhanced the calculation of beam deformation incorporating shear deformation, which addresses the limitation of the Euler-Bernoulli beam theory. The improved method of this study was validated with the software calculation. Besides, a study by Wu et al. (2023) extended the Timoshenko beam theory to account for large deflections. This research established a framework for validating FEM results by using the modified Timoshenko beam theory to model solutions for flexible beams with large deflection. These examples of studies highlighted that Timoshenko beam theory is crucial for structures with large deflection or structures with significant shear effects. In most cases, the shear effects are neglected because shear deformation is significantly smaller compared to flexural deformation. Hence, the Timoshenko beam theory is only applied to specific structures, such as deep beams, where the L/D ratio is typically less than 4 (Meng et al., 2023).

In free-spanning pipeline analysis, the Timoshenko beam theory accounts for shear strain, making it more suitable for shorter pipelines and larger cross-sections, where the shear deformation is non-negligible. Although the equation of Timoshenko beam theory is more complex, it is necessary when analysing pipelines subjected to a combination of bending and shear loads. The governing equation for the deflection calculation of Timoshenko beam theory is represented as:

$$EI\frac{d^4y(x)}{dx^4} - kGA\frac{d^2y(x)}{dx^2} = \omega(x) \qquad (2)$$

2.3 Application of Beam Theories in FEM Model Validation

Both Euler-Bernoulli and Timoshenko beam theories offer simplified methods to analyse beam behaviour, particularly in terms of deflection and stress. These theories are crucial in estimating the pipeline's maximum deflection, as free-spanning pipelines behave like beams under a specific range of span length and diameter. In summary, the Euler-Bernoulli beam theory is suitable for longer free spans, where shear deformation can be disregarded. In contrast, the Timoshenko beam theory incorporates shear deformation, which is significant in short-span or large-diameter pipelines. The appropriate selection of theory is crucial to ensure accurate deflection calculations.

The theoretical calculations that have been derived from these beam theories are essential for validating the finite element method (FEM) by comparing the deflection results of both methods. The FEM model must produce results within an acceptable range of percentage difference compared to the theoretical calculation to ensure its accuracy. The model accuracy is critical for reliable prediction in further analyses. Research by Su & Ma (2011) demonstrated the importance of validating the FEM results with theoretical calculations for their study of transient waves in a simply supported beam. According to Belytschko et al. (2014), validating FEM models using theoretical solutions, such as Euler-Bernoulli and Timoshenko beam theories, ensures numerical accuracy before applying complex loading conditions. This framework is widely adopted in structural mechanics to establish confidence in FEM predictions.

In this paper, the FEM model focuses on typical free-span lengths that significantly impact the pipeline. Since longer free-span lengths generate more stress to the pipeline, the Euler-Bernoulli beam theory is preferred for long-span conditions compared to the Timoshenko beam theory. However, according to DNV-RP-F105, the span length-to-diameter (L/D) ratio for which beam theory is applicable in free-spanning pipelines ranges from 30 to 100. Hence, this FEM model will extend the L/D ratio to verify the range recommended by DNV-RP-F105.

3.0 METHODOLOGY

This chapter outlines the methodology for conducting finite element analysis (FEA) of a free-spanning pipeline under static load. The FEA was run using Abaqus software to analyse the deflection of the pipeline in a free-span condition. The finite element (FE) model of the free-spanning pipeline is designed according to the constraints and assumptions of the Euler-Bernoulli beam theory, ensuring the accuracy of the FEA. Furthermore, the recommendation practice from DNV-RP-F105 has highlighted that free-spanning pipelines can be assumed to be the same as beam behaviour as described by the Euler-Bernoulli beam theory. Once validated, the FE model of the free-spanning pipeline was applied to conduct a parametric study. The parametric study was done to assess the impact of span length on pipeline deflection and stresses in ensuring the pipeline's reliability

3.1 Design of Pipeline

In this study, a 3D cylindrical pipeline was used. A 3D deformable solid part was created to represent the pipeline model. Table 1 lists the geometry of the pipeline model, which is based on the case study by Choi et al. (2003) that considered the actual pipeline on the field. Firstly, a whole solid pipeline was created based on the outer radius by extrusion for the pipeline's length. Then, the solid pipeline was cut based on the pipeline's thickness to form a hollow pipeline. Figure 1 shows the sketch of the pipeline's cross-section with an outer and inner radius of 0.381 m and 0.3635 m, respectively, while Figure 2 shows the example of a hollow pipeline with a span length of 10 m.

Table 1 Geometry of pipeline model

Geometry	Magnitude
Outer radius	0.381 m
Thickness	0.0175 m
L/D	10 - 320

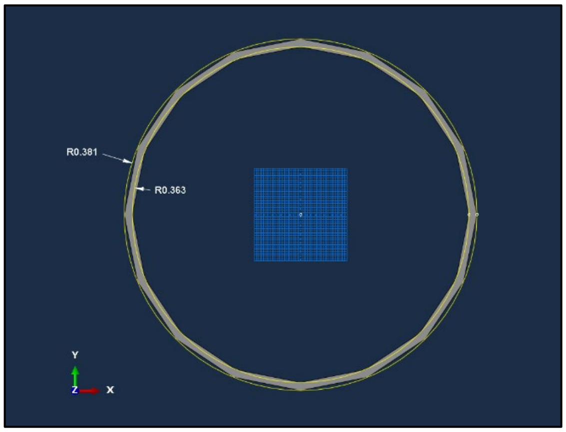


Figure 1 Cross-section of pipeline in the sketch section of Abaqus software

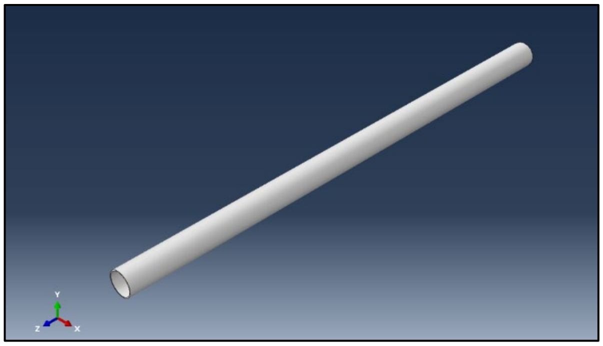


Figure 2 3D model of the pipeline in Abaqus software

3.2 Material Properties

After the pipeline model was created in the part module, the material properties needed to be assigned. A material was created in the material manager following its properties as in Table 2. The common material used for subsea pipelines is carbon steel, which is well-known for its strength and ductility, contributing to its high temperature and pressure resistance and ability to withstand dynamic forces in subsea environments. API 5L X65 is the carbon steel grade that is one of the most widely applied in subsea pipeline applications. Studies by (Choi et al., 2003; Lo et al., 2022) have applied this grade of pipeline for their research, and the data on the material properties in this research was taken from those studies.

In this study, API 5L X65 was modelled as an elastic-plastic material with strain hardening. The material properties were defined using Young's modulus of 210 GPa and a Poisson's ratio of 0.3 to capture the elastic response. Beyond the yield strength of 448 MPa, the material undergoes plastic deformation with strain hardening, ensuring a realistic representation of pipeline behaviour. Figure 3 shows the true stress-strain curve from the tensile test by Choi et al. (2003). This true stress-strain data was used as input in ABAQUS to model the material's nonlinear response accurately under loading conditions.

Table 2 Material properties of pipeline

Properties	Value
Mass density	7850 kg/m^3
Young's modulus, E	210 GPa
Poisson's ration	0.3

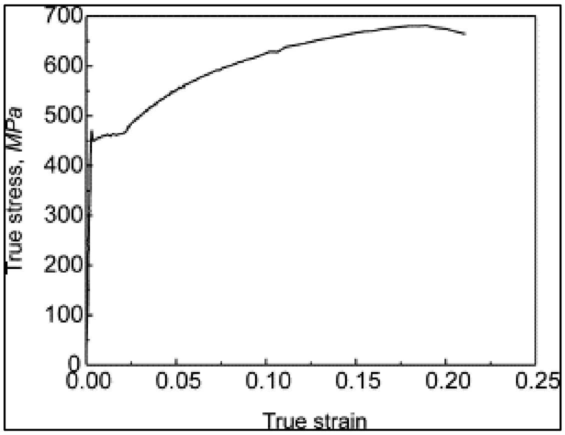


Figure 3 True stress-strain curve of API 5L X65 carbon steel (Choi et al., 2003)

3.3 Load and Boundary Conditions

In the load section, there are two considerations that need to be set. The first one is the load acting on the pipeline, which is the self-weight of the pipeline. The self-weight of the pipeline was considered the uniform distribution load acting downwards in the Euler-Bernoulli beam theory. Next, the boundary condition of the pipeline model was applied to simulate the support of the structure. Since both ends of the pipe are fixed, the boundary condition of both ends is determined as 'Encastre' in Abaqus software, indicating the fixed support condition. This fixed-fixed configuration represents constrained free spans, which are commonly observed in seabed-supported pipelines where lateral movement is restricted by soil-pipe interaction. Though actual pipeline conditions may involve varying support stiffness, this assumption was based on recommendation practice in DNV-RP-F105 for numerical simulations while maintaining structural accuracy for long-span evaluations. Figure 4 shows the load and boundary conditions acting on the pipe model.

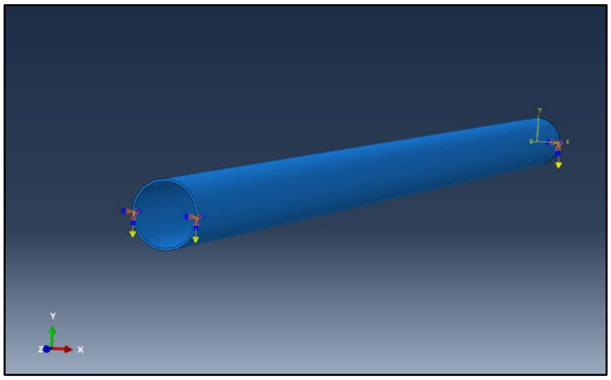


Figure 4 Load and boundary condition of the pipeline model

3.4 Meshing of Pipeline Model

In finite element analysis (FEA), the structure is broken down into numbers of discrete elements, nodes, and degrees of freedom to be solved. The structure becomes impossible to solve using hand calculation when it has a lot of elements needed to get accurate results, resulting in infinite degrees of freedom. Hence, the Abaqus software is one of the solutions that can replace manual hand calculation. In Abaqus software, meshing is the step where the part of the model is split into a discrete number of elements The element type of linear Hexahedral Elements (C3D8), which is the standard element type for 3D geometry models in ABAQUS software, was chosen for the pipeline modelling.

A mesh sensitivity analysis was conducted to determine the optimal element size for accurate FEM predictions. The pipeline was meshed using a structured mesh with varying element sizes, and FEM results were compared across different mesh densities. Mesh refinement improves accuracy by reducing discretisation errors and precisely capturing stress variations. However, excessive refinement leads to higher computational costs without significant gains in accuracy. The mesh configuration was chosen based on a balance between computational efficiency and solution accuracy, ensuring stable and reliable predictions for the free-spanning pipeline analysis. Figure 5 shows the meshing of the pipeline model.

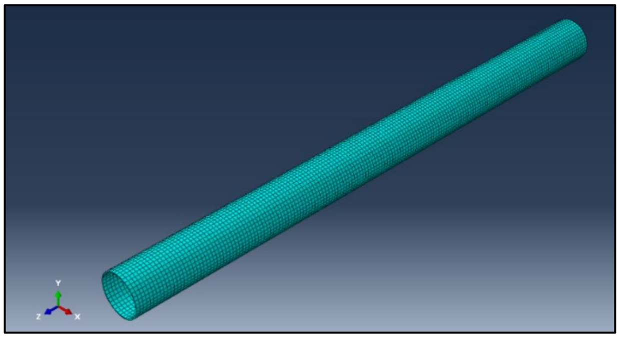


Figure 5 Meshing process of the pipeline model

4.0 RESULTS AND DISCUSSION

This section presents the software simulation results for the free-spanning subsea pipeline analysis and the study's discussion. This chapter consists of three parts: mesh convergence study, validation of the finite element model, and free-spanning pipeline parametric study.

4.1 Mesh Convergence Study of Pipeline Model

Finite element analysis (FEA) is a numeral method that breaks down a structure into smaller parts, called elements, for detailed calculations. The mesh size determines the number of elements in the structure division. In general, increasing the number of elements leads to a more accurate structural analysis by improving the node coverage and the precision of calculations across the structure. Before further analysis, a finite element model must undergo a mesh convergence study. This study is essential to ensure consistent results with an optimal mesh size, balancing both accuracy and computational efficiency. Mesh convergence is significant for balancing result precision with simulation run time, as a smaller mesh size with more elements demands significantly more computational time and resources. This convergence study was conducted by progressively refining the mesh size to observe when the output stabilises, identifying the mesh size at which the results converge as the optimal mesh size.

Figure 6 illustrates the mesh convergence graph of deflection against the number of elements. A low element count, representing a coarse mesh, caused inconsistency in deflection outputs. As the number of elements increased, the results started to converge and become more consistent, which demonstrated the accuracy of the analysis. For this subsea pipeline model, the deflection output was observed to stabilise at the number of elements above 100,000. Hence, the optimal mesh size was determined at the size of 0.06 m After this point, further mesh refinement resulted in less than a 1% change in deflection output, confirming that additional refinement does not significantly improve accuracy but increases computational cost. After the optimal mesh size is determined, the finite element model of this particular free-spanning pipeline can proceed with further analysis.

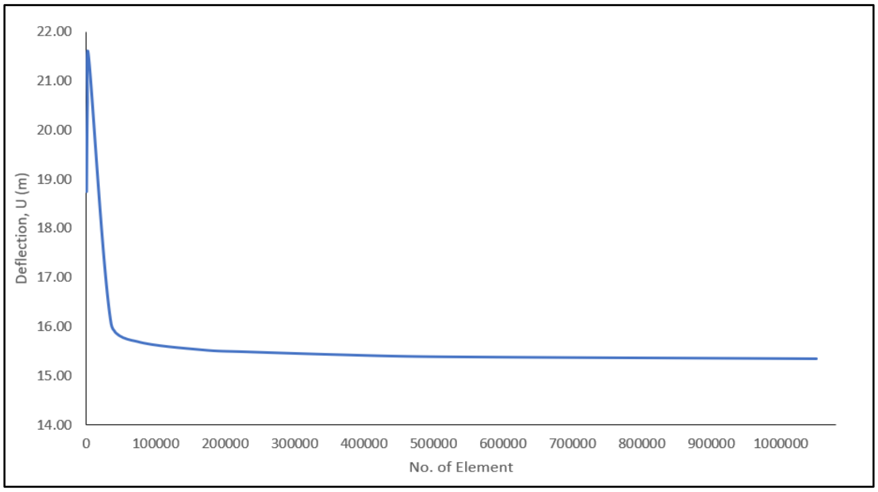


Figure 6 Mesh convergence graph of deflection against the number of elements

4.2 Validation of the Finite Element Model with Theoretical Formula

Next, the finite element (FE) model of the free-spanning pipeline must undergo a validation process to ensure its reliability and accuracy in simulating real-world conditions. For this validation, the pipeline was modelled to simulate the free-span condition based on the Euler-Bernoulli beam theory, as this theory provides simplified yet reliable approximations for deflection calculations. Therefore, the model results must be validated by comparing them to the deflection calculations derived from the Euler-Bernoulli beam theory. Fixed-fixed boundary conditions were applied to both the FE model and theoretical calculations. The percentage difference between finite element analysis (FEA) outputs and theoretical calculation was tabulated in Table 3.

Figure 7 presents a graph comparing the results from FEA and theoretical calculations. Validation was conducted across a range of length-to-diameter (L/D) ratios from 20 to 320, which was extended beyond the DNV-RP-F105 recommendation of L/D values between 30 and 100. The FEA simulation of the free-spanning pipeline failed at an L/D ratio of 240, as the von Mises stress exceeded the pipeline's ultimate tensile strength. However, up to an L/D ratio of 160, the FEA deflection outputs showed good agreement with beam theory. For L/D ratios below 160, FEM predictions maintained an error margin below 2%, ensuring reliability within engineering standards. However, beyond L/D = 160, the error exceeded 30%, suggesting that large deformations and geometric nonlinearities contributed to the increasing discrepancy. Although the nonlinear function was enabled in Abaqus, the growing divergence indicates that beam theory assumptions are no longer valid under extreme deformation conditions of the pipeline. For instance, Grondin et al. (2024) demonstrated that error margins can be influenced by various factors, hence suggesting the use of a 5% to 10% error threshold in practical applications.

Nonetheless, these results demonstrate that this FE model aligns with the findings in Phuor et al. (2023), which stated that the FEA model of the free-spanning pipeline is valid for L/D ratios below 160 to approximate beam behaviour accurately. This validation supports confidence in the FE model for predicting the static loading behaviour of a free-spanning pipeline.

Table 3 Validation study of free-spanning pipeline FEM against theoretical calculations

Length-to-diameter ratio (L/D)	**Maximum deflection, u (m)**		**Percentage Error (%)**
	Finite Element Output	Theoretical Calculation (Euler-Bernoulli beam)	
20	0.00080	0.00074	7.81
30	0.00390	0.00376	3.78
40	0.01217	0.01189	2.36
50	0.02953	0.02903	1.73
60	0.06103	0.06019	1.39
70	0.11280	0.11151	1.16
80	0.19220	0.19023	1.03
90	0.30770	0.30472	0.98
100	0.46860	0.46443	0.90
120	0.97090	0.96305	0.82
140	1.79800	1.78417	0.78
160	3.09200	3.04371	1.59
180	6.37500	4.87544	30.76
200	15.53000	7.43094	108.99
240	662.30000	15.40880	4,198.19
280	97,580.00000	28.54670	341,725.81
320	439,400.00000	48.69942	902,169.55

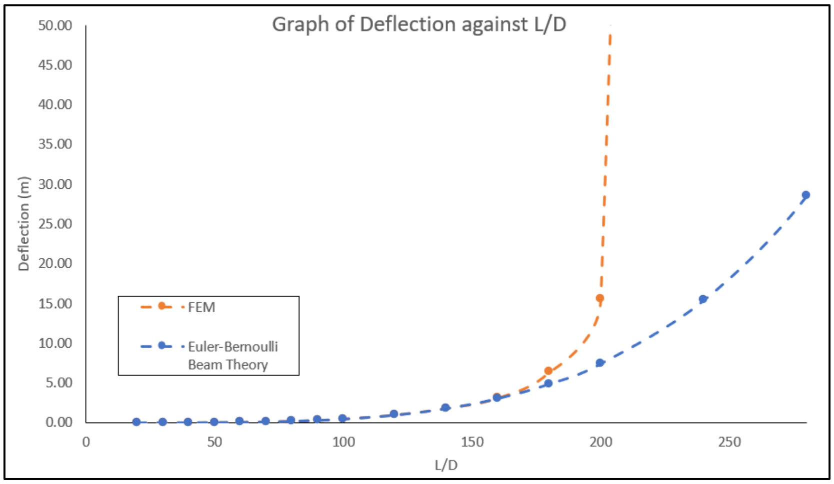


Figure 7 Comparison of FEM results and theoretical calculations

4.3 Parametric Study of Free-spanning Pipeline

A parametric study was conducted to understand the impact of free span length on pipeline stresses. Given that the finite element model (FEM) is validated for reliability up to an L/D ratio of 160, the scope of the parametric study for the free-spanning pipeline is confined to this range. Figure 8 presents the graph of the parametric study, where the pipeline behaviour was analysed for various L/D values by examining the relationship between L/D and both deflection and von Mises stress outputs. It was observed that increasing the free span length leads to greater deflection, consequently inducing higher stresses on the pipeline.

Since the material of the subsea pipeline in this study was carbon steel, it exhibits both elastic and plastic behaviour. Based on Figure 8, the pipeline begins to yield at an L/D ratio of 140, where the von Mises stress exceeds 400 MPa. Initially, the pipeline's FEM was developed based on the Euler-Bernoulli beam theory, which assumes elastic behaviour only. Therefore, the results suggest that the free span length should be limited to an L/D ratio of 140 to maintain the pipeline's structural behaviour within the elastic range of a beam. Mitigation measures should be considered if the L/D ratio exceeds 140 to preserve the beam-like behaviour of the subsea pipeline. Figure 9 illustrates the simulation result's visualisation in Abaqus software regarding deflection contour. The focus on span length alone in the parametric study is based on DNV-RP-F105 recommendations, emphasising that free-span evaluations primarily consider span length as the governing factor. Additionally, this study serves as an initial evaluation to isolate span length effects on the deflection and stress predictions, thereby verifying the validity of beam theory in this specific context.

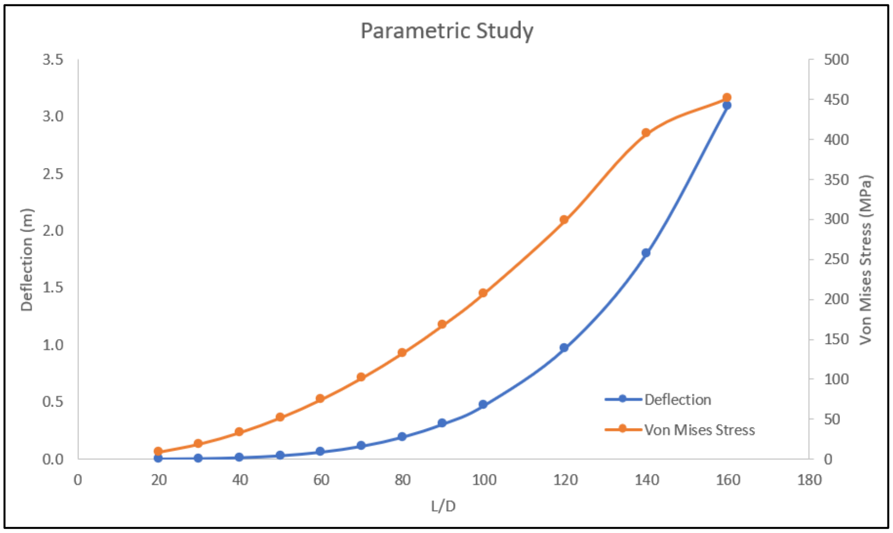


Figure 8 Parametric study of the free-spanning pipeline

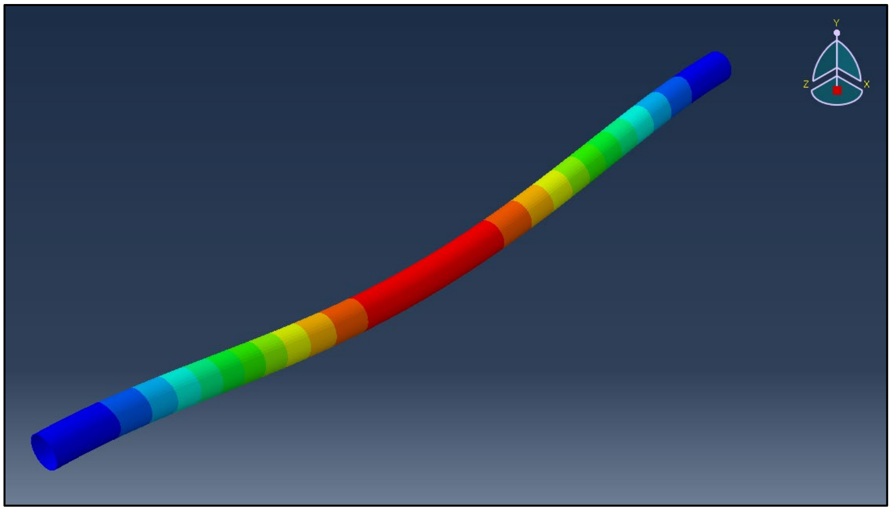


Figure 9 Result of deflection contour for free-spanning pipeline

5.0 CONCLUSIONS

A finite element (FE) model of the free-spanning subsea pipeline was developed based on the Euler-Bernoulli beam theory, assuming fixed-fixed support conditions. An optimal mesh size of 0.06m was observed and determined to ensure the model produced consistent and reliable results. One critical aspect of any finite element method (FEM) study is model validation. In this case, results from the FE model were compared against calculations based on Euler-Bernoulli beam theory, aligning with DNV-RP-F105 recommendations, which indicate that free-spanning pipelines behave like beams within an L/D range of 30 to 100. However, this study suggests that accurate results may extend up to an L/D ratio of 160. This supports the finding by Phuor et al. (2023), who indicated that beam theory remains valid for free-spanning pipelines at L/D values below 160. In addition, a parametric study was conducted to examine the effects of increasing L/D ratios on pipeline deflection and von Mises stress. In the analysis, the carbon steel pipeline began to yield at point L/D ratio over 140 with von Mises stress more than 400MPa. Future research should incorporate seabed interaction models and hydrodynamic loading effects to refine structural predictions further, ensuring more comprehensive and enhanced reliability of the free-spanning pipeline assessment in offshore engineering applications.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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