

Application Of the Finite Element Method for Evaluating the Stress Due To Operating Load In High Energy Piping System

Pekik Mahardhika¹, Adi Wirawan Husodo², Ekky Nur Budiyo³, Benedita Dian Alfanda⁴, Rina Sandora⁵
(Received: 03 April 2025 / Revised: 12 April 2025 / Accepted: 05 May 2025 / Available Online: 30 June 2025)

Abstract— The stress value of the piping system will change during operating conditions. The stress value affects the integrity of the piping system. Excessive stress will cause deformation and damage to the piping system. The operating condition parameters of the piping system are temperature and pressure. The High-Energy Piping (HEP) system is subjected to high pressures and temperatures, which can cause significant stresses on the piping components. So stress analysis needs to be carried out to ensure that the piping system has strength and flexibility. The Cold Reheat Pipe (CRP) steam line is one of the High-Energy Piping Systems in this steam power plant. CRP consists of CRP BS 130 and CRP BS 131. This paper is about evaluating the stress due to operating loads in 2024 (temperature, pressure, and remaining thickness) for steam lines on the high-energy piping system using the finite element method and refers to ASME B31.1. The output stress values in the piping system in this paper consist of stress due to sustained load, stress due to thermal load, and hoop stress. The CRP BS 130 modeling results show the maximum stress due to sustained load (166.6 kg/cm²), the maximum stress due to the thermal load (112.8 kg/cm²), and the maximum hoop stress (855.6 kg/cm²). The CRP BS 131 modeling results show the maximum stress due to sustained load (974.2 kg/cm²), the maximum stress due to the thermal load (123.5 kg/cm²), and the maximum hoop stress (938.9 kg/cm²). The results of the stress evaluation due to the operating load were still below the allowable stress and are still permitted by the ASME B31.1 Code.

Keywords— Stress, Temperature, Pressure, Finite element method, Operating condition, High energy piping

I. INTRODUCTION

The piping system design process requires static or dynamic stress analysis to ensure the safety of the pipe design and operation. If the stress that occurs exceeds the allowable stress so deformation or failure of the piping system may occur [1], [2]. Stress analysis also needs to be carried out if the piping system has specification degradation occurred, such as a reduction in pipe thickness due to operating conditions [3]. The stresses are caused by the pipe's dead weight, fluid density and isolation, thermal changes, operating and design pressure, and occasional conditions like wind, seismic, etc [4], [5]. The stress of a piping system is also due to forces and moment acting [6]. The piping system that is flowed by steam fluid has high pressure and temperature at operating conditions, especially steam produced by the Steam power generator industries [7]. This steam power generator system company in East Java has been operating since 1999. The main component of the steam

power generator is the pressure part component which consists of: a superheater, reheater, economizer, and water wall. This component will contain high energy in the steam to get more power for driving the turbine and to increase plant efficiency was called High Energy Piping (HEP). Components found in the power generation industry are often exposed to high pressure and temperatures for long periods, which affects the microstructure and mechanical properties [8], [9]. One of the steam lines from High Energy Piping (HEP) is the cold reheat piping (CRP). CRP consists of CRP BS 130 and CRP BS 131. The HP turbine bypass pathway branches off of the main steam line before the stop valve inlet and connects to the cold reheat piping line. This study was carried out on a cold reheat piping system and was last inspected in 2024. The method used to inspect the reduction in pipe thickness is using the ultrasonic test (UT) method. So according to [10] in the line of steam pipe, stress analysis needs to be carried out to ensure that the designed piping system has strength and flexibility. The HEP system is subjected to high pressures and temperatures, which can cause significant stresses on the piping components. The stress value of the piping system will change during operating conditions. The stress value affects the integrity of the piping system. The high temperature of the equipment will induce stresses [11]. Excessive stress will cause deformation and damage to the piping system. Steam pipes are affected by thermal stress due to thermal distributions and heat accumulation in operation [12]. Ignoring high stress can yield to failure of the system [13].

Many studies on stress analysis have been conducted, especially on steam piping systems. Aswin et al. [10] evaluate the stress and the effect of using pipe supports in the high-pressure and temperature steam piping

Pekik Mahardhika, Departement of Marine Engineering, Shipbuilding Institute of Polytechnic Surabaya, Surabaya, 60111, Indonesia.

E-mail: pekikmahardhika@ppns.ac.id

Adi Wirawan Husodo, Departement of Marine Engineering, Shipbuilding Institute of Polytechnic Surabaya, Surabaya, 60111, Indonesia. E-mail: adi_wirawan@ppns.ac.id

Ekky Nur Budiyo, Departement of Marine Engineering, Shipbuilding Institute of Polytechnic Surabaya, Surabaya, 60111, Indonesia. E-mail: ekky@ppns.ac.id

Benedicta Dian Alfanda, Departement of Marine Engineering, Shipbuilding Institute of Polytechnic Surabaya, Surabaya, 60111, Indonesia. E-mail: benedictadian@ppns.ac.id

Rina Sandora, Departement of Marine Engineering, Shipbuilding Institute of Polytechnic Surabaya, Surabaya, 60111, Indonesia. E-mail: rinasandora@ppns.ac.id

system by using Caesar II software. This stress analysis is to ensure that the piping system that is designed is safe and does not exceed the allowable stress under operating conditions which refer to ASME B31.3 process piping code (design pressure of 65 bars and a design temperature of 480 °C). Yogita B. Shinger et al [14] studied the design of the steam piping system and stress analysis (thermal and static analysis). The study compared manual calculation referred to as ASME B31.1 Power Piping and calculation using ANSYS software. The result focuses on maximum deflection, bending moment, and bending stress. Udin Komarudin et al [15] have researched pipe stress and load analysis of nozzles on the turbine using Bentley Autopipe software. The study is referred to as ASME B31.1 Power Piping. HP Steam Inlet for operating temperature is 460 °C and operating pressure is 60 kg/cm². MP Steam for operating temperature is 33 °C and operating pressure is 19 kg/cm². Aathres et al [16] studied to show that the piping design and stress analysis of Auxiliary steam piping to Air heater soot blowing is according to the piping code. The reference piping code used in this research is ASME B 31.1. This research used Caesar II software for pipe stress analysis. Steam operating temperature is 210 °C and pressure is 20 kg/cm². Wanda et al [17] studied steam pipe stress analysis of a High-Pressure Steam Header In the construction of the oleochemical plant project. The reference piping code used in this research is ASME B 31.3. Fluid steam has a design temperature is 210 °C and a design pressure is 9.17 kg/cm². Farih et al [18] studied piping stress analysis in the steam system. The reference piping code used in this research is ASME B 31.3 process piping. This research used Caesar II software for pipe stress analysis. Steam operating temperature is 195.4 °C and pressure is 14.3 kg/cm². Xiu et al [19] have researched expansion and structural pipe stress analysis on a steam line 350 MW unit. The main steam pipe design temperature is 576 °C and the design pressure is 25.4 MPa. Koorse et al [20] studied overview pipe stress analysis and deflection of high-energy piping due to design conditions. The reference piping code used in this research is ASME B 31.1 power piping. Riza et al

[21] have researched design and pipe stress analysis in the gas and steam power generator industry. This line pipe distributes steam from the Heat Recovery Steam Generator (HRSG) to the steam turbine and bypasses to the condenser. The reference piping code used in this research is ASME B 31.1 power piping. The steam pipe has an operating temperature is 220 °C and an operating pressure is 600 kPa. M Zainal Mahfud et al [22] studied pipe stress analysis from HRSG to the turbine. The steam pipe has an operating temperature is 535 °C and an operating pressure is 47 bar. The reference piping code used in this research is ASME B 31.1 power piping. Ahmad Husen et al.

This study introduces a new approach using the finite element method to evaluate high-energy piping systems, especially CRP lines, due to the operational load seen from pressure, temperature, and remaining pipe thickness. With this method, it can be determined whether the piping system that has been operating for 25 years is in a safe condition or not. So that the results of this research can help related industries evaluate their piping systems.

II. METHOD

A. Stress due to Sustained Load

Stress due to sustained load is the total load of longitudinal stress caused by pressure and weight on the system [23]. So it can be said that another term for stress caused by sustained load is longitudinal stress, which includes longitudinal sustained weight stress and longitudinal pressure stress. This type of stress is caused by the internal pressure of the fluid being transported through the piping system. It is the most common type of stress and is typically the dominant stress in most piping systems.

Stress due to sustained load equation [24]:

$$SLs = \frac{P \cdot D_o}{4t_n} + \frac{0.75 \cdot iMA}{Z} \leq 1.0 Sh \quad (1)$$

SLs

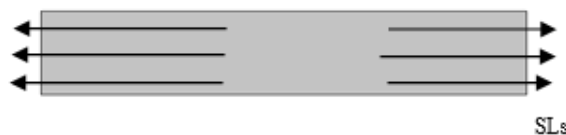


Figure 1. Longitudinal stress

B. Stress due to Thermal Load

Stress due to thermal load occurs due to the difference in temperature of the fluid flowing with the properties of the pipe material. This type of stress is caused by thermal expansion or contraction of the piping system due to temperature changes and displacement [25]. It is important to consider this type of stress, especially in piping systems that operate at high temperatures or are exposed to extreme temperature fluctuations. For straight pipes, thermal expansion analysis is based on the guided cantilever method.

Stress due to thermal load equation [24]:

$$Se = \frac{iMc}{Z} \leq Sa \quad (2)$$

$$Mc = \sqrt{Mx^2 + My^2 + Mz^2} \quad (3)$$

Where the Mc is the resultant moment loading range on the cross-section due to the reference displacement load range.

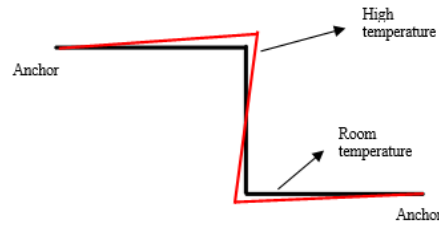


Figure 2. Stress due to thermal load visualization

The piping system must be flexible enough to expand due to excessive thermal expansion or movement of support or pipe endpoints [26].

C. Hoop Stress

Hoop stress is the stress in the tangential direction to the circumference of the pipe. The hoop stress is the stress due to a pressure gradient around the circumference of the pipe [27]. Hoop stress equation [24], [28]:

$$S_{hoop} = \frac{P \cdot D_o}{2 \cdot t \cdot Zl} - \frac{P \cdot y}{Zl}$$

Thickness nominal or actual shall not be less than that calculated by Equation (5). The minimum permitted wall thickness of pipe equation [24]:

$$t_{min} = \frac{P \cdot D}{2 (S \cdot E \cdot W + P \cdot Y)} + A \quad (5)$$

Piping stress analysis needs to be re-performed for structural or piping integrity assessment after significant wall thinning occurs [29].

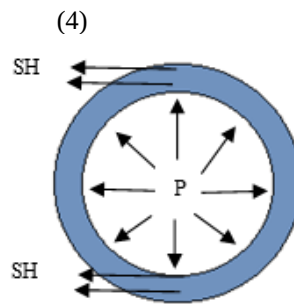


Figure 3. Hoop stress

D. Allowable stress of pipe

The American Society of Mechanical Engineering (ASME) recommended that stress due to sustained load and hoop stress value ≤ 1.0 Sh. The sum of the longitudinal stresses, due to pressure, weight, and other sustained loads and hoop stress shall not exceed the basic material allowable stress in the hot condition (Sh). The stress due to the pressure in the pipe is evaluated using the longitudinal stress (stress due to sustained load) and the hoop stress of the cylindrical pressure [30].

Stress due to thermal load value $\leq S_a$. For allowable stress due to thermal load use equation (6).

$$S_a = f (1.25 S_c + 0.25 S_h) \quad (6)$$

Where, S_a is the allowable maximum displacement stress range.

III. RESULTS AND DISCUSSION

A. Research Data

Table 1 shows the operating data of the CRP BS 130 steam line and the CRP BS 131 steam line, while Table 2 shows the technical specifications of the pipe. The modeling results of the HEP piping system can be seen in Figure 4 for CRP BS-130 and Figure 5 for CRP BS-131. The reference piping code used in this research is ASME B 31.1 power piping because it is included in its scope [24].

TABLE 1.
OPERATING DATA OF CRP BS 130 AND CRP BS 131 STEAM LINES

No	Line	Operating Pressure (MPa) / (kg.cm ²)	Operating Temperature (°C)
1	CRP BS 130 Steam Line	3.79 / 38.64	320
2	CRP BS 131 Steam Line	3.79 / 38.64	320

TABLE 2.
TECHNICAL SPECIFICATION OF PIPE

Line	Outside Diameter	Design Wall Thickness	Existing Wall Thickness (thinnest at 2024)	Minimum Wall Thickness	Insulation Thickness	Material Specification
CRP BS-130	30"/762 mm	19.5 mm	19.31 mm	15.71 mm	178 mm	SA335 P22
CRP BS-131	30"/762 mm	19.5 mm	17.63 mm	15.71 mm	178 mm	SA 672, B65, Class 31

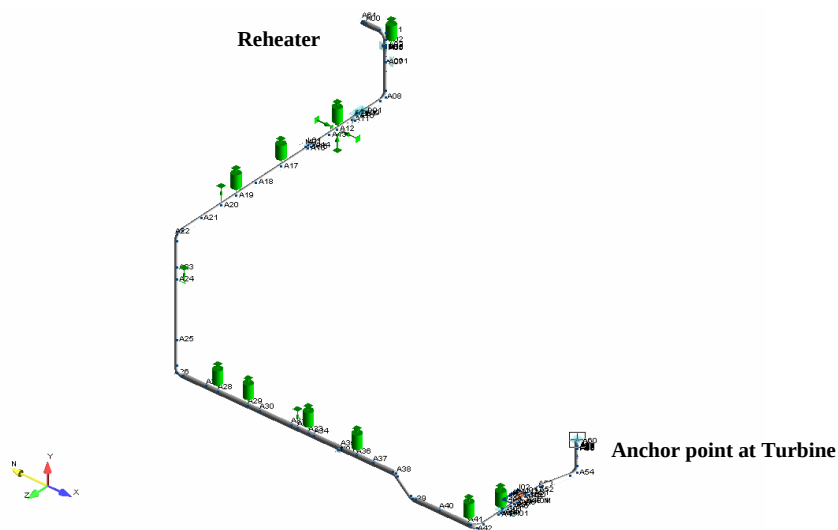


Figure 4. The high-energy piping steam line for CRP BS-130

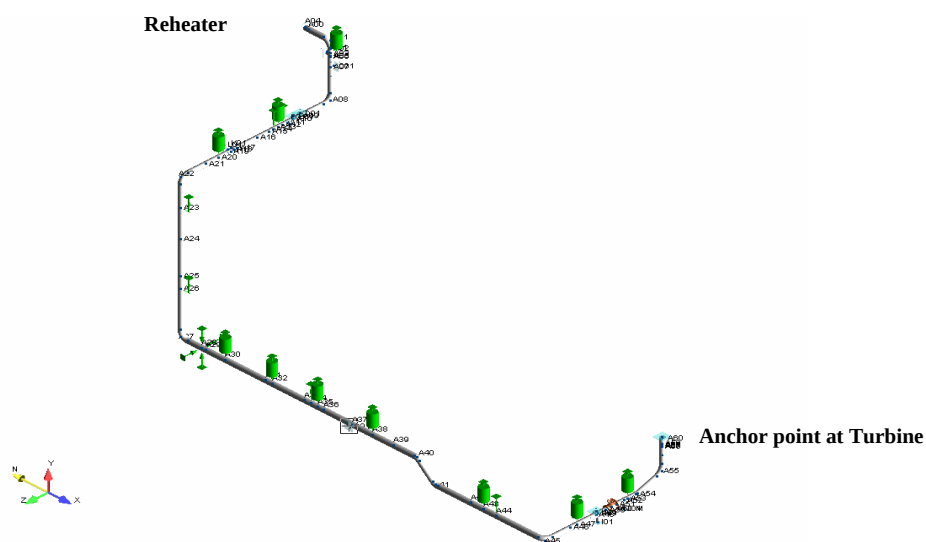


Figure 5. The high-energy piping steam line for CRP BS-131

B. Stress Check Operating Condition

The distribution of color contours in the simulation figure of this research can be explained that the purple contour is the highest stress value and the blue contour is the lowest stress value. Another color contour definition is in the top left corner. This stress value should not be greater than the allowable stress for every type of stress and the stress ratio value also should not be greater than 100% to ensure the piping system is safe when operated. The stress ratio is the comparison between the actual

code stress value and the allowable stress value.

The contour of stress due to sustained load is shown in Figure 6. The magnitude of stress due to sustained load is between 166.6 kg/cm² to 645.2 kg/cm². These stresses are lower than the allowable sustained stress (1307.7 kg/cm²). The maximum stress due to sustained load (645.2 kg/cm²) is located in point A36 (Hanger support No. S214) and has a green contour. The highest stress ratio has a value of 49 % at the same location.

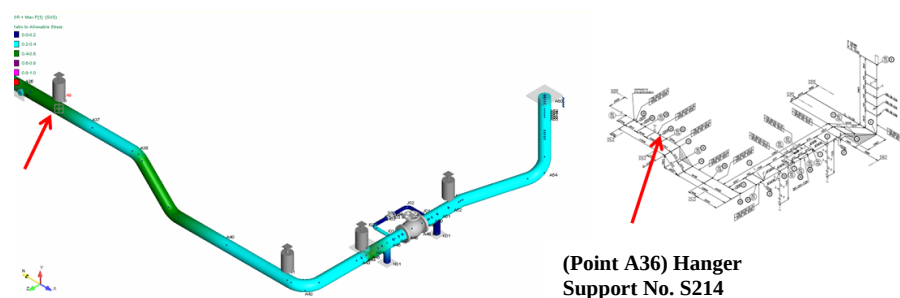


Figure 6. The contour of stress due to sustained load of CRP BS-130 in operating condition

The magnitude of stress due to thermal load is described in Figure 7. The magnitude of stress due to thermal load is between 0.0 kg/cm² to 112.8 kg/cm². These stresses are lower than the maximum allowable displacement stress range (1961.6 kg/cm²). The

maximum stress due to the thermal load (112.8 kg/cm²) is located in point M01 (Tee branch No. BS116B) and has a blue contour. The highest stress ratio has a value of 6 % at the same location.

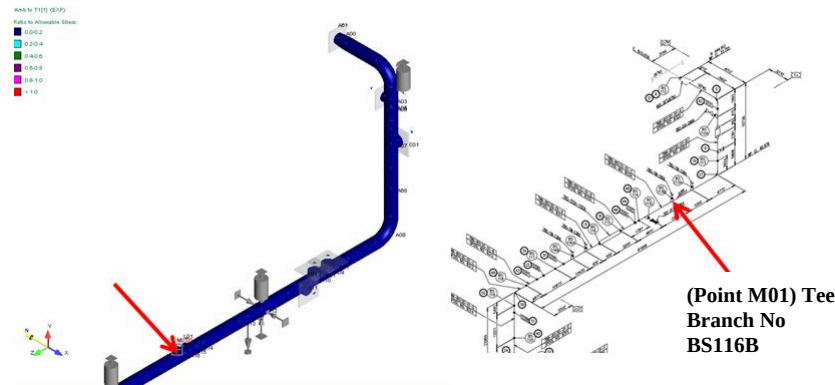


Figure 7. The contour of stress due to the thermal load of CRP BS-130 in operating condition

The magnitude of hoop stress is described in Figure 8. The magnitude of hoop stress is between 365.4/cm² and 855.6 kg/cm². These stresses are lower than the allowable hoop stress (1307.7 kg/cm²). The maximum hoop stress (855.6 kg/cm²) is located in point M01

(Hanger support No. S214), the same point where the maximum stress due to sustained load occurs, and has a purple contour. The highest stress ratio has a value of 65 % at the same location.

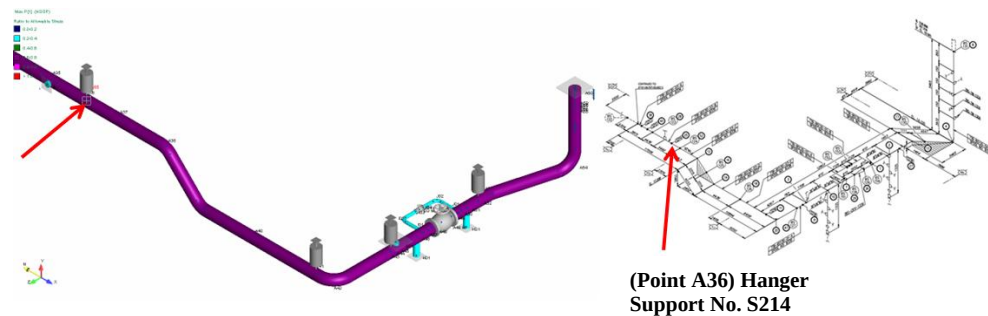


Figure 8. The contour of hoop stress of CRP BS-130 in operating condition

The contour of stress due to sustained load is shown in Figure 9. The magnitude of stress due to sustained load is between 248.7 kg/cm² to 974.2 kg/cm². These stresses are lower than the allowable sustained stress

(1307.7 kg/cm²). The maximum stress due to sustained load (974.2 kg/cm²) is located in point A44 (Solid rod support No S234) and has a purple contour. The highest stress ratio has a value of 74 % at the same location.

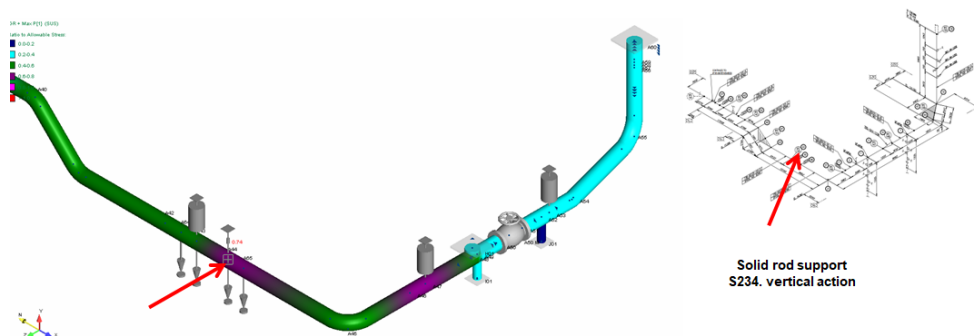


Figure 9. The contour of stress due to sustained load of CRP BS-131 in operating condition

The magnitude of stress due to thermal load is described in Figure 10. The magnitude of stress due to thermal load is between 0.4 kg/cm^2 to 123.5 kg/cm^2 . These stresses

are lower than the allowable displacement stress range (1961.6 kg/cm^2). The maximum stress due to the thermal load (123.5 kg/cm^2) is located in point L01 (Tee Branch No. BS136B) and has a blue contour. The highest stress ratio has a value of 6 % at the same location.

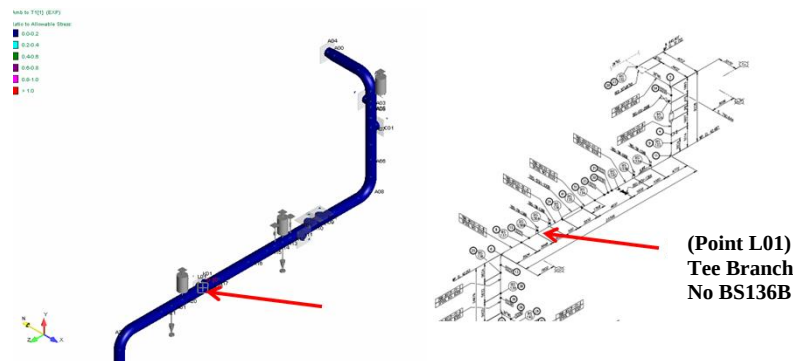


Figure 10. The contour of stress due to the thermal load of CRP BS-131 in operating condition

The magnitude of hoop stress is described in Figure 11. The magnitude of hoop stress is between 531.7 kg/cm^2 to 938.9 kg/cm^2 . These stresses are lower than the allowable hoop stress (1307.7 kg/cm^2). The

maximum hoop stress (938.9 kg/cm^2) is located in point A60 (Anchor point at Turbine No. BS150) and has a purple contour. The highest stress ratio has a value of 72 % at the same location.

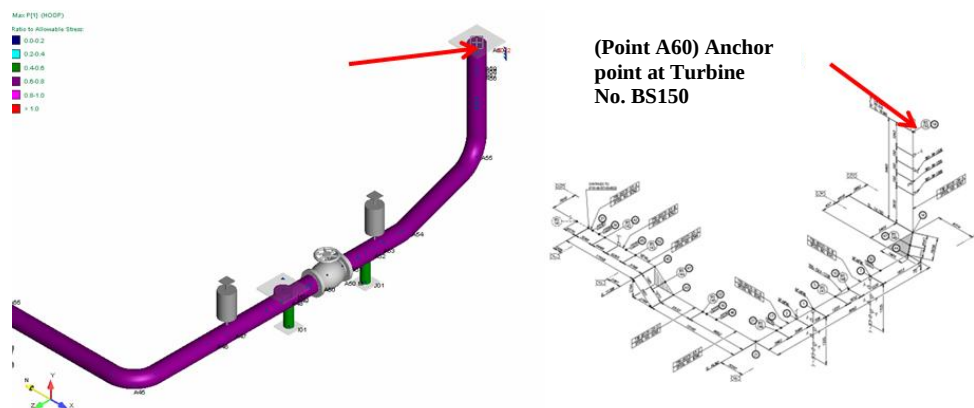


Figure 11. The Contour of hoop stress of CRP BS-131 in operating condition

C. Stress Analysis Resume

Stress characteristics of the CRP BS-130 piping system in operating conditions are shown in Figure 12. All types of stresses, stress due to sustained load, stress due to thermal load, and hoop stress lower their

allowable stress. The resume of maximum stresses of the CRP BS-130 piping system in operating condition is shown in Table 3.

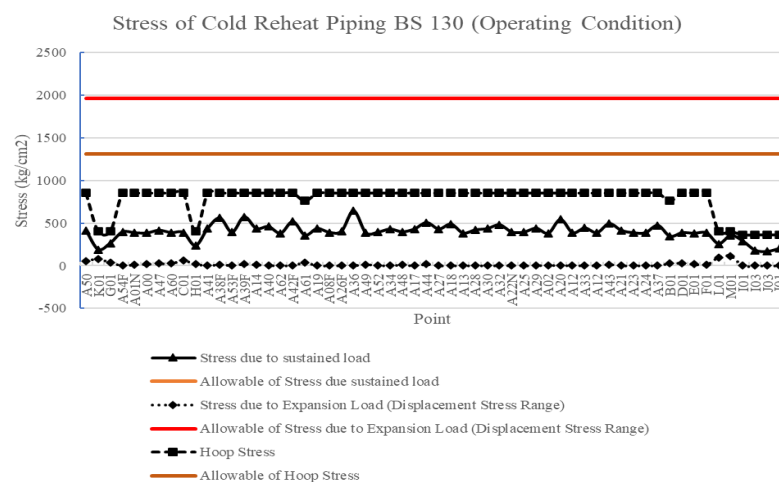


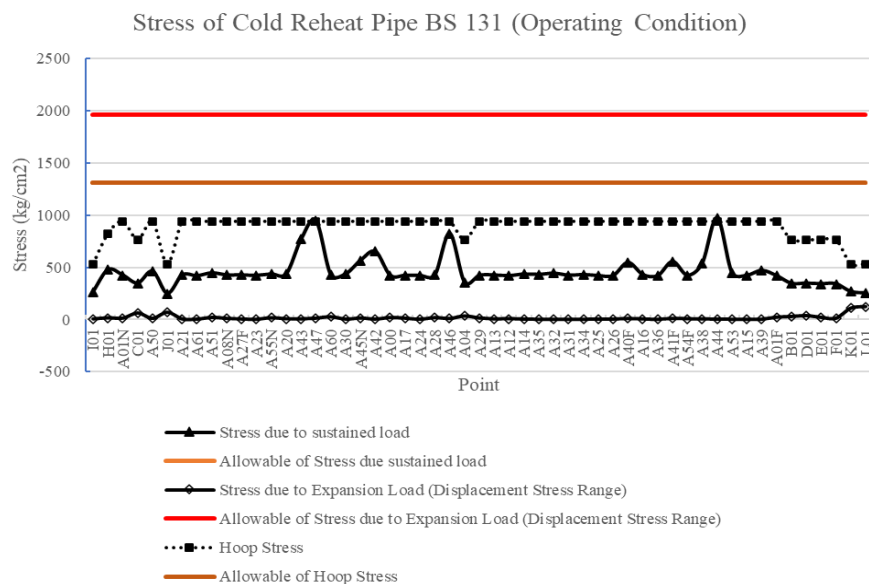
Figure 12. Stress distribution of CRP BS-130 in operating condition

TABLE 3.
RESUME OF CRP BS-130 STEAM LINE MAXIMUM STRESS IN OPERATING CONDITION

Load Case	Type of Stress	Point	Code Stress (kg/cm ²)	Allowable Stress (kg/cm ²)	Rasio (%)
GR + Max P	Max Stress due to Sustained load	A36	645.2	1307.7	49
T1 to T2	Max Stress due to Thermal Load	M01	112.8	1961.6	6
Max P	Max Hoop Stress	A36	855.6	1307.7	65

Stress characteristics of the CRP BS-130 piping system in operating conditions are shown in Figure 13. All types of stresses, stress due to sustained load, stress due to expansion thermal, and hoop stress lower their

allowable stress. The resume of maximum stresses of the CRP BS-130 piping system in operating condition is shown in Table 4.



- Structures, vol. 72, no. 102746, 2020, doi: <https://doi.org/10.1016/j.marstruc.2020.102746>.
- [4] Kumar Jha. A, and Kennedy. S, Kumar Jha. K, "Pipe Stress Analysis of Pump System in Process Plant," in *ICFTMM 2020*, IOP Publishing, 2021, pp. 1–8. doi: [doi:10.1088/1757-899X/1149/1/012004](https://doi.org/10.1088/1757-899X/1149/1/012004).
 - [5] Rani, M. J., Ramanathan, K., "Design and Analysis of Piping System with Supports Using CAESAR-II," *International Journal of Computer and Systems Engineering*, vol. 10, no. 5, pp. 980–984, 2016.
 - [6] Thakaran. V, "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 (IJARSCT)*, vol. 2, no. 1, pp. 675–684, 2022, doi: [10.48175/IJARSCT-7868D](https://doi.org/10.48175/IJARSCT-7868D).
 - [7] Ye. C, Nenghong. Z, Rui. Y, Fengbing. X, Tao. L, Renjie. H, Lijun. C, "Stress Analysis of Large Diameter Pipe Interface Structure of Boiler Main Steam Pipe," *Journal of Energy and Natural Resources*, vol. 12, no. 1, pp. 1–6, 2023, doi: [10.11648/j.jenr.20231201.11](https://doi.org/10.11648/j.jenr.20231201.11).
 - [8] Zhou, H.; Li, J.; Liu, J.; Yu, P.; Liu, X.; Fan, Z.; Hu, A.; He, Y, "Significant reduction in creep life of P91 steam pipe elbow caused by an aberrant microstructure after short-term service," *Scientific Report*, vol. 14, 2024.
 - [9] Wang. S, Shi. R, Wu. J, Yang. C, Liu. H, "Investigation on Optimization of Finite Element Model for Stress Analysis of 12Cr1MoV Main Steam Pipeline Elbow," *Crystals*, vol. 15, no. 3, pp. 1–17, doi: <https://doi.org/10.3390/cryst15030207>.
 - [10] Aswin, Hasnan. A, "Stress Analysis Evaluation And Pipe Support Type On High-Pressure And Temperature Steam Pipe," *International Journal of Mechanical Engineering Technologies & Applications*, vol. 4, no. 1, pp. 31–38, 2023, doi: <https://doi.org/10.21776/MECHTA.2023.004.01.4>.
 - [11] Rajath N. Rao, Maiya. M, Prabhu. S, Santhosh. G, Hebbar. G, "The analysis of a piping system for improvement of a system in a process unit," in *Materials Today: Proceedings*, in 7, vol. 46, 2021. doi: <https://doi.org/10.1016/j.matpr.2021.02.595>.
 - [12] Salifu S.Aa, Desai D.Aa, Kok Sb, Ogunbiyi O.F, "Thermo Mechanical Stress Simulation of Unconstrained Region of Straight X20 Steam Pipe," *2nd International Conference on Sustainable Materials Processing and Manufacturing*, vol. 35, pp. 1330–1336, 2019.
 - [13] M H A Ghaffar, S Husin, J E Baek, "Application of displacement monitoring system on high temperature steam pipe," in *IOP Conf. Series: Materials Science and Engineering*, in 012026, vol. 257, IOP Publishing, 2017, pp. 1–8. doi: [10.1088/1757-899X/257/1/012026](https://doi.org/10.1088/1757-899X/257/1/012026).
 - [14] Shinger Y.B, Thakur A.G, "Stress Analysis of Steam Piping System," *Journal of Applied Mechanical Engineering*, vol. 4, no. 2, 2015, doi: [10.4172/2168-9873.1000158](https://doi.org/10.4172/2168-9873.1000158).
 - [15] Komarudin. U, Philo. I, Nuraeni. N, Syifa Puspani. N, "Pipe Stress and Turbine Nozzle Load Analysis for HP Steam Inlet and MP Steam Extraction on Turbine Generator 51G201T Capacity 10MW," *International Journal of Engineering & Technology*, vol. 7, pp. 214–218, 2018.
 - [16] Aathresh. T. S, Kumar. V, Elmurugan. M, "Stress Analysis of Power Piping from Auxiliary Steam Piping to Air heater Soot Blowing," *International Journal of Pure and Applied Mathematics*, vol. 119, no. 2, pp. 15791–15800, 2018.
 - [17] Kurniawan. W, Rahmawaty. M, "Stress Analysis of High-Pressure Steam Header Manifold from Power Boiler to Distribution System Piping Using The Caesar II Software," *Jurnal IPTEK*, vol. 27, no. 2, pp. 113–120, 2023, doi: [10.31284/j.iptek.2023.v27i2.4652](https://doi.org/10.31284/j.iptek.2023.v27i2.4652).
 - [18] Afdhalul Ihsan. F, R. Sugeng Mulyono, "Analisis Tegangan Pipa Pada Jalur Steam System Menggunakan Perangkat Lunak Caesar II," in *Prosiding Seminar Nasional Teknik Mesin*, Politeknik Negeri Jakarta, 2021, pp. 730–736.
 - [19] Liu. X, Zhang. Y, Liu. Q, Sun. X, Wang. Y, Zhao. L, "Analysis of abnormal expansion of pipe system and optimization of structural stress in 350MW unit," in *ICEMEE*, 2021, pp. 1–6. doi: <https://doi.org/10.1051/e3sconf/202126102073>.
 - [20] Koorse, S., Roy, M., Janardhana, M., Seetharamu, S, "An overview of stress analysis of high-energy pipeline systems used in thermal power plants," *International Journal of Research in Engineering and Technology*, vol. 3, no. 3, pp. 538–542, 2014.
 - [21] Armansyah. R, Satrijo. D, Prahasto. T, "Desain Dan Analisis Tegangan Sistem Perpipaan Main Steam (Low Pressure) Pada Combined Cycle Power Plant," *Jurnal Teknik Mesin*, vol. 4, no. 2, pp. 187–196, 2016.
 - [22] Zainal Mahfud. M, Satrijo. D, Prahasto. T, "Desain Dan Analisis Tegangan Sistem Perpipaan Main Steam (High Pressure) Pada Combined Cycle Power Plant," *Jurnal Teknik Mesin*, vol. 4, no. 1, pp. 79–88, 2016.
 - [23] Grisolia. O; Scano. L, "Application Of Asme Piping Code Through A Stress Analysis Procedure And Comparison With The Italian Code," in *Proceedings of the ASME 2014 Pressure Vessels & Piping Conference*, ASME, 2014, pp. 1–14.
 - [24] ASME, *ASME B31.1 : Power Piping in ASME Code for Pressure Piping*, 2020.
 - [25] Buddhe N. V, Sopnur S. D, "Flexibility Analysis of Extraction Piping in Duplex Heater using CAESAR II," *International Journal of Innovative Science and Research Technology*, vol. 3, no. 6, 2018.
 - [26] Zahid. U; Sohaib Z. Khan; M. A. Khan; Hassan J. Bukhari; Ahmed. I; Kamran A. Khan, "A Methodology for Flexibility Analysis of Process Piping," in *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, in 6, vol. 232, pp. 751–761. doi: [10.1177/0954408917738963](https://doi.org/10.1177/0954408917738963).
 - [27] Les Skinner PE, "Hydraulic Rig Technology and Operations," in *Chapter 4 - Snubbing Theory and Calculations*, Gulf Drilling Guides, 2019, pp. 189–275. [Online]. Available: <https://doi.org/10.1016/B978-0-12-817352-7.00004-X>
 - [28] Bentley, *Hoop Stress Equation of ASME B31.1*. (2020). Bentley.
 - [29] Kim J.S, Jang J.H, Kim Y.J, "Efficient elastic stress analysis method for piping system with wallthinning and reinforcement," *Nuclear Engineering and Technology*, vol. 54, pp. 732–740, 2022.
 - [30] Hwang S.Y, Kim M.S, Lee J.H, "Thermal Stress Analysis of Process Piping System Installed on LNG Vessel Subject to Hull Design Loads," *Journal of Marine Science and Engineering*, vol. 8, no. 11, pp. 1–16, 2020.