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REVIEW PAPER

A Survey of Code-Based vs Numerical Approaches for Piping Stress Evaluation

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***Abstract*—Piping stress assessment is a major priority of making sure that pipeline systems perform safely, reliably and long term under different loads of mechanical, thermal and environmental conditions. The review gives a detailed theoretical and numerical piping stress analysis framework, which includes categorization of stress, failure modes, design criteria, and code-based and numerical methods of evaluation. Primary, secondary, peak, and occasional stresses are used to describe the theoretical background. Important stress failure approaches are also included, such as: plastic deformation, buckling, fatigue, and collapse. An overview of established piping design codes and the basis of their analysis is made to draw attention to their intended purpose of providing pressure integrity and structural integrity. Complex processes, including nonlinear material behaviour, thermal effects, and residual stress following welding, can be better modelled with the use of advanced numerical methods, particularly finite element modelling, than with simplified code-based approaches. In order to replicate the overlay weld procedures, a detailed finite element model is employed. To predict the distribution of temperatures and the development of stress, this model utilizes a specifically developed heat source, a double-ellipsoidal heat source. The paper highlights the relevance of combining theoretical knowledge, design principles, and computer analysis to obtain correct and trustworthy piping stress analysis in contemporary engineering studies.**

Keywords—Piping stress evaluation, Stress Classification, Piping Design Codes, Welding Residual Stress, Numerical Simulation.

I. INTRODUCTION

Ship piping is the system that supplies and transports numerous substances that are required by the ship, including oil, water, gas, and electricity, among many others, which have a great influence on the functionality, safety, and economy of the ship [1]. The ship's piping arrangement consumes half or more of the design team's time during the detailed phase. It takes 3,000 to 4,000 hours for an eight-person design team to complete the pipe system of a medium-sized ship. An estimated sixty percent of a ship's total budget goes towards paying for labor, according to data provided by the American Bureau of Shipping [2]. Using antiquated manual methods is fraught with problems for ship piping professionals. These include inefficiency, high economic expense, increased subjectivity, and reliance on knowledge.

A large pipeline is needed for low-cost energy transportation, a safe work setting, and a lot of transportation [3]. Most pipeline transportation takes place underground [4], [5]. The development of pipelines to transport petroleum and natural gas is critical to the progress of a revolution in energy production and consumption [6], [7]. When geological layers shift, it puts stress on pipelines and causes them to distort and shift. Corrosion occurs when the carrying medium's pressure pushes on the damaged portion of the pipe wall. Material properties such as fatigue strength, resistance to brittle fractures, and high-temperature creep cracking are diminished when defects are subjected to continuous stress. This leads to a degradation of material attributes and the possibility of accidents like explosions and leaks [8]. Safety evaluations of the corrosion states and material strains of pipeline walls are now feasible, thanks to developments in in-pipeline detection technologies.

The most efficient and cost-effective way to move petroleum and natural gas from production locations to processing companies is via pipelines [9]. Principal pipes are heavily laden structures due to the below-average safety factor they achieve throughout the design phase compared to other sectors [10], [11]. Furthermore, pipelines experience additional risks and stresses during both construction and operation. Over the course of the pipeline's long lifespan, the steel undergoes degradation on both the nano- and micro-scales, while macro-defects such caverns and cracks begin to form [12]. Hydrogen embrittlement, corrosion, mechanical property degradation, and operating stress fatigue cracking are the main challenges that long-life pipeline steels encounter.

The Italian Work-related Risks Insurance Agency (INAIL) now includes the former Italian certification agency ISPESL. This combination occurred in the year 2010. In the newly established INAIL Sector of Research, Certification and Testing, the Department of Certification—previously part of Ispesl is currently functioning as a temporary component. This year, the new, permanent organizational structure of this sector unveiled. Pressure vessel designs must also adhere to safety code criteria, such as the Italian normative on creep, which the Department is tasked with overseeing. A specialist working group applies the certification activities code; this group checks the control designer's residual life estimations and on-field testing results [13]. Numerous computational and experimental investigations have focused on pipes that are mechanically lined [14]. In cyclic bending, linear buckling can occur with or without internal pressure. Vasilikis and Karamanos conducted numerical experiments to study geometric faults, local buckling, and liner wrinkling under axial compression and bending.

A. Structure of the paper

The paper structure is as follows: Section II outlines the theoretical basis of piping stress evaluation. Part III provides both code-based and numerical methods of stress analysis.

Section IV considers the literature on piping stress evaluation and monitoring, and Section V summarizes the paper with the research directions in the future.

II. Theoretical Basis of Piping Stress Evaluation

Pipelines that go over long lengths go through a lot of different types of terrain and weather. It is important to study the stress analysis of the materials in question and to examine the responses of pipelines to different loads. Studies on pipelines have been carried out by scholars from every corner of the world. Fluid density, lowest and maximum operating pressures, temperatures, humidity, and a host of other internal and external factors have all been researched in these investigations.

A. Stress Categories in Piping Systems

That goal can be accomplished through stress classification. Different types of stress call for different restrictions, and that much is true. Sorting out all these different kinds of stress is what stress categorisation is all about. A stress group is formed for each of them. These considerations for pipe stress evaluations should be front of mind throughout the design phase:

1) Primary Stress

Dead weight, living weight, internal pressure, and other non-self-limiting sustained loads constitute primary loads. Both internal and external moments and forces can cause primary stress. The major stress-inducing load remains constant independent of the portion's motion. A main stress in a pipe may be seen here in the absence of restraining gear at an expansion junction. Pipe loops are seen in Fig. 1. The area of the pipe multiplied by the pressure of the fluid is the primary factor responsible for this stress. It occurs continuously when the system is subjected to stress. How much the pipe may also be displaced, the untied bellows continues to push on it. Primary stress limits are established at a lower level as compared to other allowable stresses since, the piping does not relieve its primary stresses through the movement or yielding of the piping. The pipe, for instance, would bloat and burst if the principal stresses were to rise above the yield point. By a safety margin, the main stresses are kept below the yield point according to the piping standard.

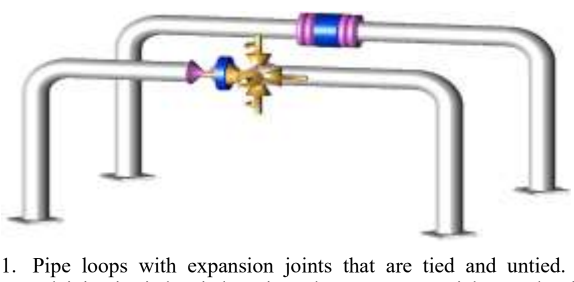

Fig. 1. Pipe loops with expansion joints that are tied and untied. The foreground joint is tied – it has tie rods to prevent axial growth of the expansion joint. The background joint has no tie rods

2) Secondary Stress

Thermal expansion loads, such as changes in temperature, anchors, constraints, and the like, can cause secondary loads that are known as self-limiting loads. As the temperature of the pipe rises and falls, the thermostat's expansion and contraction forces it to move along the pipe. The expansion can't happen unless the pipe system is adaptable enough. Ladders for horizontal pipes are shown in Fig. 2. The pipe's resistance to movement against a fixed constraint is the source of the stress. Stresses caused by heat are considered "secondary stresses" as they eventually diminish. Deformation or yielding of the component lowers stress. Because of this self-limiting behaviour, which permits larger pressures, the fundamental case's restrictions are lifted. Repeated heat cycles at high stresses might eventually overload the material's fatigue capacity, leading to failure, even if stresses over the yield point may initially be tolerated**.**

Fig. 2. Two horizontal pipe loops between fixed anchors. These pipes are subject to high temperature expansion

3) Peak Stress

The fatigue strength of welded structures can be determined using the local PSM. The PSM finds an analogous peak stress by using the opening, in-plane shear, and out-of-plane shear peak stresses calculated by FE at the weld toe and weld root. This peak stress can then be used to forecast the position and life of fatigue in welded structures, as well as to fulfil the design curves that have been appropriately defined. Ansys Mechanical includes an interactive tool that automates all the calculation procedures needed to implement the PSM onto a generic welded structure. The program that was built can fully automate the process of identifying and analysing all of the structure's weld toe and weld root lines. It also performs fatigue life estimation on each node that has been analysed.

4) Occasional Stress

The loads that are statistically generated by wind and earthquake activity are known as occasional loads. Seismic and wind loads are sporadic. Here, the stress is caused by sideways earthquake loads. Stresses generated can exceed fundamental loads due to the rarity of seismically induced loads. Seismic stress exceeds primary stresses by 20% according to ASME plumbing regulations. These stressors should be quite unusual, but the equipment should be fine with them. Fig. 3 displayed the vertical pipe loop.

Fig. 3. A vertical pipe loop subject to a seismic load in the direction shown by the arrow

B. Failure Modes and Design Criteria

Stress analysis is a part of designing and analysing process pipe networks. It is used to see if a certain setup of pipes can handle the weight, temperature, and pressure stresses that come with safe operation. When engineers examine current networks or build process pipe networks, they frequently use an iterative design and analysis cycle. The expertise of senior engineers is recorded to build the stress analysis knowledge base. The engineers' overarching plan for subsequent actions taken throughout the pipe stress analysis.

1) Plastic Collapse Analysis in Piping

Plastic collapse in piping is a term used to describe the situation when a pipe or a component of the piping experiences a gross plastic deformation that results in the loss of load carrying capacity. Plastic collapse, as opposed to fatigue, fracture, does not follow a crack initiation or propagation. Plastic collapse is important in piping stress analysis in high-pressure and large-diameter thin-walled pipes, elbows, trees, and bends when subjected to combined loading.

2) Fatigue Failure

The performance of a glass fibre reinforcing layer in a thermoplastic pipe (RTP) is largely dependent on the RTP's long-term fatigue strength [15]. The accumulation of damage due to external cyclic forcing is what fatigue mechanics mean when they talk about fatigue. When the amount of cumulative damage reaches a specific point, fatigue failure happens. If an RTP's fatigue life is longer than what's needed or anticipated for a certain application, then it's safe to infer that it has an infinite fatigue life or is fatigue-free.

3) Buckling

Pipelines subjected to high pressure and high temperature (HP/HT) often buckle. Having understanding of pipe-buckling is crucial for building a stable pipeline [16]. If the bottom is uneven, the pipeline buckle in one direction or the other. A level seabed is the most common goal of global lateral buckling. Yet, under longitudinal compressive strain, the likelihood of global upheaval buckling is extremely high for an uneven or undulated seafloor. Submerged seabeds and faults generated at the subsoil across pipelines as a result of soil movement during earthquakes are two more potential locations for downward global vertical buckling of pipelines.

4) Deformation

The magnitude and pattern of subsidence area of the mining area are used as the foundation of analyzing gas pipeline subsidence and stress development [17]. The mechanical development and deformation qualities of gas pipelines must be assessed in relation to the surrounding soil's deformation in the event of subsidence, and models of the pipes' interactions with the soil must be constructed.

III. Code and Numerical-Based Approach for Piping Stress Evaluation

Pipe stress assessment methods based on codes are based on prescriptive design guidelines and simplified analysis formulas that are given in published piping [18] standards including the ASME B31 family and EN 13480. These techniques are based on the principles of modelling of piping systems with the beam theory, with the inclusion of both the flexibility factors and the stress intensification factors to explain the geometric discontinuity (elbow and tees). The stresses are divided into sustained, expansion and occasional stresses and the limit of stresses allowed is set to avoid plastic collapse, excessive deformation and fatigue by allowable conservative margins. Although code-based analysis is computationally efficient, standardized, and well accepted by the regulators, it actually amounts to simplifying assumptions which may not necessarily capture local stress concentrations, nonlinear material behaviour and intricate load interactions, which then prompts the concomitant application of numerical techniques in advanced or non-standard piping systems.

A. Major Piping Design Codes

The oil and gas industry relies heavily on piping rules, which set the groundwork for a piping system that is safe, dependable, and efficient. These are not a mere standard in a material or a high-quality welding technology, but a high-quality and rigidly focused safety and operation standards in every design, installation, and inspection. Using appropriate codes can either turn a well-managed facility to one that has the tendency to experience operational blunders.

- **ASME B31.3- Process Piping:** The petrochemical, chemical, and power plant industries, among others, rely on ASME B31.3, which is provided by the ASME [19]. Ensuring the safety and integrity of piping systems during design, construction, and maintenance is the key concern.
- **API 570- Piping Inspection Code:** In-Service Inspection, Rating, and Alteration of Piping Systems: The API 570 standard laid out requirements for the petrochemical industry's in-service inspection, grading, and modifications to pipe systems. It ensures the dependability and safety of the pipe infrastructure and its continuity.
- **ASME B31.1- Power Piping:** The other code that is important in the ASME, B31.1, is the focus on power piping also referred to as the piping system of power plants, industrial facilities, and heating systems. ASME B31.1 does offer design, construction, and operational guidelines by focusing on safety and efficiency.

B. Analytical Basis of Code-Based Methods

Codes establish criteria for ensuring pressure integrity and offer simplified design rules to facilitate compliance with these criteria [20]. Code and standard are often thought of as being synonymous, or at least somewhat so, by designers and engineers; however, this is not the case. When designing a pipe system, it is important to adhere to the specifications laid out in the relevant codes. These standards dictate the maximum permitted working stresses, materials of construction, and loads also give guidelines for calculating the structural [21] behaviour and minimum wall thickness as a function of internal pressure, dead weight, seismic loads, live loads, thermal expansion, and any other external or internal forces. Additionally, plumbing standards specify the necessary dimensions for nonstandard parts and the reinforcing of pipe wall apertures.

1) Binary Code Analysis

Telecommunications is the backbone of modern society, as it enables all interactions and business transactions and global connectivity. This massively huge network centers on the important concept of telecom service stability. The dependability of digital infrastructure The capacity of telecommunications networks to provide consistent and dependable connectivity is known as telecom service reliability, and it is an essential component of any digital infrastructure.

2) Beam Bending Theory

Theorizing beam absorption Straight beams, which are thin structural components, can be bent and supported in various ways according to the principles of beam bending theory. It connects internal strains and stresses to geometry of the beam, material properties and the loading applied to the beam to cause bending moments, shear stress, deflection and rotation.

3) Stress Intensification Factors (SIF)

A reversing displacement test, which involves creating an alternating stress in a set of pipe elements that includes the part or joint in question, was and is used to determine the SIF (i) parameter. The assembly is subjected to reversing displacement until fatigue failure happens. Fatigue failure is defined as the start of a fracture and its propagation through the wall, resulting in a leak in the pressure boundary near or within the piping component or joint being studied. To produce a stress-to-cycle-to-failure curve for the pipe component or joint, the procedure is repeated by applying different reverse displacements to identical assemblies. The SIF is defined by comparing the resultant curve to a reference curve. When the value of the butt weld's SIF is set to one (i = 1.0), the failure curve is the as-welded circumferential butt weld failure curve.

C. Key Aspects of Piping System Design

The key aspects of piping system design are detailed below:

1) Piping system design

This is the aim of designing a safe, functional, efficient piping system.

2) Process design and load calculation

Process design [22] entails establishing the specification of the piping system in the process of determining the requirements of the system, including the type of fluid to be used, flow rate and operating conditions. Layout is the positioning of the piping system components to the space at hand in such a way that they operate in the optimum manner and can be easily maintained.

3) Structural design and load calculation

Investigate the pipe's mechanical strength, including its capacity to withstand working circumstances like high temperatures and pressures. Static, thermal expansion, and dynamic load assessments are all part of this.

4) Analysis of pipes and expansion loops

Tests the pipes to be able to withstand stress and strain caused by the internal pressure and the external forces. These are meant to support thermal expansion and contraction of piping system decreasing stress.

5) Support design and analysis

This section focusses on creating [23] the pipe supports to handle the loads so that the links don't get too stressed and the system stays stable in both static and moving situations.linkedness and steadiness of the system in dynamic and operational conditions.

D. Numerical-Based Approaches for Piping Stress Analysis

Stress analysis is an important part of plumbing engineering because it checks the stresses and strains in pipe systems to make them safe, reliable, and effective. This analysis is effective in revealing the areas where the system may be weak and avoiding failures, thereby protecting the system and users.

1) Finite Element Modeling Approach

The base pipe is a 323.8 mm outside diameter, 10 mm thick steel pipe manufactured of X52 material [24], [25]. A 303 mm outer diameter and a 3 mm wall thickness make up the liner pipe's N08825 material. In Fig. 4, shows the finite element model.

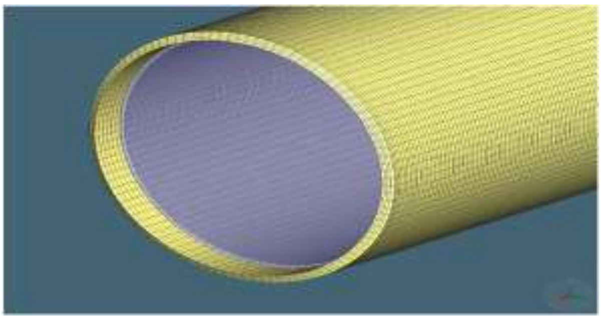

Fig. 4. Finite element model for pipe-end weld overlay

The composite pipe weld overlay cladding is 50 mm wide and has a total thickness of approximately 3.5 mm. A base pipe thickness of 9.5 mm is required for the weld overlay. As can be seen, the weld overlay is at its lowest point along its inner boundary. Here, the liner pipe and the 0.5 mm thick base pipe are chamfered at an angle of 123, such that both materials have flat chamfered sides. By applying two layers of S355J2G3-MPM-sw, the weld overlay can be made to nearly touch the inner surface of the liner pipe. The following specifications for welding have been established: welding current: 100 A; speed: 5 mm/s; voltage: 17 V.

The thermal and mechanical calculations were conducted using second-order hexahedral elements in Simufact Welding 2024, a program developed in Hamburg, Germany. This investigation relied on the composite pipe's geometric features and welding order. At its core, the model is comprised of temperature degrees of freedom (DOFs) and three translational DOFs. All simulations maintained a constant grid distribution, and the mesh, nodes, and components utilized in the mechanical and thermal investigations were same. There are 73,974 elements and 95,672 nodes in the finished finite element model.

2) Heat Source Model

Predicting the temperature field, residual stress, and bead arrangement in numerical simulations is crucial for modelling the heat input in welding. Here, the Goldak double-ellipsoidal heat source model was used to simulate the composite pipe material and the moving heat source. Because it can accurately portray the asymmetric heat distributions in the leading and trailing areas of the molten pool, this model has found extensive use in welding process simulations, and it is especially well-suited to arc welding operations [26]. Here is a schematic of the double-ellipsoidal heat source (Fig. 5). The dimensions of the heat source are denoted as af for front axis, ar for rear axis, b for breadth, and d for depth.

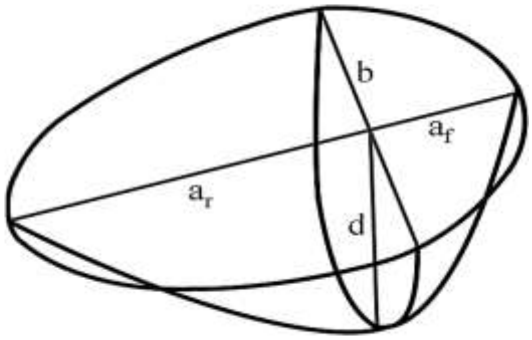

Fig. 5. Schematic diagram of a double-ellipsoidal heat source

IV. Literature Review

Advanced automation has improved real-time monitoring and decision-making in piping stress evaluation, enabling better structural integrity assessment and early damage detection. However, challenges remain in scaling monitoring systems, ensuring model reliability under variable conditions, and validating performance in complex fluid–thermal–structural environments, which are critical for intelligent pipeline systems. Table I summarizes the system study, methods, parameters, and findings of the existing studies.

Domiciano et al. (2025) A loop heat pipe's (LHP) thermal performance was examined in relation to its cooling heat transfer coefficient. The diffusion-bonded LHP, which has dimensions of 76×60×1.6mm total, was created with the express purpose of cooling electronics. The LHP started with the same amount of heat in every scenario, even when the heat transfer coefficient was between 62 and 641 W/m2 K. However, while the higher heat transfer coefficients enabled the device to dissipate greater heat loads, the overall thermal performance was compromised. The significance of the condenser in two-phase cooling system design and optimization is shown by this study [27].

Chichinelli et al. (2025) study presents the design, fabrication, and experimental evaluation of an innovative heat pipe developed as a passive thermal management solution for cylindrical lithium-ion battery cells used in EV applications. To achieve this, a copper heat pipe was fabricated by welding three convex sheets, specifically shaped to conform to the curvature of three adjacent cylindrical cells, without altering the original module configuration. The contact between the curved surfaces forms triangular axial grooves that function as effective capillary structures [28].

Boonlom et al. (2024) studied optical wireless communication heatsinks for LED arrays, with a focus on in-pipe inspection robots, and their design, modelling, and experimental assessment. The Pipe Bot project's communication performance and LED lifetime were both improved by including the optimized heatsink. Effective thermal management allowed LEDs to operate more efficiently, resulting in higher output power, increased frequency bandwidth, and reduced thermal stress. This paper highlights the critical role of heatsink design in optimizing LED-based optical communication systems [29].

Zhao et al. (2023) study explains how to use T(0, 1) mode guided waves to measure axial tension in pipelines that are filled with fluid. The dispersion curve for pipes filled with water can be found using this method, which is based on finite element analysis. For stress monitoring, the T(0, 1) mode guided wave is chosen because it is non-dispersive and has very little energy attenuation in water. To efficiently stimulate the T(0, 1) mode guided wave, a ring-shaped piezoelectric array transducer is developed [30].

Irina et al. (2022) One way to improve the accuracy of measuring the speed of ultrasonic vibration propagation is by using thermo-optical generation of acoustic vibrations. The purpose of this project is to develop a technique for testing the material of specific pipes for residual stresses without causing any damage to the pipe itself by means of thermo-optical generation of acoustic vibrations. In this article, the main methodological strategies for measuring residual stresses in specific pipes are described [31].

Cataldo et al. (2021) impact of flow regimes measured by temperature sensors on thermal performance is demonstrated experimentally according to the results. Keeping the base temperature of the pulsing heat pipe at 90 degrees Celsius while dissipating the greatest heat load from the source is how it is described as performance. Out of all the measured conditions, the refrigerant R1233zd(E) performed the best with a heat flux of 30 W/cm2 and an overall thermal resistance of 0.065 K/W. Dissipation of 850 W is possible [32].

Noshahri et al. (2021) structural condition evaluation of concrete sewage pipes relies on the ability to detect voids in the pipe surrounds. For this reason, a non-destructive testing method called impact-echo can be utilized. Exciting the concrete's surface and then tracking the stress waves' propagation with a contact-based sensor is how this technique works. The presence of deposits and humidity within the sewer pipe makes it tough to place the sensor against the pipe wall. Therefore, this study's overarching goal is to assess several contactless sensors that can serve this function [33].

TABLE I. Summary of Recent Studies on Stress Evaluation in Piping Systems

Author & Year	System Studied	Approach	Key Parameters Investigated	Main Findings
Domiciano et al. (2025)	Diffusion-bonded loop heat pipe (LHP) for electronics cooling	Experimental investigation	Cooling heat transfer coefficient (62–641 W/m²·K), startup heat load, thermal performance	Startup heat load remained unchanged for all cases; higher heat transfer coefficients allowed higher heat dissipation but degraded overall thermal performance, highlighting the condenser's critical role.
Chichinelli et al. (2025)	Copper heat pipe for cylindrical Li-ion battery cells (EV applications)	Design, fabrication, and experimental evaluation	Heat pipe geometry, capillary structure (triangular axial grooves), thermal contact with cells	The curved, groove-based heat pipe effectively provided passive thermal management without altering module configuration, improving heat dissipation for battery cells.
Boonlom et al. (2024)	Heatsinks for LED arrays in in-pipe inspection robots	Design, simulation, and experimental validation	Heatsink geometry, LED temperature, output power, bandwidth	Optimized heatsink improved LED efficiency, increased output power and bandwidth, extended LED lifespan, and reduced thermal stress.
Zhao et al. (2023)	Fluid-filled pipelines for axial stress measurement	Finite element analysis and guided-wave technique	Waveguide operating in the T(0,1) mode, properties of dispersion, transverse stress	A ring-shaped piezoelectric array allowed for effective excitation, and T(0,1) mode's non-dispersive behaviour and low attenuation in water made it suited for stress monitoring.
Irina et al. (2022)	Special pipes for residual stress measurement	Thermo-optical acoustic generation and ultrasonic testing	Ultrasonic wave velocity, residual stress, thermo-optical excitation	Thermo-optical generation improved accuracy in measuring ultrasonic propagation velocity, enhancing non-destructive evaluation of residual stresses in pipes.
Cataldo et al. (2021)	Pulsating heat pipe (PHP)	Experimental thermal performance analysis	Working fluid type, flow regime, heat load, thermal resistance	The most effective material was R1233zd(E), which dissipated 850 W and had a thermal resistance of 0.065 K/W. The thermal performance was greatly affected by the flow regime.

Noshahri et al. (2021)	Concrete sewer pipelines	Experimental comparison of sensing techniques	Contact vs. contactless sensors, impact-echo response, void detection	Contactless sensors proved more suitable than contact-based sensors in humid and deposit-filled sewer environments for detecting surrounding voids.

V. CONCLUSION AND FUTURE WORK

This paper has offered a comprehensive analysis of piping stress evaluation by integrating theoretical frameworks, code compliance methodologies, and advanced numerical techniques. Stresses classification and critical failure modes identification gives a good basis to study the behavior of the pipeline under sustained, thermal, and sporadic loads. Although the existing piping codes provide some reliable and standardized procedures that are used to assure the structural safety, the simplifications inherent in these procedures can restrict the accuracy when dealing with complex loading and geometries. It is through the use of finite element modeling and the realistic representation of welding heat sources that finer prediction of temperature fields, residual stresses, and local stress concentration can be predicted. In general, a synthesis of theoretical analysis, design codes, and numerical simulations can contribute to the high level of reliability of piping stress evaluation and aid the creation of safer and more efficient pipelines under the conditions of a high level of operational tasks.

Future research will involve incorporation of real time sensor data into numerical models of continuous piping stress monitoring. Making use of machine learning for damage prediction, multiphysics interactions, and extrapolation to complicated pipeline networks might lead to smart, self-monitoring piping systems that are more accurate and reliable.

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