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A Comparative Study of Piping Stress Analysis Methods with Different Tools, Techniques, and Best Practices

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Abstract*: Piping stress analysis could be an important step in the engineering design sequence. It is also often referred to as the stress analysis for piping systems which finds extensive application in the chemical, electricity, and oil and gas sectors, among others. This review paper aims to provide an extensive overview of numerous methodologies worked out for pipe stress analysis, together with the applicable tools and best practices. The article tries to develop the primary ideas in the stress analysis including the stress types and the applicable standard controls on its evaluation. Piping stress analysis is commonly found on the CAESAR II and other applications such as AutoPIPE and ROHR2, discussing the software features, the accuracy of results and the shortcomings of the programs. A thorough review of the relevant literature highlights gaps in existing knowledge and makes it clear – again – why sensitivity analysis is so important, in particular about static and dynamic analysis. The conclusions are meant to assist engineers and researchers in choosing appropriate tools and ways of performing seamless and dependable piping stress analysis.*

Keywords: Piping Stress Analysis, Stress Analysis Tools, CAESAR II, AutoPIPE, Dynamic Stress Analysis, Static Stress Analysis, FEA

I. INTRODUCTION

One engineering study called pipe stress analysis calculates how much stress a piping system is under due to forces and moments acting on it. The study includes determining the kind of loading, the kind of pipe material, and the internal and external factors that may affect the intended and projected system. The analysis may then find possible issues or weak places in the system and ensure the pipes can support the loads. Though it may also be used to assess the safety and dependability of existing systems, this kind of analysis is usually employed in designing new pipe systems [1].

Piping systems are found in almost every processing sector, including oil and gas, chemical, power plants, and manufacturing industries. The piping system becomes technologically advanced but has to endure a set of mechanical forces such as pressure, thermal expansion, vibration and seismic loads, and a range of temperatures [2]. All these forces, if exceed the permissible limits, can affect the performance of these systems. To address this issue, piping stress analysis identifies such stresses allowing the failure in the piping systems to be avoided and to design systems that comply with relevant standards and safety considerations. The engineering design process has become more reliable and accurate through the availability of various softwares and tools. Many software's combine graphic representation with automated stress calculations but vary on the scope of applications. Therefore, CAESAR II, AutoPIPE and ROHR2 are popular for Piping Stress Analysis and the engineering analysis models geometry and internal apparatuses [3].

The matrix method of structural analysis was first applied in the force, moments, and displacements at the ends of pipeline systems to solve problems in the 1950s. Liang-Chuan Peng, a structural engineer, issued Pipe Stress Engineering in 2009, and the method for analyzing pipeline stress was enhanced. This however is currently possible with the help of software such as the CAESAR II and the ANSYS where stress analysis of pipelines using the finite element approach is possible. First, to lay a framework for the future work of pipeline design in engineering practices, the relationship between stress and several factors including the length and angle of the inclined pipe, buttress interval,

seismic force and stress mitigation measures were addressed[4].
Design specifications, materials, components, supports, manufacturing, testing, and inspection are all pipe components. The majority of operations in a process industry take place at pressures and temperatures that deviate from typical air conditions. Despite continuous or intermediately hard conditions that their design structure must withstand, the mechanical designer must ensure that the structure will provide adequate safety for a fair amount of time and not fail[5]. One of the main prerequisites for installing the plant is this pipe system. Providing safe design is the aim of pipe stress analysis and quantification. There are several potentially safe designs.

A. Structure of the paper

The structure of the paper is as follows: Section II discusses the basics of pipe stress analysis. Section III covers tools and approaches in full. Section IV discusses best practices and techniques. Section V includes a review of the literature. Section VI offers ideas for conclusions and future research.

II. FUNDAMENTALS OF PIPING STRESS ANALYSIS

The phrase "piping stress analysis" (PSA) refers to computations that deal with static and dynamic loads brought on by gravitation, temperature differences, internal and external pressure, changes in flow velocity and earth shocks. Codes and standards set the minimal norms for stress analysis. The stress analysis carried out during the engineering design of the pipe system determines whether or not it fails.

A. Objectives of Piping Stress Analysis

The objectives of Piping Stress Analysis are centered around ensuring the safety, reliability, and optimal performance of a piping system. Here are the key objectives:

At every important point in the pipe system, the forces, moments, and stresses are estimated, as is their impact on thermal expansion.

Calculations for flexibility analysis are performed when pipes are exposed to controlled thermal expansion or contraction.

To prevent leaks and vibrations.

To guarantee that the pipeline's stresses are within acceptable bounds in cold and hot climates.

To verify that the pipe setup is safe to operate from a design perspective (temperature and pressure)

should adhere to the relevant codes (IBR, ASME, etc.)

The weight of the content and thermal insulation should be used to ensure the pipe is properly supported and does not droop or distort under its weight.

To guarantee that surrounding pipes, structures, and components are not interfered with by deflections when heat and other loads are applied[6].

B. Classification of Piping Loads and Piping Stress

The loads and stresses in a piping system are classified into different categories based on their origin, nature, and effects. Understanding these classifications helps in systematically analyzing and addressing the forces acting on a piping system. Piping loads can be classified into two categories, whereas the three categories of piping strains are as follows:

1. Classification of Piping Loads:

We explain the main piping load for this piping stress analysis:

- **Primary Loads:** Primary load includes internal fluid pressure, outside pressure, force of gravity on pipe and contained fluid, and relief or blowdown pressure and hydraulic surge due to water hammer effect are considered as steady state or cyclic loads. Primary loads result from forces on the pipe that cause shear and normal stresses, such as compression, torsion, and tension. Primary stress limits are meant to stop plastic from bursting and deforming.
- **Secondary Loads:** In essence, expansion is the cause of secondary loads. They are the result of some sort of

displacement. Once exposed to a temperature greater or lower than the one at which it was built, a pipe may expand or contract differently. It is not always the case that the secondary loads are cyclic[7].

2. Classification of Piping Stress:

We explain the main three piping stresses for this piping stress analysis.

- Primary stresses are produced by mechanical loads that are applied. Stresses like this do not go away by themselves. Burst and plastic deformation are failure modes.
- Secondary stresses, such thermal expansion, are created when the system is constrained against movement. The system can deform to release these stresses, which are self-limiting. Buckling and plastic instability are the failure mechanisms.
- Peak stresses are created locally and usually do not cause system disturbance. Stress concentrations lead to the formation of peak stresses. Fatigue failure due to cyclic loading is the mode of failure [7].

C. Regulatory Standards Compliance

To meet safe industrial designs, laying down standards and code requirements is crucial in any piping stress analysis. Key regulatory frameworks include:

- **ASME B31 Series:** of codes of documents or standards include the following; ASME B31.1 Power Piping and ASME B31.3 Process Piping They include matters such as, stress limits for pressure piping and practices in pressure piping design.
- **ISO 14692:** Recommended practice for glass-reinforced plastic (GRP) piping systems.
- API 610: Corrosive and erosive applications regarding centrifugal pumps and their communication with pipe structures.
- **PED (Pressure Equipment Directive):** Concerns with the design and installation of pressure equipment within the European region. Compliance with these standards ensures that piping system designs incorporate the operating stresses and safety environmental norms [8].

III. METHODS OF TOOLS AND TECHNIQUES

Piping stress analysis relies on advanced tools and techniques to evaluate piping systems' performance, safety, and reliability under various operating conditions. These tools help identify stress concentrations, manage loads, and ensure compliance with industry codes and standards. Below is an overview of commonly used tools and techniques.

A. Piping Stress Analysis Tools

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. These two types of software are both available at professional institutions, which results in some cost consumption. It is necessary to use general Finite Element software to design a specialized platform [9].

1. CAESAR II

A comprehensive software application for pipe stress analysis, CAESAR II 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. Unlike other programs, CAESAR II incorporates analytical choices and calculating methodologies.

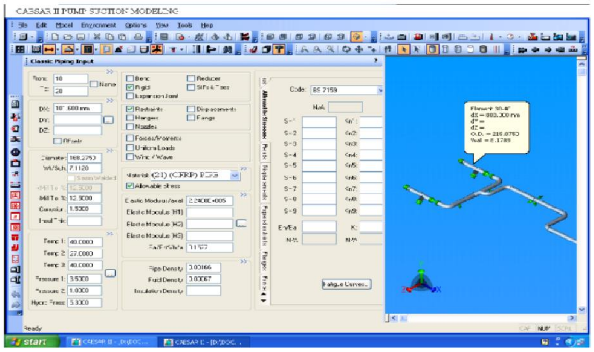

Fig. 1.CAESAR II Tool

- **Data Input:** All the basic data necessary to precisely formulate a Pipe system analysis model is easily incorporated & displayed by CAESAR II[10]. One can retrieve or modify the input on an element-by-element basis, or one can select datasets for across-the-board change.
- **Cutting-edge Graphics:** In addition to quickly creating analytical models, the CAESAR II input graphics module identifies problem areas and gives a great picture of the flexibility of the pipe system.
- **Design Tools and Wizards:** Tools and wizards that facilitate tasks like seeing plant models in the analysis space or generating expansion loops aid in bridging the knowledge and experience gap. These technologies eliminate the need for guesswork to produce precise analysis and suggest useful design modifications.
- **Analysis Options:** Besides pressure, dead weight and heat load effects on a pipe system, CAESAR II also looks into the effects of lateral loads such as wind loads, settling supports and seismic and wave loads respectively.
- **Error Checking and Reports:** CAESAR II has an integrated error checker that forms part of the software. This error checker looks at user input to determine if it is consistent when viewed from the finite element
- **Material and Assemblies Databases:** In addition to expansion joints, structural steel sections, spring hangers, and pipe materials and components properties, such as allowed stress.
- **Bi-directional Interface with Design:** The first and only bi-directional, real-time link between CAD plant design and engineering analysis is integrated into CAESAR II[11].

2. AutoPIPE

AutoPIPE is a very general and effective software developed by Bentley Systems to analyze and design piping stress. The tool is geared towards enabling engineers and designers examine the impact of different loads and stresses in piping systems which is relevant in industries in oil and gas, power sector, petrochemicals amongst others. AutoPIPE stands apart because of its rich features, ease of use and compliance with standards.

- **Load Analysis:** Allows for supporting the analysis of several types of loads such as thermal expansion load, pressure load, weight load, seismic load, wind load, and others, including dynamic loads such as water hammer or vibrations load. Compliance with Codes and Standards: AutoPIPE also contains the check against codes like the ASME B31 for pipes, ISO, API, and EN standards.
- **Advanced Modeling Capabilities:** Provides accurate pipe work modeling of numerous components such as bends, tees, valves, flanges, and supports. Integration of possible composable add-ins such as STAAD Pro and Open Plant that facilitate transdisciplinary operations.
- **Dynamic Analysis:** They offer sound tools for conduct dynamic load assessment, including time history assessment, harmonic assessment, and operational assessment, to assess the response of the piping system to transient loads and cyclic loads.
- **Stress and Flexibility Analysis:** Determine locations under pressure stress and develop flexibility to avoid failures by expansion or other forces like displacements.

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- **Visualization and Reporting:** Composited with 3D base visualization of piping systems; stress contour and load distribution for further vision. Provides elaborate, hastily customizable report writing for documentation and compliance checks.
- **Integration with Digital Twins:** AutoPIPE has digital twin technology compatibility to bring design models to real-time monitoring and predictive maintenance [12].

3. ANSYS

ANSYS Inc. develops ANSYS, ANSYS stands as a notable simulation software suite for purposes spanning that of piping stress analysis, yet, it is more widely regarded for its advanced engineering analysis tools designed to meet the needs of different engineering fields. ANSYS is arguably more popular in the aerospace, energy, automotive, and manufacturing sectors, and that is for good reason as the software is both precise and elegant, allowing its users to solve intricate challenges [13].

- **Detailed Finite Element Analysis (FEA):** Utilizing FEA, ANSYS can greatly reproduce the performance of a piping system under varying loading conditions and Contains efficient informative solvers to effectively compute stresses, deformations and failure in pipes.
- **Static and Dynamic Load Analysis:** includes an examination of both static and dynamic loads, including flow inside the structures, seismic loading, temperature fluctuations, pressure, and fluid weight. Also includes dynamic elements, for instance, the water hammer effect and vibrations.
- **Multiphysics Advanced Simulations:** Combines thermal, structural and fluid flow simulations to the complexity existing in the piping networks[14]. Emulates heat distribution and thermal expansion/contraction stresses where the temperatures change [15].
- **Compliance with Standards:** Assures that the design passes the international codes of practice such as ASME B31, ISO and API thereby providing the regulatory-compliant designs.
- **Material Library:** Provides material parameters and options for the simulations of nonlinear material, creep and fatigue in a broad range of materials .
- **3D Modeling and CAD:** Three-dimensional modeling of piping structures that can be integrated with the main CAD software for import and export purposes. Allows the representation of stress, shape change and fluid flow [16]

B. Key Techniques in Piping Stress Analysis

Several methods are used in pipe stress analysis to ensure the system operates dependably and safely under various loading scenarios. Each technique addresses specific aspects of the system's structural integrity and operational performance. Below is an explanation of the key techniques.

1. Finite Element Analysis (FEA):

FEA, otherwise known as Finite Element Analysis, involves dissecting a system into sub-sections to ease calculations, particularly with stress, deformation, and strain in mind for the aspects of the system that would be put under load. This method is highly suited for loads applied to irregular shapes, elevated temperatures on the printed structures and analyzing critical elements such as the nozzles and flanges. FEA is accurate and provides many details and insights into the nature of failures, allowing engineers to better the design and create safer structures.

- **Advantages:** A high degree of accuracy in analysis of stress and strain is achieved.The tool is applicable in complex geometry and multi-material systems. o Thermal stress, creep, and fatigue are some advanced analyses allowed.
- **Limitations:** The tool is demanding and significantly impacts the computational power available.Because of the geometry involved, it is a lengthy process for large systems. o It is considered a specialist’s tool, hence modeling and analysis of results require a specialist [17].

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2. Dynamic Analysis:

Dynamic analysis inspects the behavior of piping systems subjected to nonlinear forces such as seismic waves, vibrations, and pressure gradients. Response spectrum analysis, time history analysis, and modal analysis. In this simulation ensures the piping network's structural integrity at dynamic conditions thus reducing the chances of resonance, fatigue or complete failure of the pipe network.

- **Advantages:** Crucial for survivability in an earthquake and high-vibration cases.Points out the weak spots that could fail when rested on a time dependent load.Demands the principle working with both linear and nonlinear systems.
- **Limitations:** Setting up of such a dynamic simulation could be relatively more complex.Great reliance on the precision of input data (for instance, seismic spectra or transient load profiles).Software and in-depth information related to the subject may be necessary for analysis[18].

3. Fluid-Structure Interaction (FSI) Analysis:

Fluid-structure interaction analysis researches the influence of fluctuating fluid density on structures. Fluid forces especially in the presence of internal forces caused by fluid such as vibrations, hydraulic hammer, slug flows, etc. Considering CFD and structural analysis together, FSI offers a complete picture of the problem in which a fluid flows across a pipe system.

- **Advantages:** Integrates fluid and structural dynamics for better understanding.Critical for operating systems with high pressure, multiphase or turbulent flow. o Reduces the risks of flow-induced vibrations and dynamic instabilities.
- **Limitations:** Quite expensive because of the combined fluid and structural models. o Greatly affected by the definitions of the boundary conditions and the mesh quality.Demands a high level with ANSYS Fluent, COMSOL Multiphysics and highly trained staff [19].

4. Analysis of Stress Using Computer Based System

The analysis of computer assisted piping begins with the application of the use of special aids such as CAESAR II, Auto PIPE and ROHR2 for better stress analysis. By integrating code compliance and number of quick simulations these utilities help in design considerably. It also increases the precision and speed of piping evaluations by removing repetitive calculations in piping analysis.

- **Advantages:** Eliminates the need for manually processing exhaustive calculations which in turn, saves time. Provides means of compliance with industry codes for example, AMSE, EN standards. Intuitive graphic options and suitable tools for generating reports - graphical outputs.
- **Limitations:** There is at most times low versatility for particular or special designed systems. There could be an overdependence to the default settings that could distort intended accuracy of the computations. Overreliance on specific computer programs will need lots of money[20].

IV. BEST PRACTICES OF COMPARATIVE PIPING STRESS ANALYSIS

- **Amassing Sufficient Information:** This approach reduces the chances of making errors during the simulation since a proper analysis requires data such as pipe dimensions, connectors, material, work conditions, and the environment to be included.
- **Observing Standards and Codes:** It is imperative to always observe the applicable standards of practice, such as the ASME B31, ISO 14692, or the API codes, for safety and regulatory purposes. Knowing these codes helps the engineers in making sound design choices.
- **Reasonable Representation of Loads:** Proper identification and accounting of thermal, pressure, weight, wind, seismic and transient loads should be made. Not recognizing critical load conditions can bring about misleading results and might cripple the system[21].

- **Application of Simple Models Where Necessary:** High accuracy is possible with detailed models, but they can be too much in terms of computer time and possibly lead to too many errors. Maintenance of the thoroughness of the task by simplifying models with the critical accuracy requirements makes it efficient.
- **Validation of Input Data and Results:** All input data should be reverified with the real world, hand calculations, or different software tools, which is also the case for results. This is useful in locating errors and guaranteeing proper output.
- **Integration with Design Tools:** Choose programs that allow easy integration like CAESAR II or AutoPIPE, enabling the design and analysis teams to work smoothly. Bi-directional data exchange diminishes data mismatch chances and consumes less time [22].
- **Dynamic Analysis for Complex Systems:** For the systems that may be subjected to changing physical conditions like earthquakes or dynamic pressures due to rapid changes in flow, dynamic analysis should be performed.
- **Optimization of Support Systems:** Utilize modeling techniques to effectively place supports in the beam to decrease stresses and displacements. Good support placement prevents unnecessary loads and ensures the system will settle properly in the long term.
- **Regular Training and Skill Development:** Allocate budget for training programs for engineers, in order to keep up to date with the newest tools, technologies, and standards. Advancing knowledge of such options within software as ANSYS, Auto PIPE, and CAESAR II increases quality and speed of analyses [23].

V. LITERATURE REVIEW

This section discusses previous research on Comparative Study of Piping Stress Analysis Methods with different Tools, Techniques, and Best Practices.

In this study, Gengadevi (2020) in order to ensure that the piping is not carrying its dead weight and the deflection during the thermal loading is minimal, it becomes mandatory to analyze the stresses and elemental force in pipes. The design is then optimised for pipe thickness reduction by comparing the outcomes of the two approaches. Stress analysis defines the forces exerted on the piping system's pipe, anchorages, and other support points or bounds. The stress created within the pipe has to be measured against other allowable stress. Following analysis of the findings, supports or other design changes are made to the pipe to lessen stress. For the first time, the stresses examined by CAESAR II and FEM are compared [24].

In this study, Bisht and Jahan (2014) will present the general scope and perspective of pipe stress analysis at a simple level. They should be suitable for students with different abilities and experiences. Design requirements are met, and the program is set up to provide students a thorough grasp of the technical concepts underlying material selection, coding criteria application, and the features and tools included in stress analysis software. Stress analysis is an essential part of pipe design that allows for the early inspection and correction of crucial factors including piping safety, the safety of associated components and linked equipment, and piping deflection. By keeping piping stresses within acceptable bounds, pipe stress analysis helps to prevent early failure of pipes and piping components [11].

In this study, Verma *et al.* (2018) provides information on the FWHCS approach, findings, and pipe stress analysis. For the many ITER operating states intended for TBMs, the pipe stress analysis is performed for sustained and sporadic loads simultaneously. Pipework for FWHCS. As per ASME B31.3, the pipe stress study is carried out. The chosen pipe supports, their placement, and the validation of the embedded plate loading requirements all depend on the acquired reaction and moment forces. In addition to being employed in the preliminary design phase, this pipe stress study is also applied in the analysis of the FWHCS arrangement [25].

In this study, Prabhu Kishore and Prabhu (2018) provide three sections describing the stress analysis approach. Pump model Creating analytical load scenarios and examining the resulting outcomes. High loads may cause misalignment; this again has the potential of degrading the mechanical characteristics and may lead to uncomfortable vibrations. Pump allowable forces and moments for general refinery duty can be expressed by the following form: APIs 610 equation. The actual loads, however, may be defined by using the modulus of elasticity of the pipe material, when at the operating temperature. Hot modulus will lower loads because the pipe becomes more flexible at higher temperatures. This course will evaluate the basic concepts required for Pipe Stress Analysis and will be equally useful for students with basic and advanced levels of experience [26].

In this study, da Costa Mattos *et al.* (2016) examine metallic pipes with thin walls that have localized corrosion damage and are strengthened by composite restoration techniques based on polymers. The goal is to offer a functional method for determining the failure pressure of a reinforced specimen with arbitrary localized corrosion damage with only some details about the shape of the Pipeline metal's ultimate stress and the elastic characteristics of the composite sleeve. The formulae have been developed to estimate the burst pressure of a corroded pipe which does not include a composite reinforcing system. Hydrostatic burst tests are generally recommended where pipes are corroded to determine the structurally sound condition of the pipe. There is good agreement between the theoretical predictions and the outcomes of a series of hydrostatic tests [27].

In this study, Amaya-Gómez *et al.* (2019) intend to assist in choosing a reliability model for corroded pipelines to inform future intervention tactics. It looks into well-known limit state functions when pipe is corroded and discusses their effectiveness and assumptions made corresponding to them. As applied to academic research and standards of oil and gas industries, this work is concerned with burst limit pressures only. It presents the complete comparison on the grounds of failure criteria, allowable spatial extent in plane of defects, failure probability and prediction of errors from burst testing both experimental and numerical. The goal is to assess each simplified model's degree of conservatism about material toughness and corrosion rate [28].

In this study, (2020) expound on the advantages and disadvantages of using CAESAR II stress analysis in real-life situations and perform related analyses using examples. Many of the prescriptive methods utilize stress analysis of the pressure pipeline as one of the primary technologies that can be used to decide if a design unit can survive in the highly competition market environment. In the international market for pipe stress analysis software, CAESAR Ⅱ is more widely used. It has high technical practicality and is easy for novices to use because of its straightforward data entry and intuitive visual display [29].

VI. CONCLUSION AND FUTURE WORK

Piping stress analysis continues as a critical aspect of engineering design for safe, reliable and efficient piping systems for any industry and application. The comparative analysis done in this review has encapsulated the best practices, tools and techniques in existence and their weaknesses. CAESAR II and AutoPIPE are very popular as they contain many features and can be made to conform to accepted engineering standards. However, they struggle with issues such as geometry and dynamic loads. CCB realized practicing according to codes, enhancing modeling accuracy and employing advanced form of simulation as significant in improving stress analysis reliability. Therefore, the results also highlight that new technologies must address current difficulties and improve analysisFuture works should aim to create tools that could become more adaptive to users and additional technologies such as machine learning and digital twins. Real time collaboration and better data sharing through use of cloud-based platforms also have the potential of revolutionizing the field. Further, more integration of stress analysis tools with other activities around engineering will be done to ensure that space is efficient enough. This advancement will propel change in piping stress analysis to satisfy the current demand and future project requirements in the industrial field.

A piping engineer would have much open space to pick from such options, the one which is least expensive, or least complex etc. Good piping system designing is always a blend of thorough understanding about the fundamentals and lot of creativity. This specific project aims to plan and accurately evaluate the piping systems based on the standard piping Code.

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