ISSN 2581 – 3781

AJCSE
ASIAN JOURNAL OF COMPUTER SCIENCE ENGINEERING

Available Online at www.ajcse.info
Asian Journal of Computer Science Engineering 2025;10(4):1-8

REVIEW ARTICLE

Integrated Stress and Flexibility Analysis in Piping Design: A Cross-Platform Software Comparison

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Received on: 12-10-2025; Revised on: 18-11-2025; Accepted on: 05-12-2025

ABSTRACT

The growing sophistication of contemporary piping systems and the enlarged dependence on specialized analysis platforms point to the possibility of the research enhancements to the extent of higher accuracy, a test of flexibility, and cross-platform trustworthiness in piping design. The isolated software modeling was usually constrained and would result in conservative assumptions and design inefficiencies. This paper will carry out a comparative evaluation of the integrated stress and flexibility analysis techniques with reference to key software within piping industry. The work discusses the consideration of both the static and dynamic loading, the modeling of the boundary conditions, the materials and geometric effects, and such methods of analysis as finite-elements evaluation. The major engineering papers are analyzed to emphasize the development of heat transfer systems, automated pipeline design, vibration measurement, the use of unmanned aerial vehicle in inspection, the mechanism of cooling, and integrated energy systems. Detected gaps in the validation, interoperability, and scalability are critical as the accurate load-case simulation and code compliance are highlighted in the analysis. The total result of this work is a full comprehension of the existing methods and how they can be implemented to design piping system in a safer and more efficient manner.

Key words: Cross-platform comparison, flexibility evaluation, piping design software, piping stress analysis

INTRODUCTION

The current state of practice in the nuclear industry relies on specialized piping analysis software for piping stress analysis and establishing safety with respect to governing design codes and regulations.[1] The calculation of the margins of flexibility is a paramount necessity in design of a piping system to assure that the system has a protection against thermal effects and also its movability. This is a down-set of stress analysis whose aim is to ensure adherence to design codes, to establish the nozzle loads of a pressure vessel, to establish displacement associated with the thermal expansion, and estimating the support types and their locations during flexibility analysis,[2] the elongation capabilities of the pipe conduit and the elastic behavior of the same are specifically considered in order to ascertain that piping systems have sufficient flexibility that prevents stresses related failures or movements induced failures. The use of a specialized piping software[3] in isolation poses challenges to the highly collaborative environment needed among various experts during the design, construction, and maintenance of such systems. Each piping system is modeled and analyzed independently by itself.[4] Its connections to the attached equipment and buildings are considered as a boundary condition. Piping system design is crucial in process and power industries, analogous to the human circulatory system for a plant.

Piping system is the heart of any process plant. The performance of the plant depends on the pipe line sizing, equipment layout, and pipe routing with minimum possible pressure drop, considering all mechanical and operational safety.[5] Piping system comprises pipes, fittings like elbows, tees, reducers, sockets, half couplings, unions, flanges, and valves. These all are used to transfer the fluid from one point to another through straight pipes, changing the direction with most

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economical means – elbow, branching through tees, size variation through reducers or reducing tee at branches, connecting each other or to the instruments through flanges, union, sockets, half couplings, and on-off conditions or fluid control through different types of valves. Modeling each piping system by itself in isolation from attached equipment or buildings requires simplifications in the analysis methodology.[6] These simplifications lead to conservative assumptions, which then result in significant overdesign, and in some cases, incorrect interpretation of piping performance.

The goal of the software platform[7] is to integrate the data, methods, models, and technologies into a total system health management support tool to aid in decision-making and planning by the pipeline operators.[8] Pipe design mainly depends on stress analysis. The main objective of pipe stress engineer is to verify the routers, hangers and supports are placed correctly in the process plant, and the allowed pipe stress is not to exceed by various loads acting along the piping system specified by ASME B31 conditions and standards.[9] Mechanical behavior of pipes is strictly evaluated under various loading conditions. CAESAR II: Computer-Aided Engineering Stress Analysis and Routing is a complete software related to pipe stress analysis developed by INTEGRAPH corporation used to calculate and measure quick analysis of piping system that is bullied to weight, pressure, thermal, seismic and static and dynamic loading resulting from the effects of gravity, temperature changes, internal and external pressures, and changes in fluid conveyance flow rate and seismic activity.

Structure of the Paper

The paper structure is as follows: Section II describes piping stress analysis framework comparatively. Section III refers to the flexibility analysis and system behavior. In section IV, the most important elements of piping design are outlined. Section V contains the literature review. Section VI summarizes the research and points toward future research.

COMPARATIVE FRAMEWORK FOR PIPING STRESS ANALYSIS

Popular software in the subject of pipe engineering includes CAESAR II, AutoPIPE, and others. Engineers find it easy to enter data and create analytical models using a simple user interface. The program may do computations and processing automatically to make the procedure easier.

- CAESAR II: This enables fast and precise analysis of piping systems under various static and dynamic loads, including weight, pressure, heat, seismic, and others. Any size or complexity of the pipe system may be analyzed by it.
- AutoPIPE: It is a very general and effective software developed by Bentley Systems to analyze and design piping stress. The tool is geared toward enabling engineers and designers examine the impact of different loads and stresses in piping systems which are relevant in industries in oil and gas, power sector,[10] and petrochemicals, among others. AutoPIPE stands apart due to its rich features, ease of use, and compliance with standards.

Piping Stress and Analysis Techniques

PIPESTRESS is a program for performing linear elastic analysis of three-dimensional piping systems subject to a variety of loading conditions. The purpose of stress analysis and evaluation for piping is to prove that the piping will not fail in various working conditions. Stress analysis of piping includes static analysis and dynamic analysis. Static analysis typically includes pressure, sustained load, thermal expansion, and endpoint displacement.[11] Dynamic analysis is usually the accidental loads, and seismic analysis is an important part of the dynamic analysis. The use of Peps for nuclear piping stress analysis and evaluation is mainly in the following five steps: (1) Establish the geometric model and finite element model. (2) Apply boundary conditions. (3) Apply loads associated with each kind of condition. (4) Stress analysis. (5) Stress evaluation as shown in Figure 1.

i. Establish the geometric and finite element model: The initial step is to develop a true to life geometric model of the piping system and turn it into a finite element model.[12] His makes sure that the pipes, joints, supports, and all connections are defined to ensure that the stress is simulated in a reliable manner.
ii. Apply boundary conditions: The constraints and support conditions are then allocated to

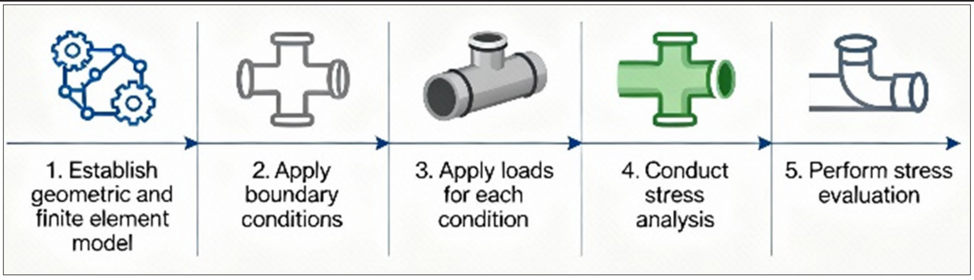

Figure 1: Piping stress evaluation

the model. These boundary conditions are a reflection of the way in which the piping is fixed, guided, or freely move about in real installations so that realistic behavior can be achieved through simulation.[13]

iii. Apply loads for each condition: All the applicable loads that include internal pressure, thermal expansion, sustained weight, displacement, and occasional loads are applied. These load cases describe the different operating, environmental, and accidental conditions that the piping can be exposed to.

iv. Conduct stress analysis: The program evaluates both the static and dynamic calculations to establish the behavior of the piping system to each load.[14] The step determines the location of stress, deformation, and possible critical areas of the structure.

v. Perform stress evaluation: Lastly, computed stresses are contrasted with permissible levels which are set in relevant design codes. This testing is done to make sure that the piping system is safe, reliable, and compliant with all anticipated operating conditions.

Critical Parameters Influencing Piping Flexibility and Structural Integrity

Stress evaluation will feature prominently in flexibility analysis as it can be wise both together and separately to include static and dynamic loads and more like self-weight, pressure, and temperature. Displacement factors take into account movements of the part due to thermal[15] expansion or contraction to include operational movements and ensure that failure does not occur due to excessive deformation. Loads constitute operating loads, sustained loads, and expansion loads, each of which has its own impact on design, safety, and performance of the system.

i. Material and geometric factors: The numerical model is enhanced with pipe elements, having the geometric and material characteristics of the pipeline under consideration, connected to the shell elements, extending the pipeline to the desired length, whereas nonlinear springs are distributed in the axial direction along the pipe elements.[16] One should note that pipeline design has been based traditionally on the ‘‘allowable stress’’ concept, for normal operating conditions; in that design procedure, hoop stress is the primary design parameter, which is limited by the allowable stress of the pipeline material, specified as a percent of yield stress

ii. Loads, supports, and stress effects: All piping systems experience two types of loads such as force-based loads and strain-based loads. The force-based loads arise from factors such as internal pressure, components weight, and fluids flowing through the system. On the other hand, strain-based loads originate from thermal fluctuations, seismic forces, and machinery-induced forces (uneven forces resulting from operating equipment).[17] These combined loads (forced and strain-based loads) play a crucial role in the design and analysis of piping systems ensuring safe and efficient operation of the piping system.

FLEXIBILITY ANALYSIS AND SYSTEM BEHAVIOR

Flexibility analysis is concerned with the ability of pipe to change its length and deform elastically. Commercial programs designed for flexibility analysis were too complex and time consuming. Due to this underlying issue, a simplified flexibility analysis program based on stiffness method was developed which could also be used to accurately evaluate the flexibility of piping components such as elbows.[18] Piping system must be flexible enough to cater for excessive thermal expansion or movement of support or pipe end points, thus preventing failure of pipe and support structure due to excessive stress. The considerations deciding the minimum permissible flexibility in a piping system are as follows:

1. Displacements existing within the piping system.
2. Maximum allowable limit of stress range in the system.
3. Maximum allowable forces and moments that the piping system can impose on the connected equipment.
4. Maximum allowable load that can be applied on the supporting structure.

Analytical Approaches Used in Modern Piping Design

The design of modern piping is based on the analytical method that involves a combination of classical mechanics, computational methods, and code assessment techniques that will provide mitigation assurance on structural stability and operational safety. Such methods involve flexibility examination and load testing, as well as identification of load cases as per the recommendations of ASME B31.1 and B31.3. The dynamics of piping behavior in response to the effects of internal pressure, thermal expansion, sustained loads, vibration, and seismic forces are evaluated using analytical models.[19] One of the areas where there is an increased use of finite element analytical techniques is the definition of complex interactions at bends, nozzles, and support locations with greater accuracy than in the traditional hand-calculations. These analytical principles are combined in modern tools such as CAESAR II,[20] ANSYS, and PIPESTRESS to simulate a real-life situation, the concentration of stress, and adherence to allowable values. Analytical approaches have established the basis of safe, reliable, and optimized design of piping systems in power industry, petrochemicals, nuclear, and process industries and other industries, combining theoretical formulations with computational efficiency.

Load Cases in Modern Piping Design

To verify the accuracy of different FE models in this work, some relevant structural behavior analyses of the flexible pipes are done through ABAQUS software package[21] and the numerical simulation results.[22] Sustained loads are those loads which are caused by mechanical forces and these loads are present throughout the normal operation of the piping system. These loads include both weight and pressure loadings. The support must be capable of holding the entire weight of the system, including that of that of the pipe, insulation, fluid components, and the support themselves.

COMPONENTS OF PIPING DESIGN

Pipes, supports, valves, expansion joints, anchors, reducers, and flanges are all considered in the model (as shown in Figure 2). Butterfly valves, globe valves, and check valves are modeled by the valve element (which is supported by finite element) with properties such as valve type and connection type.[23] The pressure class of the valve was determined according to the ASME B16.354 standard grade. Since the piping stress depends on the position and number of supports and the suitability of expansion joints, the final objective of this study is to analyze the effect of the supports and expansion joints on stress.

FRF of the Piping System

After attaching the NDVA to the piping system, the FRF of the coupling system is influenced by the impedance characteristics of the NDVA. We select one of the layers of the resonant units for analysis, and the process for the other layers is similar. Figure 3 presents the discrete model of the resonant unit, illustrating its two states when arranged vertically and obliquely. A global coordinate system x-o-y and a local coordinate system o- are defined[24]; m_n represents the mass of the n-th vertical resonant unit, k_x and k_γ represent the spring stiffness in the x and y directions, and c_x and c_γ represent the damping coefficients in these directions. All resonant units are assumed to have the same damping ratio. θ denotes the rotation angle. Under oblique placement of the resonant unit, mass, spring stiffness, and damping coefficients do not change; however, the point of analysis moves to the local frame, instead of the global frame. The oblique resonant unit in this state has a bending mode that is a x direction and tensile mode that is a y direction.

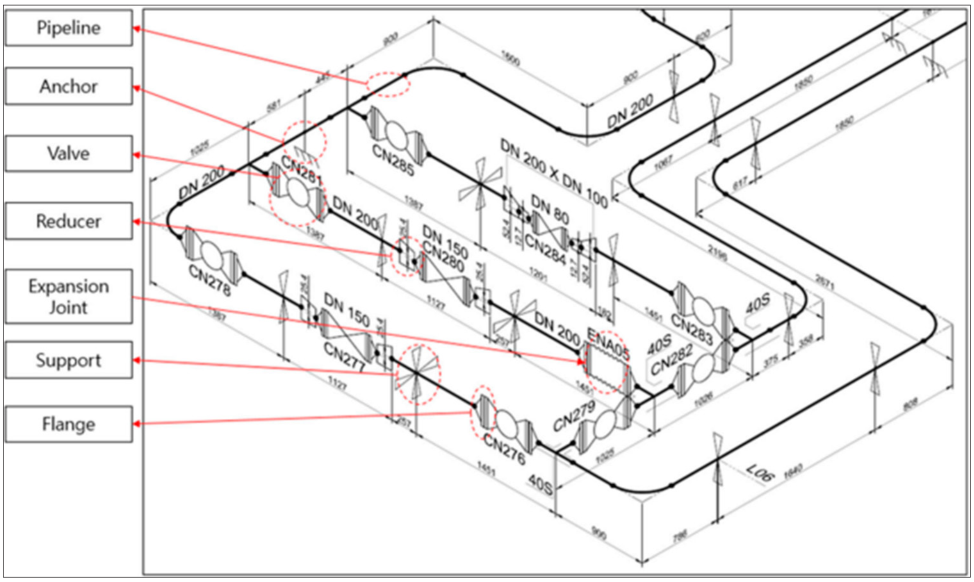

Figure 2: International organization for standardization drawing of main liquid pipeline

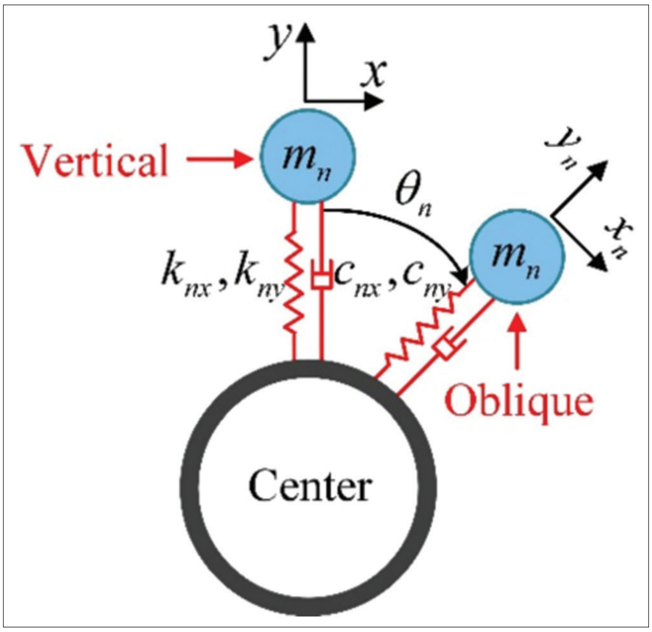

Figure 3: Discrete model of the resonant unit

Valves in Piping Design

Valves are important parts of piping system and they are categorized according to their purpose as blocking, regulating, and control valves. The design must also have minimal or no use of valves because they are expensive and cause excessive loss of pressure. They should be easily accessible for operation and maintenance. Blocking valves are recommended at the boundaries of each process unit, while check valves should be placed close to the equipment's interconnection with the lines.[25] In the case of control valves, blocking valves and a bypass line with a regulating valve must be installed so that the flow can be maintained on the other side of the repair. The stems on the valves also should not be down-facing to prevent piling of debris in the valve bonnet. The stems in pump suction lines would be better horizontal or inclined, to prevent the presence of air pockets.

LITERATURE REVIEW

The latest research demonstrates the evident advancement in the piping design, enhancement of thermal performance, computerized layout, precision of vibration, and inspection techniques. Nevertheless, their practical impact is still limited due to inadequate real-world validation and sensor limitations as well as scalability.

Lao *et al.*, have shown that a reduction in the heat flux of up to 20–40% of the heat in lunar conditions occurs with a poor fluid return as a result of low gravitational forces. The proposed LHP incorporates a miniature pump and sintered nickel wick and uses benzene (density 876 kg/m^3, latent heat 433 kJ/kg) as the working fluid to obtain a thermal efficiency of 90–95%. Matlab R2024b simulations have a system level net power output (Wnet) of 94102 kW, which is close to the target of 10125 kW and a specific power (SP) of 21.08 W/kg. In comparison to the conventional heat pipes, the LHP improves the single-tube Wnet by 25.5% and provides remarkable advantages in thermal management of lunar bases and sustainable energy provision in harsh environment.[26]

Liu *et al.* aimed to achieve the automatic design of long-distance water transmission steel pipes through the development of a system using

Table 1: Summary of key studies on piping design, heat pipes, cooling, and inspection technologies

Author (year)	Key findings	Methods/approach	Challenges addressed	Limitations/gaps
Lao *et al*. (2025)	Traditional heat pipes lose 20–40% heat flux in lunar environments; proposed LHP with sintered nickel wick and pump achieves 90–95% efficiency and increases Wnet by 25.5%.	MATLAB R2024b simulations; design of lunar loop heat pipe with benzene as working fluid.	Low heat flux performance in reduced gravity; inefficient fluid return.	Limited real-environment testing; lunar validation required.
Liu *et al*. (2024)	Developed an automatic design system for long-distance steel water transmission pipelines with three functional modules.	AutoLISP-based automated design framework applied to Tianxingba Water Diversion Project.	Time-consuming manual pipeline design; calculation accuracy.	System applicability limited to similar pipeline projects; needs broader validation.
Haris *et al*. (2024)	Insulation thickness significantly affects piping vibration measurement accuracy; loose insulation causes highest amplitude deviation.	Experimental vibration measurements using portable diagnostic tools under varying insulation conditions.	Measurement inaccuracy caused by insulation variability.	Findings depend on specific frequencies and insulation types; limited generalization.
Roos-Hoefgeest *et al*. (2023)	UAV visual inspection system enables autonomous center-line tracking of elevated refinery pipes and identifies defects.	UAV with depth sensor for navigation and defect highlighting in pipe racks.	Safety risks & high costs of manual high-altitude inspection.	Technology accuracy depends on sensor limitations and environmental conditions.
Chai *et al*. (2022)	Designed high-torque PMSM and verified superior cooling performance of heat-pipe-assisted cooling over natural cooling.	Electromagnetic design of PMSM and heat-dissipation comparison experiments.	Motor overheating in high-power applications.	Study focuses on a specific PMSM design; scalability not assessed.
Li and Chengpeng (2022)	Developed integrated solar PV–photothermal building system using micro heat pipe arrays and optimized energy management for Tibet.	System modeling, cogeneration unit design, optimization strategies, microgrid control framework.	Energy efficiency, renewable integration under harsh climatic conditions.	Requires implementation-scale testing; geographical limitation to Tibet.

UAV: Unmanned aerial vehicle

AutoLISP programming language. The Tianxingba Reservoir Water Diversion Project is taken as an example for case study. The automatic design system for long-distance water transmission steel pipes described in this paper comprises three core modules: Pipeline horizontal and vertical optimization and hydraulic calculation module, steel pipe structure calculation module, and engineering quantity calculation module.[27]

Haris *et al*., aimed to examine the results of varying insulation thickness on the precision of measuring piping vibration with portable diagnostic instrument. The findings show that the amplitude of measurement increases with increasing insulation thickness. Loose insulation is found to give higher amplitude deviation compared to a good insulation condition. This tendency is more evident at 100 Hz, the highest amplitudes were recorded. Overall, the study emphasizes the importance of considering insulation thickness and condition when taking vibration measurement on piping systems.[28]

Roos-Hoefgeest *et al*., have shown that a particular case is represented by the inspection of oil and gas refinery facilities consisting of different long pipe racks to be inspected repeatedly. This task is costly in terms of human safety and operation costs due to the high altitude location in which the pipes are placed. In this domain, Roos-Hoefgeest *et al*. also proposed a visual inspection system for unmanned aerial vehicles, enabling autonomous tracking and navigation along the centerline of industrial pipes. The proposed approach exploits a depth sensor to generate the control data for the aerial platform and, at the same time, highlight possible pipe defects.[29]

Chai *et al*., have designed a high torque density permanent magnet synchronous motor (PMSM). The cooling form of PMSM that heat pipe inserted into the stator slot is first determined. Based on this, the electromagnetic design scheme of the motor is designed. In addition, the high heat dissipation capacity of the heat pipe is verified according to comparing the cooling effects of two methods: Natural cooling and heat pipe cooling.[30]

Li and Chengpeng (2022) integrated system model of solar photovoltaic photothermal building, build the photovoltaic cell module based on micro heat pipe array, design the integrated solar cogeneration unit, optimize the system energy control and operation management scheduling scheme, and establish the system microgrid monitoring and control system to provide technical support for the integration of solar energy and building in Tibet, On the basis of energy conservation and emission reduction.[31]

Table 1 provides a brief comparison of significant engineering research, summarizing its most important findings, the performance, tasks, obstacles to overcome, and a list of current limitations. It offers an accurate account of the recent developments and the loopholes that remain to be resolved.

CONCLUSION AND FUTURE WORK

The development of piping stress and flexibility analysis has been motivated by the fact that the engineering in industrial systems requires safer, more efficient, and more integrated engineering practices. With more and more complicated loading environments with thermal, mechanical, seismic, and operational effects on piping networks, the precision of the analysis tools becomes a necessity to the structural integrity and long-term reliability of the piping network. This paper will make a comprehensive comparison of the key software platforms and methods of analysis, to identify how well they meet some of the design requirements of the real world. The results emphasize the fact that the contemporary tools, namely, CAESAR II, AutoPIPE, PIPESTRESS, and finite-element models, are well-established in terms of their analytical strengths, but not effective in cases when the systems are modeled separately or without detailed boundary interactions. The literature survey has shown that considerable progress has been made in the field of thermal systems, inspection systems, vibration diagnostics, and automatic pipeline design, but there has been a persistent problem in terms of validation, interoperability, and the management of variability in the real environment.

Future studies need to concentrate on improving interoperability across software platforms that allow unified modeling environments that minimize design inconsistencies. The thermal, dynamic, and vibration-related simulations could use more experimental validation in realistic operating conditions to be more accurate. The use of AI-assisted inspection, digital twins, and automated stress-evaluation tools may take the design reliability even further.

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