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Stress Analysis and Code Compliance Evaluation of Offshore Gas Production Piping Systems Using CAESAR II and ASME B31.3

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ABSTRACT– Offshore gas production piping systems operate under high-pressure and elevated-temperature conditions, requiring accurate stress analysis to verify code compliance and ensure reliable structural performance. This study investigates the stress behavior of a piping system connecting a production well to a test manifold using analytical calculations and CAESAR II simulations in accordance with ASME B31.3. Engineering data, including piping geometry, material specifications, operating conditions, and support configurations, were obtained from project design documents. Sustained and thermal expansion stresses were first estimated using simplified analytical calculations and subsequently verified using CAESAR II simulations. The maximum sustained stress occurred at Node 9100, with analytical and numerical values of 124.00 MPa and 96.70 MPa, respectively, corresponding to a deviation of 28.24%. For the thermal expansion load case, the maximum stress was observed at Node 9320, yielding analytical and numerical values of 2.89 MPa and 2.44 MPa, respectively, with a deviation of 18.45%. These deviations are primarily attributed to the simplified assumptions adopted in the analytical calculations, differences in boundary condition representation, and the more detailed three-dimensional pipe flexibility modeling incorporated in CAESAR II. All calculated stresses remained below the allowable stress limits specified by ASME B31.3 (177.20 MPa for sustained loading and 206.84 MPa for thermal expansion loading). Therefore, the investigated piping system satisfies the code allowable stress requirements under the evaluated sustained and thermal expansion loading conditions. The findings demonstrate that simplified analytical calculations can provide a practical independent engineering verification of numerical simulations during preliminary piping design, while CAESAR II remains essential for comprehensive code-compliance evaluation.

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Introduction

Piping systems are fundamental components in industrial facilities, serving as the primary means for transporting fluids between process units. These systems are composed of interconnected components such as pipes, elbows, tees, reducers, flanges, valves, and nozzles, which must satisfy the allowable stress requirements specified by ASME B31.3 under the applicable sustained and thermal expansion loading conditions [1]. Piping networks are extensively utilized in petrochemical plants, power generation facilities, geothermal systems, and oil and gas production installations. In offshore oil and gas facilities, piping systems play a critical role in transporting production fluids and supporting reliable plant operation under demanding pressure and temperature conditions [2].

In these offshore environments, piping systems are subjected to more complex operating conditions than their onshore counterparts. In addition to internal pressure and dead weight, they may experience thermal expansion, equipment displacement, vibration, and environmental loading that significantly affect stress distribution throughout the pipeline network [3]. Excessive stress can lead to deformation, leakage, fatigue damage, support failure, or catastrophic rupture. Therefore, stress analysis has become an essential part of piping design verification to demonstrate compliance with the allowable stress requirements specified by applicable engineering codes under the prescribed loading conditions [4].

The American Society of Mechanical Engineers (ASME) B31.3 Process Piping Code is one of the most widely accepted standards for evaluating piping system integrity. The code establishes allowable stress limits and design criteria for various loading conditions, including sustained loads, thermal expansion loads, and occasional loads [5]. In engineering practice, stress evaluation is commonly performed using specialized software such as CAESAR II, which employs finite element-based analysis to simulate the

behavior of piping systems under realistic operating conditions [6]. The software enables engineers to assess stresses, displacements, support reactions, and code compliance more efficiently than conventional analytical approaches.

In current engineering practice, the structural integrity of offshore process piping is commonly verified using commercial piping stress analysis software, particularly CAESAR II, due to its capability to evaluate stresses, displacements, support reactions, and code compliance under multiple loading conditions [7]. The software has become an industry-standard tool for piping design verification because it efficiently models complex three-dimensional piping systems operating under pressure, weight, and thermal loads.

Despite its widespread application, numerical stress analysis is highly dependent on modeling assumptions, including boundary conditions, support configurations, equipment restraints, and geometric representation. In engineering practice, insufficient verification of numerical simulation models may reduce confidence in the predicted stress distribution and the resulting code compliance evaluation, particularly for high-pressure offshore piping systems. Furthermore, published studies rarely discuss how analytical engineering calculations can be used as an independent verification tool to support simulation-based code compliance evaluation.

Previous studies have successfully applied CAESAR II for industrial piping analysis. However, Prachi et al. [8] utilized the software to evaluate stress distributions in industrial piping systems and identified critical locations susceptible to excessive loading. Jannot et al. [9] compared software-based analysis with analytical calculations for industrial and geothermal piping applications and reported differences attributable to modeling assumptions and boundary conditions. More recent investigations have focused on thermal loading effects [10], support optimization [11], reliability assessment using finite element methods [12] , and integrity evaluation of offshore piping structures [13].

Although these studies have contributed significantly to the development of piping stress analysis, several research gaps remain. First, most published works focus on onshore industrial facilities, whereas investigations involving offshore gas production piping systems operating under high-pressure conditions remain relatively limited. Second, previous studies primarily emphasize numerical simulation results, with limited attention to independent engineering verification that can increase confidence in simulation-based stress evaluation and code compliance assessment. Third, studies integrating numerical simulation with independent analytical verification for the stress analysis and code compliance evaluation of offshore gas production piping systems in accordance with ASME B31.3 remain limited. Consequently, the applicability of simplified analytical calculations as a practical verification tool for preliminary design validation has not been sufficiently discussed.

To address these gaps, this study investigates the stress behavior and structural integrity of an offshore gas production piping system transporting natural gas from a wellhead to a test manifold located in the Mahakam Delta, East Kalimantan, Indonesia. Because the piping system operates under high-pressure conditions, stress assessment is an essential part of design validation to ensure compliance with ASME B31.3 requirements. A three-dimensional piping stress analysis was conducted using CAESAR II under sustained and thermal expansion loading conditions. Conventional analytical calculations were performed solely as an independent engineering verification of the numerical simulation results. Therefore, the primary objective of this study is to assess the structural integrity of the investigated offshore gas production piping system rather than to evaluate or compare analysis methods.

The present study makes three principal contributions to offshore piping engineering. First, it provides a case study on the stress analysis and ASME B31.3 code compliance evaluation of an actual offshore gas production piping system operating under high-pressure conditions, thereby extending the limited body of published studies on offshore production piping. Second, the numerical results obtained from CAESAR II are independently verified using conventional analytical calculations to increase confidence in the stress evaluation and ASME B31.3 code compliance assessment rather than to compare the performance of the two analysis methods. Third, the study demonstrates how the combined use of numerical simulation and analytical verification can support engineering decision-making during piping design validation by confirming code compliance, identifying critical stress locations, and evaluating the structural adequacy of the piping system. The findings are expected to provide practical guidance for engineers involved in the stress analysis, design verification, and ASME B31.3 code compliance evaluation of offshore gas production piping systems.

Materials and Methods

A. Study Area and Piping System Description

This study was conducted on an offshore gas production piping system located in the Mahakam Delta offshore production area, East Kalimantan, Indonesia. The analyzed piping system functions as a gas transportation line connecting a production wellhead to a test manifold on an offshore platform. The pipeline operates under high-pressure conditions and constitutes an important component of the production facility, requiring compliance with applicable piping design codes to ensure reliable operation under the prescribed operating conditions.

In offshore production facilities, piping systems are subjected to multiple loading conditions, including internal pressure, dead weight, fluid weight, thermal expansion, equipment displacement, and environmental loads. These load combinations may generate significant stresses and deformations that affect structural integrity and service life [14]. Therefore, piping stress analysis is required during the

design verification stage to demonstrate compliance with the allowable stress requirements specified by applicable engineering standards [15].

B. Research Framework

The research methodology adopted in this study is summarized in Figure 1. The study began with problem identification and literature review to establish the theoretical foundation related to piping stress analysis, piping design codes, and finite element-based simulation methods. Subsequently, engineering data were collected from project documents, including piping and instrumentation diagrams (P&ID), isometric drawings, operating conditions, material specifications, and support configurations.

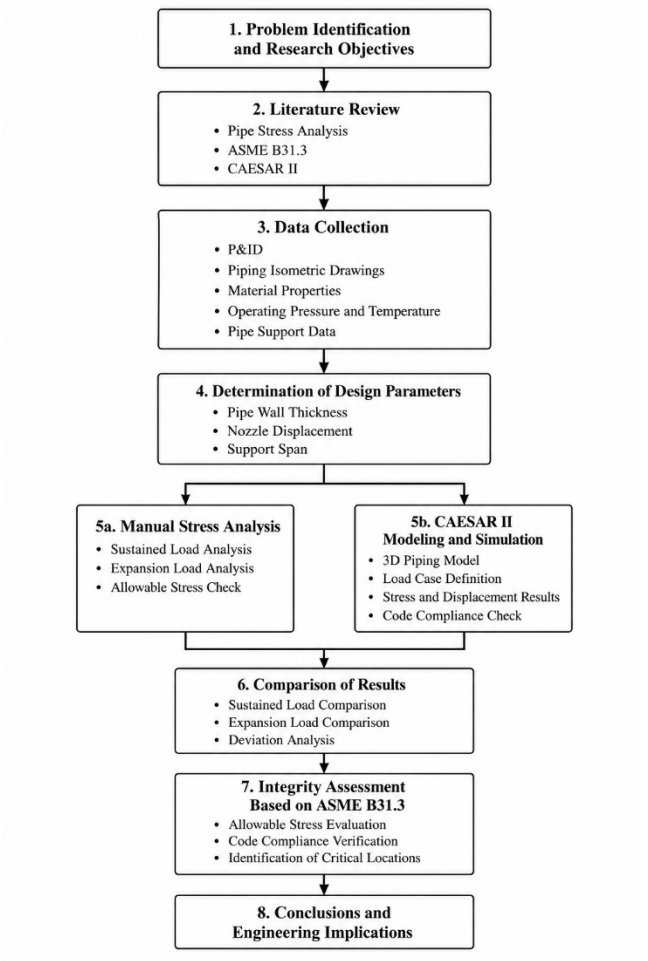

Figure 1. Research flowchart

The collected data were used to determine the required design parameters and to develop both analytical and numerical models of the piping system. Manual calculations were performed to evaluate stresses caused by sustained and thermal expansion loads based on engineering mechanics principles and ASME B31.3 requirements. In parallel, a three-dimensional piping model was developed in CAESAR II to simulate the actual operating conditions of the offshore gas production piping system.

The investigated piping system transports natural gas from the production wellhead to the test manifold under high-pressure operating conditions. The piping layout and engineering specifications were obtained from the project piping isometric drawings and associated design documents. The isometric drawing, shown in Figure 2, was used as the basis for developing the three-dimensional CAESAR II model and performing the subsequent stress analysis.

Figure 3 shows the piping isometric drawing used as the basis for developing the three-dimensional model in CAESAR II. The isometric drawing defines the routing configuration, pipe segments, fittings, and support locations incorporated into the numerical model.

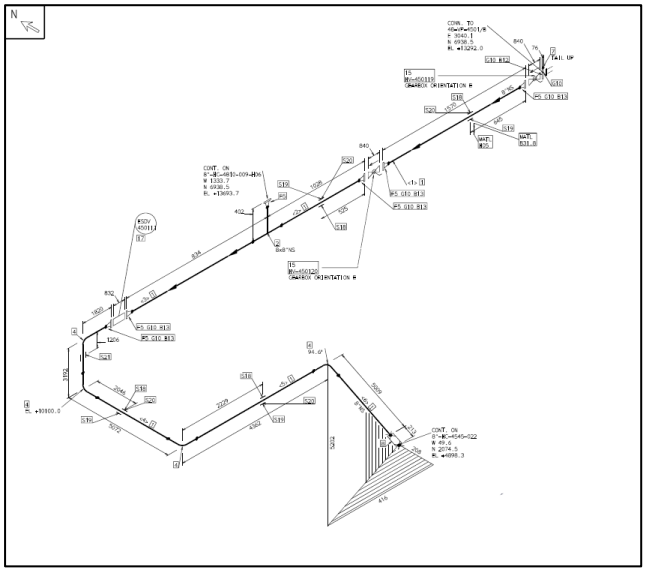

Figure 2. Piping isometric drawing of the investigated piping system.

Figure 3 presents the three-dimensional CAESAR II model developed from the piping isometric drawing. The model was used to simulate the structural response of the piping system under sustained and thermal expansion loading conditions in accordance with ASME B31.3 requirements.

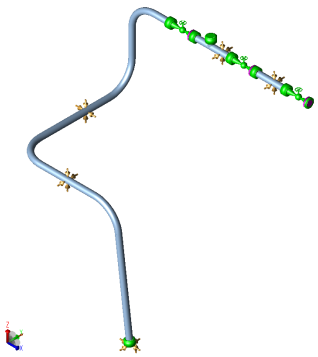

Figure 3. Three-dimensional CAESAR II model of the offshore gas production piping system

C. Data Collection and Engineering Parameters

The engineering data used in this study were obtained from project design documentation and technical specifications associated with the offshore gas production facility. Data acquisition was conducted through a comprehensive review of engineering documents and technical consultations with personnel involved in the design and operation of the facility. This approach was adopted to

ensure that the piping model accurately represented the actual field conditions and operating environment.

The investigated piping system was constructed using API 5L Grade B carbon steel pipe with an outside diameter of 219.075 mm (NPS 8), Schedule 140, and an actual wall thickness of 20.625 mm, including a corrosion allowance of 5 mm. The pipeline has a total length of 25.77 m and forms a three-dimensional piping network connecting the production wellhead to the test manifold. The network consists of straight pipe sections, elbows, flanges, valves, and equipment nozzles supported by rigid pipe supports designed according to the project specifications. The operating pressure and operating temperature were 22.8 MPa and 90°C, respectively, while the installation temperature was 50°C. The material properties used in both the analytical calculations and CAESAR II simulation included an elastic modulus of approximately 200 GPa, Poisson's ratio of 0.30, density of 7850 kg/m³, and a coefficient of thermal expansion consistent with the ASME B31.3 material database.

The primary sources of information included the Piping and Instrumentation Diagram (P&ID), piping isometric drawings, material specifications, operating conditions, and supporting design documents. The P&ID was used to identify the process flow configuration and system connectivity, while the isometric drawings provided detailed information regarding pipe routing, dimensions, fittings, and support locations. Material specifications were utilized to determine the mechanical properties of the piping components, including allowable stress, elastic modulus, density, and thermal expansion coefficient. In addition, operating data such as pressure, temperature, and fluid characteristics were collected to define the loading conditions applied to the piping system during analysis.

Following data collection, all engineering parameters were verified and compiled as input data for both analytical calculations and numerical simulations. According to ASME B31.3, accurate representation of piping geometry, material properties, and operating conditions is essential for obtaining reliable stress analysis results and ensuring proper code compliance assessment [8]. Therefore, particular attention was given to the validation of design and operating parameters before conducting the stress analysis.

The principal engineering parameters considered in this study included the pipe outside diameter, wall thickness, pipe schedule, material properties, operating pressure, operating temperature, fluid density, pipe density, corrosion allowance, and pipe support configuration. These parameters significantly influence the structural response of the piping system because they determine the magnitude of internal pressure stresses, dead-weight loads, thermal expansion effects, and support reactions that develop during operation [4]. Furthermore, the interaction between these parameters governs the overall flexibility and stress distribution of the piping network, making their accurate characterization a critical step in evaluating the structural integrity of the system.

Table 1 summarizes the principal engineering parameters used in the stress analysis. These parameters served as the basis for both manual calculations and numerical simulations.

Table 1. Engineering Specifications Used for the Piping Stress Analysis

Parameter	Value	Unit
Pipe Material	API 5L Grade B Carbon Steel	—
Nominal Pipe Size	NPS 8	—
Outside Diameter	219.075	mm
Pipe Schedule	SCH 140	—
Nominal Wall Thickness	25.625	mm
Corrosion Allowance	5	mm
Effective Wall Thickness	20.625	mm
Young's Modulus	200	GPa
Poisson's Ratio	0.3	—
Thermal Expansion Coefficient	12×10^{-6}	/°C
Material Density	7850	kg/m³
Fluid Density	85	kg/m³
Operating Pressure	22.8	MPa
Operating Temperature	90	°C
Installation Temperature	50	°C
Total Pipe Length	25.77	m
Design Code	ASME B31.3-2022	—

As illustrated in Figure 4, the calculated minimum required wall thickness of 19.10 mm already includes the specified corrosion allowance of 5 mm.

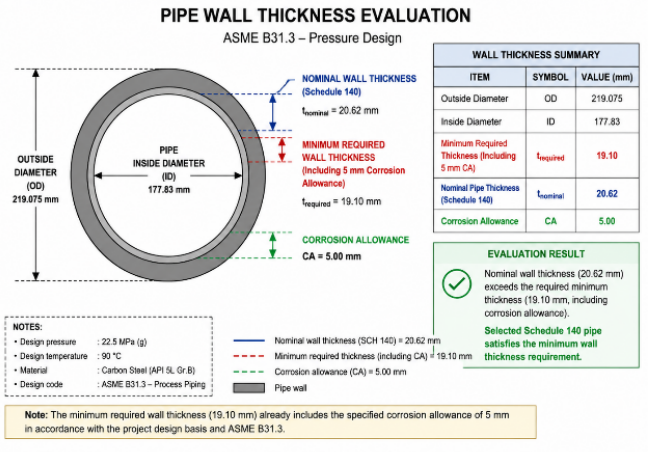

Figure 4. Cross-sectional representation of the selected Schedule 140 pipe illustrating the relationship between the nominal wall thickness and the minimum.

Therefore, the nominal wall thickness of the selected Schedule 140 pipe (20.625 mm) exceeds the required minimum thickness and provides an additional design margin of approximately 1.52 mm.

The verified engineering data were subsequently used as the basis for determining design parameters, developing the three-dimensional piping model in CAESAR II, and performing manual stress calculations in accordance with the requirements of ASME B31.3.

D. Determination of Pipe Design Parameters

Prior to conducting the stress analysis, several critical design parameters were evaluated to establish the baseline configuration of the piping system. The determination of these parameters is an essential step in piping design because the structural response of a piping network is strongly influenced by its geometric characteristics, material properties, thermal behavior, and support conditions. Accurate estimation of these parameters ensures that the analytical calculations and numerical simulations accurately represent the actual operating conditions of the offshore gas production facility.

One of the primary design considerations was the determination of the minimum required pipe wall thickness. Pipe wall thickness directly influences the ability of the pipeline to withstand internal pressure while maintaining structural integrity under operational loading conditions. In accordance with the ASME B31.3 Process Piping Code, the minimum wall thickness was calculated using the applicable pressure design equations, taking into account operating pressure, allowable material stress, pipe dimensions, and design factors. The calculated minimum thickness was subsequently compared with commercially available pipe schedules to determine the most appropriate pipe specification for the system. The selected pipe schedule was then incorporated into both the manual calculations and the CAESAR II model. Previous studies have shown that wall thickness significantly affects pressure-induced stresses, pipe stiffness, and overall system reliability [16].

In addition to pipe wall thickness, nozzle displacement was also evaluated because the piping system is connected to process equipment that may experience thermal expansion during operation. Temperature variations can cause dimensional changes in equipment, leading to displacement at nozzle connection points. These displacements may introduce additional forces and moments into the piping system, thereby influencing stress distribution and support reactions. To account for this effect, nozzle displacement was estimated based on thermal expansion theory and incorporated as a boundary condition in the numerical model. Several researchers have reported that equipment-induced nozzle displacements can significantly affect piping flexibility, stress concentration, and equipment loading, particularly in systems operating at elevated temperatures [17], [18].

Another important parameter considered in this study was the spacing of pipe supports. Pipe supports play a critical role in maintaining the structural stability of a piping system by carrying the combined weight of the pipe, conveyed fluid, insulation, and other operational loads. Inadequate support spacing may increase pipe sagging and bending stresses, while excessive restraint can reduce system flexibility and generate higher thermal expansion stresses. Therefore, the allowable support span was estimated based on the beam deflection approach commonly adopted in piping engineering practice following the Grinnell method. The pipe was idealized as a simply supported beam subjected to the combined weight of the pipe, conveyed fluid, and insulation. The maximum allowable span was determined by limiting the vertical deflection within the recommended design criteria while maintaining the bending stress below the allowable value specified by ASME B31.3. The calculated span was subsequently compared with the actual support arrangement adopted in the investigated piping system to verify its adequacy. The resulting support spacing was subsequently used to assess the adequacy of the support configuration represented in the CAESAR II model. Proper support arrangement is widely recognized as one of the most influential factors affecting stress distribution and structural integrity in process piping systems [19]. The maximum vertical deflection of the pipe between adjacent supports was estimated using Eq. (1). The allowable support span was selected such that the calculated deflection remained within the recommended limit specified by the Grinnell design method.

$$\delta = \frac{5wL}{384EI} \tag{1}$$

where δ is the maximum deflection (mm), w is the uniformly distributed load (N/mm), L is the support span (mm), E is the Young's modulus of the pipe material (MPa),and I is the second moment of area (mm^4).

The evaluated design parameters, including pipe wall thickness, nozzle displacement, and support spacing, served as the foundation for the subsequent analytical and numerical stress analyses. By incorporating these parameters into the piping model, the calculated stress responses were expected to more accurately represent the actual behavior of the offshore gas production piping system under operational loading conditions.

E. Manual Piping Stress Analysis

Manual stress calculations were performed as an independent engineering approach to evaluate the structural response of the piping system and to verify the results obtained from numerical simulations. The analytical procedure followed the requirements of ASME B31.3 and conventional piping stress analysis methods described by Bhattacharya [20]. The manual calculations presented in this study were intended to provide preliminary engineering estimates and an independent verification of the numerical simulation results. Therefore, simplified analytical formulations based on elementary mechanics of materials were adopted, whereas the final code compliance assessment was performed using CAESAR II in accordance with ASME B31.3.

Sustained Load Analysis

Sustained loads represent loading conditions that continuously act on the piping system during operation,

including pipe self-weight, fluid weight, and internal pressure. The longitudinal stress due to sustained loading was determined by combining the effects of axial stress, pressure stress, and bending stress.

The axial stress was calculated using Eq. (2). The resulting axial stress was then combined with pressure-induced stress and bending stress to determine the longitudinal stress under sustained loading conditions.

$$\sigma_a = \frac{F_a}{A} \tag{2}$$

where σ_a is the axial stress (MPa), F_a is the axial force (N), and A is the cross-sectional area of the pipe (mm²).

The circumferential (hoop) stress induced by the internal pressure was calculated using Eq. (3). Hoop stress represents the principal stress acting tangentially around the circumference of the pipe wall and is generally the largest pressure-induced stress component in thin-walled cylindrical pressure vessels. According to pressure vessel theory, the magnitude of hoop stress is directly proportional to the internal pressure and pipe diameter and inversely proportional to the wall thickness.

$$\sigma_h = \frac{PD}{2t} \tag{3}$$

where σ_h is the hoop stress (MPa), P is the internal pressure (MPa), D is outside diameter of the pipe (mm), and t is the pipe wall thickness (mm).

The longitudinal pressure stress generated by the internal pressure was calculated using Eq. (4). Unlike hoop stress, the longitudinal pressure stress acts parallel to the pipe axis and typically has a lower magnitude.

$$\sigma_p = \frac{PD}{4t} \tag{4}$$

where σ_p is the longitudinal pressure stress (MPa), P is the internal pressure (MPa), D is outside diameter of the pipe (mm), and t is the pipe wall thickness (mm).

The bending stress resulting from pipe self-weight, fluid weight, and other external loads was determined using Eq. (5), where the bending moment is related to the loading configuration and support arrangement of the piping system. The combination of axial, pressure-induced, and bending stresses was subsequently used to evaluate the sustained longitudinal stress in accordance with ASME B31.3 requirements.

$$\sigma_b = \frac{M}{Z} \tag{5}$$

where σ_b is the bending stress (MPa), M is the bending moment (N.mm), and Z is the section modulus of the pipe (mm³).

The calculated sustained stress was compared with the allowable sustained stress specified in ASME B31.3 to determine code compliance requirements.

Expansion Load Analysis

Expansion stresses arise from thermal expansion caused by differences between installation and operating temperatures. The thermal displacement of the piping system due to temperature variation was estimated using the linear thermal expansion relationship given in Eq. (6). Thermal expansion is directly proportional to the coefficient of thermal expansion, the original pipe length, and the temperature difference between installation and operating conditions. The resulting displacement may generate restraint forces, bending moments, and secondary stresses within the piping system, particularly when pipe movement is restricted by supports, equipment nozzles, or structural restraints. Consequently, thermal expansion must be considered in piping flexibility and stress analyses to ensure compliance with ASME B31.3 requirements.

$$\Delta L = \alpha L \Delta T \tag{6}$$

where ΔL is the thermal expansion or change in pipe length (mm), α is the coefficient of thermal expansion (mm/mm°C), L is the original pipe length (mm), and ΔT is the temperature difference between operating and installation conditions (°C).

Thermal expansion of the piping system generates restraint forces and moments that contribute to secondary stresses throughout the piping network. Following the flexibility method, the thermal bending stress was determined using Eq. (7), while the torsional shear stress induced by thermal loading was calculated using Eq. (8).

$$\sigma_{be} = \frac{M_b}{Z} \tag{7}$$

where σ_{be} is the bending stress due to thermal expansion (MPa), M_b is the thermal bending moment (N.mm), and Z is the section modulus of the pipe (mm³).

$$\tau = \frac{Tr}{J} \tag{8}$$

where τ is the torsional shear stress (MPa), T is the torsional moment (N.mm), r is the outer radius of the pipe (mm), and J is the polar moment of inertia (mm⁴).

The combined effect of bending and torsional stresses was subsequently evaluated through the expansion stress range defined in Eq. (9). The calculated expansion stress range was then compared with the allowable expansion stress specified by ASME B31.3 to assess the flexibility and structural integrity of the piping system under thermal loading conditions.

$$S_E = \sqrt{\sigma_{be}^2 + 4\tau^2} \tag{9}$$

where S_E is the expansion stress range (MPa), $\sigma_{be}$is the thermal bending stress (MPa), and τ is the torsional shear stress (MPa).

It should be noted that Equation (9) represents a simplified analytical formulation used for preliminary estimation of the expansion stress range. Unlike the complete ASME B31.3 code equation, this simplified approach does not explicitly incorporate stress intensification factors (SIFs) because the objective of the manual calculation is to provide

an independent engineering verification of the CAESAR II simulation rather than a full code-compliance evaluation. The complete code compliance assessment, including stress intensification effects, was performed using CAESAR II in accordance with ASME B31.3.

The analytical results obtained from the sustained load and expansion load calculations were subsequently compared with the numerical results generated by CAESAR II. This comparison provided an assessment of the consistency between conventional analytical methods and finite element-based simulations in evaluating the integrity of offshore gas production piping systems.

Numerical Simulation Using CAESAR II

To complement the analytical calculations and provide a more comprehensive assessment of the piping system behavior, numerical stress analysis was conducted using CAESAR II software. CAESAR II is one of the most widely adopted piping stress analysis tools in the oil and gas industry and has been extensively applied in the design, stress evaluation, and code compliance verification of industrial piping systems [15]. The software employs finite element analysis (FEA) techniques to evaluate the structural response of piping networks under various loading conditions and automatically verifies compliance with applicable piping design codes.

A three-dimensional model of the offshore gas production piping system was developed based on the piping isometric drawings and project design documentation. The model was configured to represent the actual geometry and operational characteristics of the pipeline connecting the production well to the test manifold. All relevant engineering parameters obtained during the data collection stage were incorporated into the numerical model, including pipe dimensions, material properties, operating pressure, operating temperature, fluid density, corrosion allowance, support locations, and equipment nozzle displacement conditions. By incorporating these parameters, the model was able to realistically simulate the mechanical behavior of the piping system under operating conditions.

The material properties assigned to the model included elastic modulus, Poisson's ratio, density, and thermal expansion coefficient, while the operating parameters consisted of internal pressure and service temperature. These parameters are critical because they directly influence the magnitude of pressure-induced stresses, thermal expansion effects, and overall system flexibility. Furthermore, pipe supports and boundary conditions were modeled according to the actual support arrangement to accurately capture restraint effects and load transfer mechanisms throughout the piping network.

The ASME B31.3 Process Piping Code was selected as the governing design code for all stress evaluations. This code provides the allowable stress criteria and acceptance limits used to assess the structural adequacy of the piping system under various loading conditions. By implementing ASME B31.3 within CAESAR II, the software automatically evaluates the calculated stresses against the corresponding code allowable values and generates code compliance reports.

Following model development and verification, several load cases were generated to represent the operational conditions of the piping system. Particular attention was given to sustained and thermal expansion loading conditions because these loads constitute the primary sources of stress in high-pressure process piping systems. The sustained load case considered the combined effects of pipe weight, fluid weight, and internal pressure, whereas the expansion load case evaluated stresses induced by thermal expansion resulting from temperature variations between installation and operating conditions. Table 2 summarizes the load cases applied in the CAESAR II model. The sustained load case consisted of the pipe self-weight and internal pressure, whereas the operating load case additionally included the operating temperature. The expansion load case evaluated the thermal stresses generated by temperature-induced expansion and the imposed equipment displacement. These load cases were defined in accordance with the load combinations recommended by ASME B31.3 for piping stress evaluation.

Table 2. Load Cases Used in the CAESAR II Analysis

Load Case	Description	Load Components	Purpose
L1	Sustained Load	Weight (W) + Internal Pressure (P)	Evaluation of sustained stress
L2	Operating Load	Weight (W) + Pressure (P) + Temperature (T)	Evaluation of operating condition
L3	Expansion Load	Thermal expansion resulting from operating temperature and imposed displacement	Evaluation of thermal expansion stress in accordance with ASME B31.3

The simulation results provided detailed information regarding the mechanical behavior of the piping system, including stress distribution, nodal displacements, support reactions, bending moments, and code stress ratios. The software also identified critical locations where the maximum stresses occurred and automatically compared the calculated values with the allowable stress limits specified by ASME B31.3. These results were subsequently used to assess the structural integrity of the piping system and to compare the performance of the numerical approach with the analytical calculations presented in the previous section.

The numerical simulation results obtained from CAESAR II served as the primary basis for evaluating the stress distribution within the offshore gas production piping system and for determining whether the design satisfied the integrity requirements established by the applicable piping code.

Verification of Numerical Results

One of the primary objectives of this study was to evaluate the level of agreement between conventional analytical calculations and finite element-based numerical simulations in assessing the structural integrity of offshore gas production

piping systems. Although piping stress analysis software such as CAESAR II is widely used in engineering practice, manual calculations remain important for preliminary design verification and engineering validation. Consequently, a comparison between the two approaches was conducted to assess the reliability of analytical calculations and to identify potential differences arising from modeling assumptions, geometric simplifications, and numerical solution procedures.

The comparison was performed for both sustained load and thermal expansion load conditions, as these loading categories represent the dominant sources of stress in process piping systems operating under high-pressure and elevated-temperature conditions. For each loading case, the maximum stress values obtained from the analytical calculations were compared with the corresponding results generated by the CAESAR II model. The comparison focused on evaluating the consistency of the predicted stress levels and determining whether both methods produced similar conclusions regarding compliance with the allowable stress limits specified by ASME B31.3.

The percentage deviation between the analytical and numerical approaches was quantified using Eq. (10). This parameter was employed to evaluate the level of agreement between manual calculations and CAESAR II simulations. Lower deviation values indicate a higher degree of consistency between the two methods, whereas larger deviations may reflect the influence of geometric simplifications, boundary condition assumptions, or numerical modeling procedures.

$$D = \left|\frac{\sigma_{manual} - \sigma_{CAESARII}}{\sigma_{CAESARII}}\right| \times 100\% \quad (10)$$

where D is the percentage deviation (%), σ_{manual} is the stress obtained from manual calculations (MPa), and $\sigma_{CAESARII}$ is the stress obtained from CAESAR II simulations (MPa).

The percentage deviation provides a quantitative measure of the agreement between the two methods. Smaller deviation values indicate a higher degree of consistency, whereas larger deviations may suggest the influence of modeling assumptions, boundary condition representation, geometric idealization, or simplifications inherent in analytical calculations. Similar comparison approaches have been widely employed in previous studies to evaluate the accuracy and applicability of numerical piping stress analysis techniques [20], [21].

In addition to comparing the stress magnitudes, the assessment also considered whether both approaches led to the same engineering conclusion regarding piping system integrity. A piping system was considered to exhibit satisfactory agreement when both analytical and numerical methods indicated compliance with the allowable stress criteria prescribed by ASME B31.3. Therefore, the evaluation was not limited to numerical differences alone but also considered the engineering significance of the observed deviations with respect to stress evaluation and ASME B31.3 code compliance verification.

The results of this comparison provide valuable insights into the applicability of conventional analytical methods for preliminary piping design and their effectiveness in predicting the structural behavior of offshore gas production piping systems relative to more sophisticated finite element-based simulations. Furthermore, the analysis contributes to a better understanding of the strengths and limitations of each approach in engineering practice.

Code Compliance Assessment

The final stage of the analysis involved evaluating the structural integrity of the offshore gas production piping system based on the requirements specified in the ASME B31.3 Process Piping Code. Stress analysis and code compliance evaluation are critical components of piping design verification because they determine whether a piping system satisfies the allowable stress limits specified by ASME B31.3 under the evaluated loading conditions. [22].

The assessment was conducted by comparing the calculated stresses obtained from both manual calculations and CAESAR II simulations with the allowable stress limits prescribed by ASME B31.3. The code establishes allowable stress criteria to ensure that piping systems operate within acceptable stress limits under the evaluated loading conditions, thereby reducing the likelihood of excessive deformation and overstress while maintaining compliance with ASME B31.3.

Particular attention was given to the sustained stress and expansion stress conditions because these load categories represent the primary loading mechanisms affecting the investigated piping system. Sustained stress was evaluated to determine the ability of the piping system to withstand continuously acting loads, including pipe self-weight, fluid weight, and internal pressure. Excessive sustained stress may lead to permanent deformation or failure due to prolonged exposure to operational loads. Therefore, the calculated sustained stress was required to remain below the allowable sustained stress specified by ASME B31.3.

In addition, the expansion stress range was evaluated to assess the flexibility of the piping system in accommodating thermal expansion resulting from operating temperature variations. Thermal expansion can generate significant secondary stresses, particularly in restrained piping systems. According to ASME B31.3, the calculated expansion stress range must not exceed the allowable expansion stress limit to ensure that repeated thermal cycles do not compromise the structural integrity of the piping system through excessive stress accumulation or fatigue-related damage.

Compliance with ASME B31.3 was considered achieved when both the sustained stress and expansion stress remained within their respective allowable limits and no overstress condition was identified for the evaluated loading cases. Compliance with these criteria indicates that the piping system satisfies the allowable stress limits specified by ASME B31.3 for the evaluated sustained and thermal expansion loading conditions, demonstrating adequate

strength and flexibility under the specified operating pressure and temperature.

Furthermore, the stress evaluation served as the basis for assessing whether the piping system satisfied the allowable stress requirements specified by ASME B31.3 under the evaluated loading conditions. The results of this evaluation were subsequently used to verify the acceptability of the offshore gas production piping system and to support engineering decision-making during the design validation process.

Results and Discussion

A. Piping System Characteristics

The offshore gas production piping system investigated in this study transports natural gas from the production wellhead to the test manifold under high-pressure operating conditions. Engineering data were obtained from project design documents, including the Piping and Instrumentation Diagram (P&ID) and piping isometric drawings. These documents provided the information required to define the piping geometry, material specifications, operating conditions, and support configurations used in both the analytical calculations and CAESAR II simulations.

Based on the collected engineering data, the piping system was modeled according to the actual field configuration. The principal input parameters included pipe diameter, wall thickness, operating pressure, operating temperature, material properties, corrosion allowance, fluid density, and pipe support arrangement. These parameters directly influence the structural response of the piping system and therefore play an important role in determining the resulting stress distribution.

The investigated piping system consists of several straight pipe sections connected through elbows and fittings, resulting in a three-dimensional routing configuration. Such geometrical complexity affects the flexibility characteristics of the system and contributes to the development of thermal expansion stresses and support reactions. Therefore, accurate representation of the piping geometry is essential for obtaining reliable stress analysis results.

B. Design Parameter Evaluation

Prior to conducting the stress analysis, several critical design parameters were evaluated to verify the adequacy of the piping configuration and to ensure compliance with ASME B31.3 requirements. These parameters served as the foundation for both the analytical calculations and the numerical simulations and directly influenced the structural behavior of the piping system under operating conditions.

One of the most important parameters evaluated was the pipe wall thickness. Based on the pressure design equations specified in ASME B31.3, the minimum required wall thickness for the investigated pipeline was calculated to be 19.1 mm. The calculated minimum required wall thickness of 19.1 mm already includes the specified corrosion allowance of 5 mm in accordance with the project design basis and the requirements of ASME B31.3. Therefore, the selected Schedule 140 pipe, having a nominal wall thickness of 20.625 mm, exceeds the minimum required thickness and provides an additional design margin of approximately 1.53 mm. Consequently, no further deduction of the corrosion allowance was applied during the verification of the pipe wall thickness. As summarized in Table 3, the selected wall thickness exceeds the minimum required thickness specified by ASME B31.3, providing an adequate design margin for the evaluated pressure loading conditions and supporting compliance with the code requirements.

Table 3. Summary of Design Parameter Evaluation

Parameter	Calculated Value	Selected Value	Unit	Remarks
Minimum Wall Thickness	19.1	20.625	mm	Schedule 140 selected
Operating Pressure	22.8	22.80	MPa	Design condition
Operating Temperature	90	90	°C	Design condition
Installation Temperature	50	50	°C	Reference temperature
Thermal Expansion (Nozzle Displacement)	13.50	13.50	mm	Applied in CAESAR II
Allowable Support Span	1.62	1.62	m	Support design criterion

In addition to pressure resistance, thermal expansion behavior was also considered during the design evaluation. The operating temperature of the piping system is significantly higher than the installation temperature, resulting in thermal expansion of the pipeline and connected equipment. The calculated thermal expansion displacement was applied as an imposed nozzle displacement boundary condition in the CAESAR II model at the equipment connection point. The displacement was introduced along the pipe axial direction to represent the thermal expansion of the connected equipment resulting from the difference between installation and operating temperatures. This boundary condition enabled the numerical model to evaluate the restraint forces, bending moments, and secondary stresses generated throughout the piping network due to thermal expansion. The calculated nozzle displacement due to thermal expansion was approximately 13.5 mm. This displacement was subsequently incorporated into the CAESAR II model as a boundary condition because equipment nozzle movements can introduce additional forces and moments into the piping system.

Another parameter evaluated in this study was the allowable support span. Pipe supports play a crucial role in controlling pipe deflection, limiting bending stresses, and maintaining the structural stability of the piping system. Based on the pipe geometry, material properties, and operating loads, the allowable support spacing was calculated to be approximately 1.62 m. This value was used as a reference to assess the adequacy of the support arrangement

incorporated in the piping layout. Proper support placement is essential because excessive support spacing may increase pipe sagging and bending stress, whereas excessive restraint may reduce system flexibility and increase thermal expansion stresses.

The evaluated design parameters demonstrate that the investigated piping system satisfies the preliminary design requirements prior to stress analysis. The selected pipe wall thickness provides adequate pressure-retaining capacity, the calculated nozzle displacement has been incorporated into the boundary conditions of the numerical model, and the support spacing satisfies the allowable span criteria. Consequently, the piping configuration was considered suitable for subsequent stress analysis and ASME B31.3 code compliance evaluation under sustained and thermal expansion loading conditions.

C. Stress Analysis Results

Sustained Load Condition

The sustained load analysis was performed to evaluate the structural response of the piping system under continuously acting operational loads, including pipe self-weight, fluid weight, and internal pressure. These loads represent the primary loading conditions that influence the long-term integrity of process piping systems because they are present throughout normal operation.

The results of the manual calculations indicated that the maximum sustained stress occurred at Node 9100, with a calculated stress value of 124.00 MPa. This stress resulted from the combined effects of axial stress, pressure-induced longitudinal stress, and bending stress generated by dead-weight loading. The calculated stress remained below the allowable sustained stress specified by ASME B31.3, indicating that the piping system possesses sufficient structural strength to withstand the applied operational loads. The concentration of sustained stress at Node 9100 is primarily attributed to the local geometric discontinuity and the interaction between internal pressure, dead-weight loading, and support restraints. This node is located near a directional change in the piping system where bending moments become more significant than in straight pipe segments. Similar stress concentration behavior has been reported in offshore piping systems with elbow-supported configurations, where changes in pipe direction increase local bending stresses.

Table 4. Sustained Stress Results

Method	Critical Node	Stress (MPa)	Allowable Stress (MPa)	Utilization (%)
Manual Calculation	9100	124	177.20	69.98
CAESAR II	9100	96.70	177.20	54.60

A similar assessment was conducted using the CAESAR II model. The numerical simulation identified the same critical location, namely Node 9100, as the point experiencing the highest sustained stress within the piping network. The maximum sustained stress predicted by CAESAR II was 96.7 MPa, corresponding to approximately 54.6% of the allowable stress limit of 177.2 MPa prescribed by ASME B31.3. A summary of the sustained stress results obtained from both methods is presented in Table 4. As shown in Table 3, both methods identified the same critical location, although the stress predicted by CAESAR II was lower than that obtained from the manual calculation. The stress distribution obtained from the simulation is presented in Figure 5, while the critical stress location is highlighted in Figure 6.

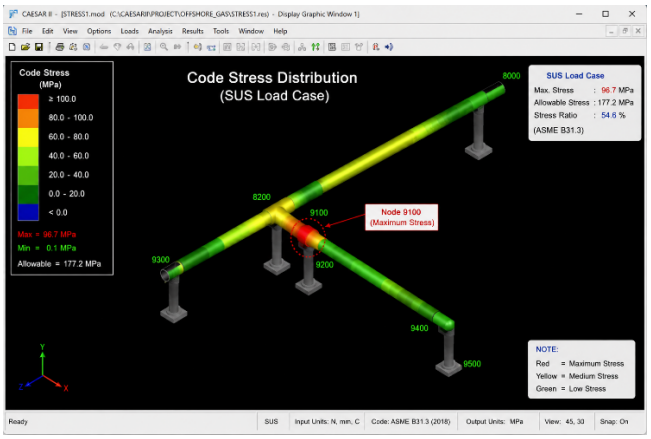

Figure 5. Sustained stress distribution obtained from the CAESAR II simulation showing the critical location at Node 9100.

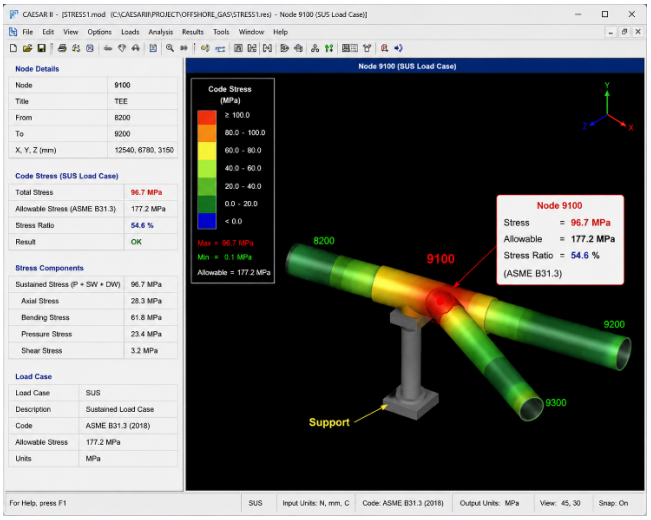

Figure 6. Location of the maximum sustained stress at Node 9100.

The fact that both analytical and numerical approaches identified the same critical node provides confidence in the consistency of the analysis. Furthermore, the calculated sustained stress remains substantially below the allowable stress limit specified by ASME B31.3, indicating that the piping system satisfies the code requirements and provides an adequate design margin for the evaluated sustained loading condition. From an engineering perspective, this result demonstrates that the selected pipe dimensions, material properties, and support arrangement are adequate to resist the combined effects of pressure and dead-weight loads without experiencing overstress conditions. Although both approaches identified Node 9100 as the critical location, the stress predicted by CAESAR II was lower than that obtained from the manual calculation. This difference is primarily

attributed to the simplified assumptions adopted in the analytical method, whereas CAESAR II considers the three-dimensional geometry, support restraints, and load redistribution effects in greater detail. A comparison between the sustained stresses obtained from the two methods is presented in Figure 7.

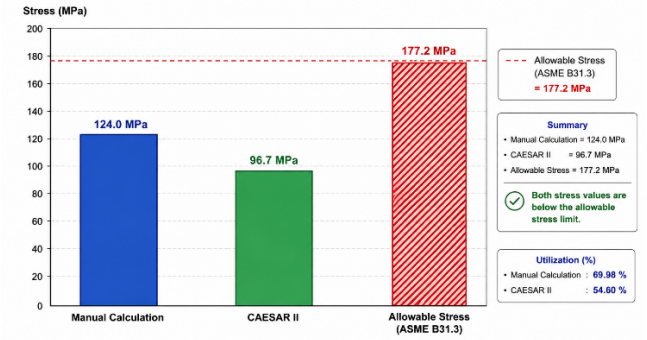

Figure 7. Comparison between sustained stresses obtained from manual calculations and CAESAR II simulations.

As shown in Figure 7, both stress values remain significantly below the allowable stress limit specified by ASME B31.3. The manual calculation produced a higher stress value than the CAESAR II simulation, indicating that the analytical approach provides a more conservative estimate of piping behavior. Nevertheless, both methods lead to the same engineering conclusion: the piping system satisfies the allowable stress requirements specified by ASME B31.3 for the evaluated sustained loading condition and provides an adequate design margin relative to the allowable stress limit.

Expansion Load Condition

Expansion stress analysis was conducted to evaluate the influence of thermal expansion resulting from the difference between installation and operating temperatures. Thermal expansion is an important consideration in offshore piping systems because restrained thermal movements may generate secondary stresses, support reactions, and equipment nozzle loads that affect the overall flexibility of the system.

Using the Grinnell flexibility method, the manual calculation predicted a maximum expansion stress of 2.89 MPa at Node 9320. The calculated value was significantly lower than the allowable expansion stress range specified by ASME B31.3, suggesting that the piping system possesses sufficient flexibility to accommodate thermal expansion. The relatively low expansion stress indicates that the piping layout provides sufficient flexibility to accommodate thermal displacement without generating excessive restraint forces. This behavior is mainly attributed to the three-dimensional routing configuration and the appropriate spacing of pipe supports, which allow thermal expansion to be distributed throughout the system instead of being concentrated at a single location. Consequently, the piping system exhibits good flexibility characteristics in accordance with ASME B31.3 requirements.

The expansion stress predicted by CAESAR II was only 2.44 MPa, corresponding to approximately 1.18% of the allowable expansion stress specified by ASME B31.3. This relatively low value confirms that the applied thermal loading and boundary conditions do not generate significant secondary stresses within the investigated piping system. In the numerical model, the thermal expansion load case was established using the operating temperature of 90°C, the installation temperature of 50°C, and the corresponding nozzle displacement of 13.5 mm derived from the analytical calculation. The support arrangement and boundary conditions were modeled according to the project isometric drawings and equipment connections. The low expansion stress is primarily attributed to the adequate flexibility of the piping layout, which allows thermal expansion to be distributed along the three-dimensional routing rather than being concentrated at localized restraint points. Consequently, only limited restraint forces and bending moments were developed during thermal expansion, resulting in a relatively small expansion stress while maintaining full compliance with ASME B31.3.

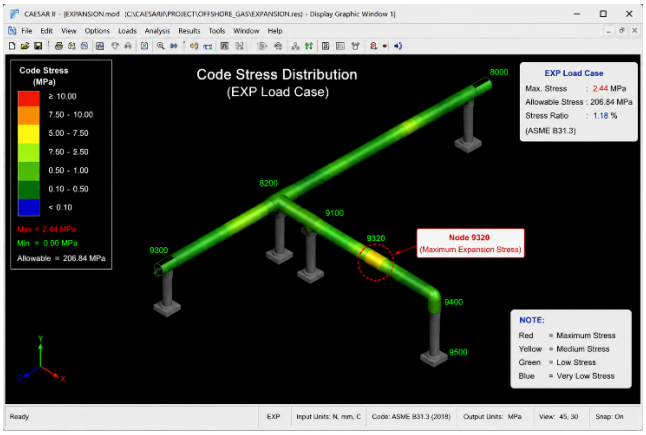

Figure 8. Expansion stress distribution obtained from the CAESAR II model.

The CAESAR II simulation produced comparable results and also identified Node 9320 as the critical location under thermal loading conditions. The maximum expansion stress obtained from the numerical model was 2.44 MPa, representing only 1.18% of the allowable expansion stress range of 206.84 MPa. The corresponding results are summarized in Table 5. As indicated in Table 5, the calculated expansion stresses were substantially lower than the allowable stress range specified by ASME B31.3. The stress distribution obtained from the CAESAR II model is shown in Figure 8. The simulation identified Node 9320 as the critical location under thermal loading conditions, although the calculated stress remained significantly below the allowable stress limit specified by ASME B31.3.

Table 5. Expansion Stress Results

Method	Critical Node	Stress (MPa)	Allowable Stress (MPa)	Utilization (%)
Manual Calculation	9320	2.89	206.84	1.4
CAESAR II	9320	2.44	206.84	1.18

To provide a clearer representation of the critical region, Figure 9 presents a detailed view of Node 9320. The maximum expansion stress recorded at this location was 2.44 MPa, corresponding to only 1.18% of the allowable expansion stress range of 206.84 MPa. This result indicates that thermal expansion generates only minor stress levels within the investigated piping system and does not pose a threat to structural integrity.

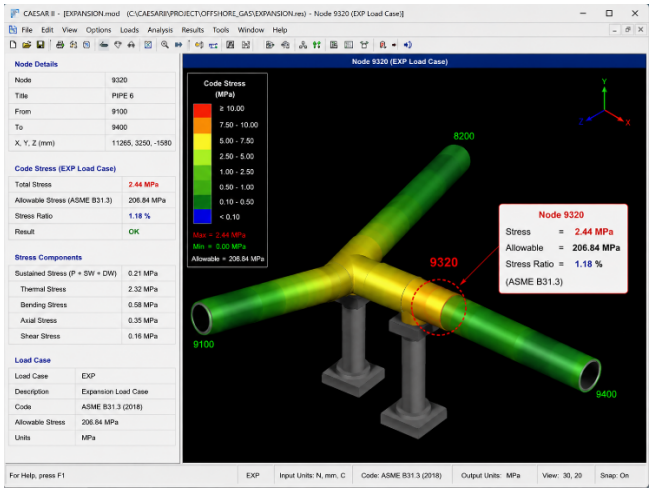

Figure 9. Location of the Maximum Expansion Stress Identified in the Piping System.

The low expansion stress level is primarily attributed to the adequate flexibility of the piping layout, which allows thermal movements to be absorbed without generating excessive restraint forces. The displacement behavior predicted by the CAESAR II simulation is illustrated in Figure 10.

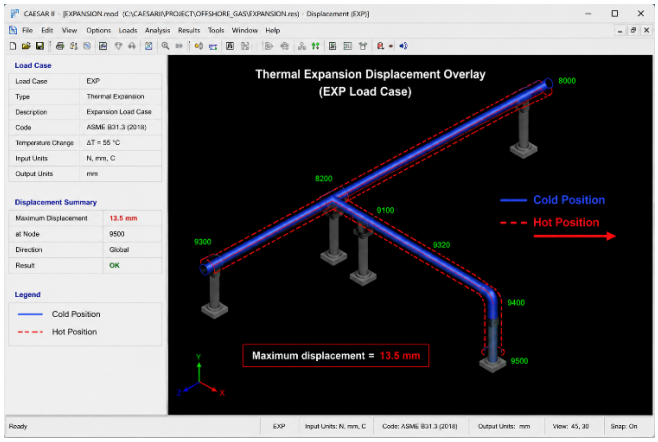

Figure 10. Thermal Expansion Displacement Predicted by the CAESAR II Simulation

The extremely low stress utilization ratio indicates that thermal expansion does not impose a significant structural burden on the investigated piping system. The presence of adequate flexibility within the piping layout allows thermal displacements to be absorbed without generating excessive restraint forces or stress concentrations. Consequently, the piping system can accommodate operating temperature variations while maintaining compliance with the stress limits prescribed by ASME B31.3.

The present findings are consistent with those reported by Prachi et al. [7], who also observed that the maximum sustained stresses were concentrated near elbow regions because of increased bending moments. Likewise, Harper et al. [9] reported that thermal expansion stresses could be effectively reduced through adequate piping flexibility and support configuration. These similarities suggest that the stress distribution observed in the investigated offshore piping system follows the general mechanical behavior reported in previous studies despite differences in operating conditions.

Overall, the results of both sustained and expansion load analyses demonstrate that the investigated offshore gas production piping system satisfies the code requirements for structural integrity. No overstress condition was identified in either loading case, and all calculated stress values remained well below their respective allowable limits. These findings confirm that the piping design possesses adequate strength and flexibility to satisfy the allowable stress requirements specified by ASME B31.3 under the evaluated sustained and thermal expansion loading conditions.

Verification of CAESAR II Results Using Analytical Calculations

The analytical calculations produced slightly higher stress values than the CAESAR II simulations. This difference is expected because the analytical approach adopts simplified assumptions, whereas CAESAR II considers three-dimensional geometry, support restraints, and load redistribution. Despite these differences, both approaches consistently indicate that the piping system satisfies the allowable stress limits prescribed by ASME B31.3. Therefore, the analytical calculations serve as an independent verification supporting the validity of the numerical simulation results rather than as an evaluation of the analysis methods themselves.

For the sustained load condition, the manual calculation produced a stress value of 124.00 MPa, whereas CAESAR II predicted a stress of 96.7 MPa. The resulting deviation between the two methods was 28.24%. For the expansion load condition, the manual calculation yielded an expansion stress of 2.89 MPa, while the CAESAR II simulation produced a value of 2.44 MPa. The corresponding deviation was 18.45%. The higher stress predicted by the analytical calculation is expected because the simplified analytical approach assumes conservative loading conditions and cannot fully represent the redistribution of loads throughout the piping network. In contrast, CAESAR II employs finite element analysis to account for pipe flexibility, support stiffness, and three-dimensional structural interaction, resulting in a more realistic prediction of stress distribution. Therefore, the observed deviation does not indicate inconsistency but reflects the different modeling assumptions adopted by the two approaches.

Although measurable differences were observed, both methods identified the same critical regions and produced the same engineering conclusion, namely that the piping system

remained within the allowable stress limits prescribed by ASME B31.3. The observed deviations are primarily attributed to differences in modeling approaches. Manual calculations employ simplified analytical assumptions and generalized equations, whereas CAESAR II utilizes finite element analysis to account for geometric complexity, support restraints, boundary conditions, and load interactions in greater detail.

The lower stress values predicted by CAESAR II suggest that the software can represent load redistribution and system flexibility more realistically than simplified analytical calculations. Similar observations have been reported in previous studies comparing analytical and finite element-based pipe stress analyses.

Compliance Evaluation and Engineering Implications

The stress evaluation demonstrated that the maximum sustained and expansion stresses obtained from both analytical and numerical approaches remained below the allowable stress limits specified by ASME B31.3. Consequently, the investigated piping system satisfied the code requirements for the sustained and thermal expansion load cases evaluated in this study. The sustained stress utilization ratio obtained from CAESAR II was approximately 54.6%, while the expansion stress utilization ratio was only 1.18%. These values indicate that the piping system maintains an adequate design margin relative to the allowable stress limits specified by ASME B31.3 under the evaluated operating conditions.

From an engineering perspective, the results indicate that the investigated piping configuration provides an adequate design margin relative to the allowable stress limits specified by ASME B31.3 for the evaluated sustained and thermal expansion loading conditions. The stress utilization ratio indicates that the piping system maintains an adequate design margin under the evaluated loading conditions. Furthermore, the analytical verification demonstrates that simplified calculations can be effectively used during the preliminary design stage, whereas detailed numerical stress analysis using CAESAR II remains essential for final design verification and ASME B31.3 code compliance evaluation.

Conclusion

This study evaluated the stress behavior and code compliance of an offshore gas production piping system under sustained and thermal expansion loading conditions using CAESAR II in accordance with ASME B31.3. The results indicate that both sustained and expansion stresses remain below the allowable limits specified by ASME B31.3, demonstrating that the investigated piping system satisfies the code requirements for the evaluated load cases. Conventional analytical calculations were employed as an independent engineering verification and showed good agreement with the numerical simulation, thereby increasing confidence in the numerical stress evaluation. These findings demonstrate the applicability of the proposed approach for piping design verification of offshore gas production piping systems.

The present study is limited to the evaluation of sustained and thermal expansion loading conditions. Additional investigations incorporating support reactions, nozzle loads, occasional loading, vibration, fatigue, and long-term corrosion effects are recommended to provide a more comprehensive assessment of offshore piping performance.

Author Contributions

Author Contributions: E.S.: Conceptualization, Methodology, Data Collection, Writing–Original Draft. M.S.H.: Formal Analysis, Validation. B.H.: Supervision, Review and Editing. H.A.K.: Data Interpretation, Review and Editing. S.P.S.: Methodology, Visualization, Review and Editing.

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Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper. Although technical data were obtained from an industrial project, the analysis, interpretation of results, and conclusions presented in this study were conducted independently by the authors.

References

[1] M. Kellog, “Calculation Methodologies for The Design of Piping Systems,” *International Journal of Engineering Research and General Science*, vol. 2, no. 6, 2014.

[2] F. Paolacci, M. S. Reza, O. S. Bursi, A. M. Gresnigt, and A. Kumar, “Main issues on the seismic design of industrial piping systems and components,” in *American Society of Mechanical Engineers, Pressure Vessels and Piping Division (Publication) PVP*, 2013. doi: 10.1115/PVP2013-97642.

[3] K. Vedeld, H. A. Sollund, and J. Hellesland, “Closed Analytical Expressions for Stress Distributions in Two-Layer Cylinders and Their Application to Offshore Lined and Clad Pipes,” *Journal of Offshore Mechanics and Arctic Engineering*, vol. 137, no. 2, 2015, doi: 10.1115/1.4029357.

[4] A. Aswin and A. Hasnan, “Stress Analysis Evaluation and Pipe Support Type on High-Pressure and Temperature Steam Pipe,” *International Journal of Mechanical Engineering Technologies and Applications*, vol. 4, no. 1, 2023, doi: 10.21776/mechta.2023.004.01.4.

[5] C. Ilincă, M. Tănase, and M. G. Petrescu, “Example of stress evaluation for a pipe subjected to impeded thermal expansion according to ASME code,” *Journal of Research and Innovation for Sustainable Society*, vol. 3, no. 2, 2021, doi: 10.33727/jriss.2021.2.13:120-131.

[6] V. Thakran, “A Review of Flexibility Analysis in Piping Systems: Insights from CAESAR-II Applications,” *Technix International Journal for Engineering Research*, vol. 10, no. 10, 2023, doi: 10.56975/tijer.v10i10.159020.

[7] R. N. Rao, M. Maiya, S. Prabhu, G. Santhosh, and G. Hebbar, "The analysis of a piping system for improvement of a system in a process unit," in *Materials Today: Proceedings*, 2021. doi: 10.1016/j.matpr.2021.02.595.

[8] M. Prachi, N. Tambe, K. K. Dhande, and N. I. Jamadar, "Flexibility and Stress Analysis of Piping System using CAESAR II-Case Study," *IJERT*, vol. 3, no. 6, 2014.

[9] Y. Jannot, A. El Maakoul, C. Moyne, and A. Degiovanni, "A new analytical model for transient heat transfer modeling of geothermal monotube heat exchangers," *Geothermics*, vol. 121, 2024, doi: 10.1016/j.geothermics.2024.103039.

[10] C. Harper, P. Crowther, and C. Chauvet, "Computational Analysis of a Piping Structure Subject to Thermal Striping," in *American Society of Mechanical Engineers, Pressure Vessels and Piping Division (Publication) PVP*, 2023. doi: 10.1115/PVP2023-107602.

[11] X. Liu, W. Sun, Y. Gao, and H. Ma, "Optimization of pipeline system with multi-hoop supports for avoiding vibration, based on particle swarm algorithm," *Proc. Inst. Mech. Eng. C J. Mech. Eng. Sci.*, vol. 235, no. 9, 2021, doi: 10.1177/0954406220947115.

[12] N. Kumar, J. C. Hernández Azucena, H. Liao, and E. Pohl, "Modeling the Impact of Corrosion Orientation and Location on Pipeline Reliability," in *Proceedings - Annual Reliability and Maintainability Symposium*, 2025. doi: 10.1109/RAMS48127.2025.10935239.

[13] S. Adumene, F. Khan, S. Adedigba, S. Zendehboudi, and H. Shiri, "Offshore pipeline integrity assessment considering material and parametric uncertainty," *Journal of Pipeline Science and Engineering*, vol. 1, no. 3, 2021, doi: 10.1016/j.jpse.2021.09.005.

[14] K. Yu, E. V. Morozov, M. A. Ashraf, and K. Shankar, "A review of the design and analysis of reinforced thermoplastic pipes for offshore applications," 2017. doi: 10.1177/0731684417713666.

[15] Vikas Thakaran, "A Comparative Study of Piping Stress Analysis Methods with Different Tools, Techniques, and Best Practices," *International Journal of Advanced Research in Science, Communication and Technology*, 2022, doi: 10.48175/ijarsct-7868d.

[16] S. L. Golofast, "Assessment of the main gas pipeline strength reliability considering the actual regularities of the distribution of the pipe wall thickness," *Bezopasnost' Truda v Promyshlennosti*, vol. 2020, no. 6, 2020, doi: 10.24000/0409-2961-2020-6-21-28.

[17] Z. Pu, B. Ren, J. Wang, P. Song, and D. Chen, "Stress analysis of in-service flare gas pipeline system and equipment nozzle," in *American Society of Mechanical Engineers, Pressure Vessels and Piping Division (Publication) PVP*, 2020. doi: 10.1115/pvp2020-21130.

[18] K. A. Damle, P. S. Gharat, R. Neufeld, and W. Peters, "Effect of nozzle junction and equipment stiffness on absorption of pipe thermal loads," *Journal of Pressure Vessel Technology, Transactions of the ASME*, vol. 138, no. 2, 2016, doi: 10.1115/1.4031719.

[19] T. Chiba, S. Okado, I. Fujii, K. Itami, and F. Hara, "Optimum support arrangement of piping systems using genetic algorithm," *Journal of Pressure Vessel Technology, Transactions of the ASME*, vol. 118, no. 4, 1996, doi: 10.1115/1.2842222.

[20] A. Bhattacharya, "Stress analysis of pipe support attachments: A comparison of analytical methods and finite element analysis for circular and non-circular attachments," in *American Society of Mechanical Engineers, Pressure Vessels and Piping Division (Publication) PVP*, 2013. doi: 10.1115/PVP2013-97622.

[21] P. Mahardhika, A. W. Husodo, G. E. Kusuma, R. D. E. Witjonarko, and E. N. Budiyanto, "Analysis of Symmetrical and Nonsymmetrical Vertical Expansion Loop to Increase Flexibility And Reduce Pipe Stress Based On ASME B31.3," *TEKNIK*, vol. 42, no. 1, 2021, doi: 10.14710/teknik.v42i1.29244.

[22] C. A. Schell, E. Lever, and K. M. Groth, "Strain-based design and assessment for pipeline integrity management: A review of applications and gaps," 2023. doi: 10.1016/j.ijpvp.2023.104973.