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Finite Element Analysis (FEA) of Fiber-Reinforced Polymer (FRP) Repair Performance for Subsea Oil and Gas Pipelines: The Recent Brief Review (2018-2022)

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ABSTRACT

Fiber-reinforced polymer (FRP) materials are used to reinforce and repair subsea pipelines in the oil and gas (O&G) industry due to their great strength-to-weight ratio as well as corrosion resistance. The extreme environmental conditions that subsea pipelines must endure include high pressure, high temperature, as well as corrosion. Modelling the effects of these conditions on the repaired pipeline can be challenging, and inaccuracies in modelling the underwater environment can lead to incorrect predictions regarding the repaired pipeline's behaviour. The finite element method (FEM)'s capabilities, as well as applications, are examined in this work. FEM is being used in place of time-consuming processes and conventional codes since they have demonstrated their strength as prediction tools. This article provides information on the to better understand the accuracy and reliability of the FEA modelling techniques used to simulate the behaviour of the FRP repair system under different operating conditions. The descriptions focus on the many types of composite fibres and the qualities that come from their components. Related document gathering was conducted from 2018-2022 and research on 53 papers were downloaded and acquired from the Scopus and Science Direct database. The review also discusses the insight into the practical implementation of finite element analysis (FEA) modelling involves understanding how FEA is used to solve real-world problems. Moreover, the findings show that by diversifying the FRP materials used in the repair design, the overall performance of the repaired pipeline can be optimized, leading to increased safety and reliability in subsea O&G operations. Also, the scope for future studies.

1. Introduction

Recently, the employment of FRP composites concerning the repair and rehabilitation with respect to subsea pipelines in the O&G industry has become increasingly popular due to their corrosion resistance, high strength, as well as durability. Nevertheless, the design and

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implementation of such repairs require a thorough understanding of the complex mechanical behaviour with respect to the composite materials as well as their interaction with the surrounding environment. An essential tool for simulating the FRP repair behaviour in O&G pipelines is FEA. FEA can predict the stress distribution and failure mechanism of FRP composite repair, which helps engineers optimize the repair design and ensure the long-term structural integrity of pipelines [1,2]. Moreover, FEA modelling can also aid in the determination of the optimal thickness and orientation of FRP laminates, as well as the appropriate adhesive properties required for effective bonding [3]. Figure 1 displays a sample FE model sketch diagram. FEA modelling has proven to be a cost-effective solution for analyzing and optimizing the FRP composite repair techniques' performance in O&G pipelines, reducing the need for expensive physical testing and trial-and-error approaches [4]. In addition, FEA modelling allows for the analysis of the performance of FRP composites able to be repaired under various loading and environmental conditions, making it a valuable tool for predicting the behaviour of pipelines in real-world scenarios. For O&G pipelines to operate safely and effectively, FEA modelling is essential, providing valuable insights into the behaviour of FRP composite repair and helping to minimize downtime and maintenance costs. With the increasing demand for energy and the aging of existing pipelines, FEA modelling will continue to be an essential tool for pipeline engineers and researchers to evaluate the performance of FRP composite repair techniques, ultimately contributing to the sustainability, safety as well as reliability of O&G transportation systems. Therefore, engineers and researchers must embrace the use of FEA modelling in analyzing and optimizing the FRP composite repair performance in O&G pipelines [5]. The application of FEA modelling has revolutionized the way engineers' approach FRP composite repair techniques, enabling them to predict the behaviour of pipelines under various conditions and optimize repair designs for long-term structural integrity. As such, FEA modelling should be an integral part of any pipeline engineering project, providing a cost-effective and reliable solution for analyzing and improving the FRP composite repair techniques' performance in O&G pipelines. By incorporating FEA modelling into pipeline engineering projects, engineers can confidently make data-driven decisions that prioritize safety, reliability, and sustainability in O&G transportation systems. This is particularly important as the demand for energy continues to increase and existing pipelines age, making it crucial that engineers and researchers stay up to date with the latest technology and techniques. Objective these reviews to synthesize and evaluate the current state of research and knowledge in this area. The focus of the literature review would be on identifying and analyzing the various factors that affect the performance of FRP repairs on subsea pipelines, such as the type of FRP material used, the adhesive and bonding agents, the design and installation of the repair system, the environmental conditions, and the loading and stress conditions of the pipeline. The review would also aim to assess the different approaches and methods used in FEA modelling of FRP repairs, including the different software and simulation techniques employed. It would evaluate the accuracy and reliability of these models and their ability to predict the behaviour of FRP repairs under different loading and environmental conditions. Hence, the literature review would seek to identify gaps in knowledge and research in this field, as well as potential areas for further investigation and development of FEA modelling techniques for FRP repairs in subsea pipelines.

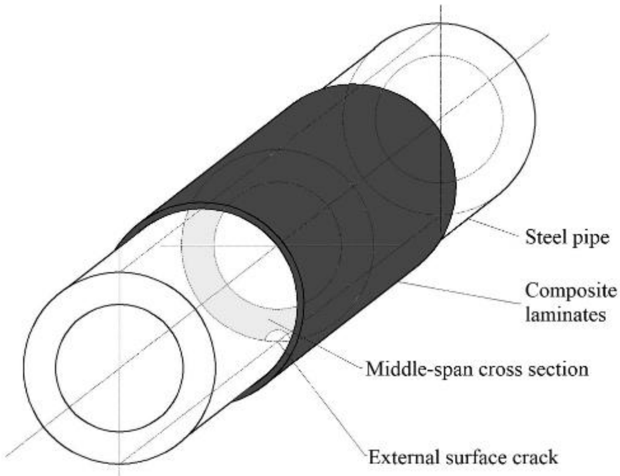

Fig. 1. The composite reinforced sketch diagram [3]

2. Review of Study

2.1 Pipeline Applications Utilizing FRP Composite

Because of their qualities that have many beneficial consequences, FRP composites are employed in various pipeline applications. Due to FRP composites' advantages, they are widely utilized in numerous pipeline applications. To reduce replacement costs and create high-performance and lightweight pipe systems, FRP pipes' strength-to-weight ratio and fatigue endurance are among the essential properties [5]. Based on a study, Rajak *et al.,* [6] found that numerous studies have looked into the possibility of employing FRP composites to increase stability, reinforce durability, and prolong the fatigue life of conventional pipelines. Metal pipes are used most often in O&G transportation pipelines. Here, polymeric composites are a typical practice, a cost-effective solution, and a useful measure for corroded pipes in the O&G industry [7]. Moreover, the efficacy with respect to this type of repair for pipes with mild to severe corrosion has been examined by numerous researchers. FRP material is frequently used in onshore and offshore applications caused of its high strength and resistance to corrosion [8]. The majority of the literature on regaining strength following localized metal loss had focused on onshore pipelines, taking into account FRP composites for their durability as well as high-pressure capacity. Furthermore, glass fiber, as well as epoxy resin, were used primarily in the characterization and failure pressure studies of FRP [9]. In terms of fixing broken pipes, raising burst pressure, and lessening strain, composite materials have proven reliable. In addition, as a comprehensive overview illustrated in Figure 2, epoxy was used to connect carbon half shells to the pipe's exterior. Rehabilitating the pipe by including wraps made of FRP composite materials to its outside surface for the purpose of modulus/weight, as well as high strength/weight ratios in the repair method, is an option for replacing it to address corrosion in the offshore pipeline.

Fig. 2. Example of the process of carbon half-shells installation [10]

Barbosa *et al.,* [11] begun by reviewing some of the innovative technologies that have been used in offshore Brazil during the past 20 years and drawing a comparison to the market's growing acceptance of Thermoplastic Composite Pipe. In a different study, Zhang *et al.,* [12] proposed that there is a possibility that the Yanchang group may use flexible composite pipes for the transmission of high-pressure fluids, the FRP pipeline, as well as steel pipeline. Moreover, Sa *et al.,* [13] examined the performance of anti-agglomerants (AAs) under the flow of oil and water on ice formation and gas hydrates formation preceded by ice formation employing the rock-flow cell. This allows direct visual observation to observe where, how as well as when those solids form. There are currently no governing standards or codes for restoring metallic structures in general, or damaged metallic decks specifically, utilizing composite materials. Since there was no applicable governing design standard or code at the time this paper was written, a novel repair solution was created and put forth to improve the standing of using this method and to demonstrate its suitability as a viable repair choice [14]. The corrosion-resistant composite material that is provided can endure the temperature and pressure conditions that are anticipated in the offshore environment [15]. In order to examined the deposition of scale in multiphase systems (oil/water/gas), which are frequently observed in the petroleum sector, Salgado *et al.,* [16] provide an approach. Three specimens of pipes obtained from (Al-Nasiriyah oil field, Al-Daura refinery, as well as composite material) are provided in the core of the training and workshop at the University of Technology with (3 and 5 mm) thicknesses and (30 mm) diameters immersed in distinct types of Iraqi crude oil fields (East-Baghdad, Al-Nasiriyah, and Al-Rumaila) in distinct times (0, 14, 28, 42, and 56 days) [17]. Other influential work includes by Karya and Lim [18], Abegunde and Adeyemi [19], and Gemi *et al.,* [20]. Moreover, Table 1 provides an overview of current FRP composite research, development, and usage in various pipeline applications across the globe. Each application is categorized based on the type of reinforcement and resin employed. The benefits of utilizing FRP composites in various pipeline applications were acknowledged by all authors. Given their high strength, stiffness, lightweight, great fatigue capabilities as well as good corrosion resistance, fiber-reinforced composites are recognized as the finest potential alternative for the material to be used in the restoration, developing, and strengthening of conventional transportation pipes.

Table 1
Summary of the present research, development, and FRP composite practices in various pipeline applications [5]

Fiber type	Resin type	Pipeline application	Advantages of utilizing FRP	Fabrication process	Type	Testing	Year
Glass fiber	Polyester	Water feed steel pipe of a hydraulic power station	Corrosion resistance plus strengthening	Composite tube	Repair	Static fracture tests	2018
	Polyurethane Resin	Offshore stainless-steel pipes	Resistance to corrosion, having excellent mechanical properties	Hand lay-up	Repair	Hydrostatic tests	2017
	Epoxy	Aluminum pipe	Strengthening	Wrapped by Repair Patch	Repair	Tensile axial stress	2017
	Epoxy	Underground steel Pipe	Resist the bucket tooth penetration force	Composite sleeve	Repair	Burst pressure Loading	2018
	Epoxy	Steel gas pipeline	Excellent resistance and mechanical strength	Composite sleeve	Repair	Uniaxial tensil Tests	2018
	Epoxy	O&G steel pipe	Restoring the loading capacity	Composite wrap by wet lay-up process	Repair	High burst pressure	2019
	Epoxy	Underwater steel pipe used for marine application	Great pressure and strength capacity	Wrapping by wet lay-up	Repair	High burst pressure	2020
	Epoxy	O&G steel pipes	Great strength of HAZ areas and corrosion resistance	Filament winding	Strengthening	Three-and four-point bending	2020
	Epoxy	Cracked steel pipe	Serviceability and rack initiation pressure increased.	Hand lay-up patch (numerical)	Repair	Cyclic loading	2020
	Epoxy	PVC pipelines for sewage and water transportation	Strengthening	Filament winding	Newly Fabricated	Four-point bending test	2020
	Epoxy	Buried O&G pipelines	Decreasing the deformation of buried pipes against explosions	Filament winding	Newly Fabricated	Internal pressure and explosion	2021
Carbon fiber	Epoxy	Offshore O&G aluminum riser pipe.	Great performance plus lightweight	Filament winding	Newly Fabricated	Axial compression	2017
	Epoxy	O&G steel pipe	Capable of carrying high internal pressure	Smart repairing mechanisms, allowing the system to rotate and open.	Repair	Internal pressure And corrosion	2018
	Epoxy	Steel pipes for petroleum and chemical industry	Great pressure and strength capacity	Wrapping by wet lay-up	Repair	High burst pressure	2020

	Epoxy grout	Petroleum steel pipes with a localised defect metal loss	Restoring the capacity of the steel pipe with defects, approximately 70% metal loss	Standoff sleeve	Repair	Internal pressure Test	2021
Aramid fiber	Epoxy	Aluminum pipes for O&G process	New pipeline joining method utilising FRP composites	Hand lay-up	Joining and Repair	Three-point Bending	2019
Natural fibers	Kankara clay	PVC plastic pipelines for sewage and water transportation	Lightweight, good mechanical properties, and low cost	Composite mold	Newly Fabricated	Water absorption	2018
	Kankara clay	PVC plastic pipelines for sewage and water transportation	Lightweight, excellent mechanical properties, and low cost	Composite mold	Newly Fabricated	Water absorption Test and hardness	2018
	Urea-Formaldehyde (Thermoset)	Water supply pipes	Better environmental effects	High tension winding	Newly Fabricated	Life cycle inventory	2019
Hybrid Fibers	Epoxy	• Crude transportation Carbon alloy steel pipe	Reducing strain on the defective region and burst pressure increased by 20% and	Hand lay-up	Repair	High burst pressure	2020
	Epoxy	• Cracked fluid. • Transportation steel Pipe in the offshore industry	Prolonging the residual fatigue life and decreasing the crack growth rate	Hand lay-up	Repair	Fatigue tests (four-point Bending)	2020
	Subsea epoxy	Offshore and onshore steel pipe	Improving the ultimate strength	Hand lay-up	Repair	Combination of axial compression and bending loads	2021
	Epoxy	Offshore composite Pipe	Corrosion resistance plus strengthening	FEA	Newly Fabricated	Flexural loading (bending)	2021
	Epoxy	Offshore composite Pipe	Corrosion resistance plus strengthening	FEA	Newly Fabricated	3-point bending	2021

2.2 Limitations of the Existing FRP Technologies in Pipelines

Many methods and material options have been created by researchers. It has been demonstrated how composite material repairs to corroded and damaged pipes allowed them to regain their initial load-carrying capacity. Coating steel pipes with thin layers of FRP composites has been demonstrated that it has a beneficial impact on the corrosion resistance and heat loss properties of the pipes [21]. Moreover, it was found that the maximum pressure that may be safely applied to plastic pipes that have been reinforced with FRP composites is significantly higher than before. Here, the available literature on the use of fiber-reinforced composites in transportation pipes can be utilised effectively to increase the market and improve the fluid transportation process with the minimum amount of pipe failure and cutouts. Yet, some repair kinds require the employment of intricate techniques. Another technological problem that has not been sufficiently investigated to give rise to the confidence to be implemented in various field applications is the half-shell sleeves repairing procedure, which necessitates a heavy-weight installation to join the sleeve. As filament winding cannot be deployed on-site to replace or reinforce the standard transportation pipes, high-tension wrapping procedures must be used. There is a demand for a portable robotic repairing system with high-tension winding [22]. FRP composite in oil and chemical pipelines has been the subject of much research by various researchers. To clearly comprehend each matrix type's dissolving rate, it is necessary to analyze how distinct polymeric matrices behave in various acidic solutions and concentrations. With time, the pipeline may degrade significantly as a result of the polymeric matrix's dissolution [23]. To increase the confidence in expanding the market via this enticing material system, additional research on the joining of FRP pipes, interfacial properties between the FRP layers and the conventional pipe, and the mechanism of load transfer between the layers of FRP composite systems should be performed.

2.3 Recent Advancements in Finite Element Analysis (FEA) on FRP Composite Pipelines

FEA is a broadly employed technique to predict complex structures' behavior, including corrosion processes. The dramatic escalation in the usage of numerical simulation in science and technology is due to the advancement of computers and their processing power. Numerous pieces of software, such as ABAQUS, ANSYS, I-DEAS, and internally designed programs, were used to carry out the numerical analysis. Using supercomputers, the FEM was originally employed for aerodynamics as well as structural analysis of aircraft [24,25]. Later, it broadened its scope to include engineering-related sectors like machining, automobile, civil, and other related ones. To lower the price of real-time analysis, the analysis of pipes utilizing FEM is essential [26]. It also discloses the material's preliminary findings. FEM analysis of the pipe in the construction industry was first applied in the late 1960s, and the assessment of embankments to calculate strain, displacement as well as stress under the premise of isotropic condition as well as simple stress [27]. In several industries, including maritime, oil & gas, automotive, and chemical, FEM is the most well-known numerical method to address piping issues. Among other uses, the FEM technique can be applied to plastic and creep, dynamic analysis, bubble point pressure and heat transfer analyses [28,29]. As shown in Figure 3, the base model consisted of a composite wrap, grout (putty), and corroded pipes.

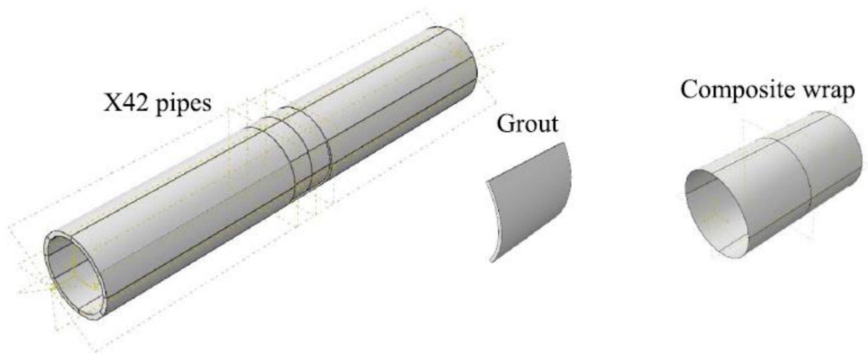

Fig. 3. Illustration for the structural modeling of the FEM, which includes a composite wrap, grout, and a type X42 steel pipe as the component parts [30]

Numerous researchers began to investigate the FRP pipes' numerical analysis in the 20th century. For instance, a study by Sun and Cheng [31] discovered that a three-dimensional (3D) finite element-based model had been created in order to investigate the mechano-electrochemical (M-E) interaction with several corrosion faults that were longitudinally aligned on an X-46 steel pipeline that was submerged in a soil solution. For the purpose of validating the deformation approach, one pipeline having a length of 50 m and one Polyvinyl Chloride (PVC) pipeline with a length of 4 m, correspondingly, were built as finite element methods [32]. The aim of Nahal and Khelif [33] is to study the failure probability in an irregular area in a pipeline (elbow) throughout its lifetime. A finite element-based model was created to simulate the stressing condition brought on by the interaction between the pipe and the soil and to examine the M-E interaction between adjacent, circumferentially aligned corrosion defects on an X46 steel pipe extensively used in West Canada [34]. The objective of Monti *et al.,* [35] is to provide an engineering strategy for the consequences' assessment with respect to an underwater explosion as well as to evaluate the offshore buried pipeline's structural integrity. Pipelines are evaluated from a variety of factors as part of the enhanced evaluation, and they satisfy the pipeline operation as well as integrity limit requirements [36]. Lu *et al.,* [37] provide an alternative 3D nonlinear FEM that explains the response of flexible pipes with respect to combined axisymmetric as well as bending loads. A brand-new semi-empirical burst capacity model for corroded O&G pipelines operating under simultaneous internal pressure and longitudinal compression is put forth by Zhang and Zhou [38]. For the purpose of investigating the M-E synergistic impact at an exterior corrosion defect on an X100 pipeline elbow, a nonlinear FE model coupled with multiple physical fields was created [39]. A nonlinear simplified finite element model was created by Tang *et al.,* [40] to examined the material behavior of flexible pipe armor wires under various stresses. Some studies, such as that of Dong *et al.* [41], concentrate on experimental and numerical research on the behavior of underground pipelines under impact loads. The hammer-soil-pipeline simulation model was developed to examine the buried pipeline's dynamic reaction. Investigation of the formation of surface cracks in steel plates reinforced with carbon fiber-reinforced polymer (CFRP) under tensile load was carried out by Li *et al.,* [42]. Some important observations are noted and can be seen. Most previous studies have focused on assessing the mechanical behavior of the repaired pipelines under various loading conditions. However, this review offers opportunities for additional research. First, simplified assumptions which many FEA models of FRP-repaired pipelines have made simplified assumptions about the geometry and loading conditions, which may not reflect the complex nature of the subsea environment. Second, lack of experimental validation and some FEA models have not been validated through experimental testing, which can limit their accuracy and applicability. Third, limited material data that the availability of material data for FRP composites used in pipeline repairs is limited, which can lead to inaccuracies in FEA models. Finally, due to the difficulty in modeling composite behavior, the behavior of FRP composites can be difficult to model accurately in FEA due to their anisotropic nature and the complexity of their failure mechanisms. Despite these limitations, FEA modeling has been shown to be a valuable tool in understanding the behavior of FRP-repaired subsea pipelines and can provide insights into the design of effective repair strategies. To enhance the applicability as well as the accuracy of FEA models for FRP-repaired pipelines in the subsea environment, more study is required.

2.4 Insight into the Practical Implementation of Finite Element Analysis (FEA) Modeling

Providing insight into the practical implementation of FEA modeling in the O&G industry involves understanding how FEA is used to solve real-world problems. This can involve understanding the specific challenges faced by engineers in the industry, such as the need to design structures that can withstand extreme loads, harsh environments, and complex geometries. As mentioned, FEA is a computational technique broadly employed in engineering to analyse complex structures and systems. In the context of subsea O&G pipelines, FEA may be utilized for modeling and predicting the performance of pipeline repairs. An understanding of the practical implementation of FEA modeling in subsea pipeline repair can be defined. FEA modeling can be used to predict the performance of various pipeline repair methods, such as clamping, welding, and composite wrapping. Practical implementation is the use of FEA modeling to design and analyze repairs for subsea pipelines. For example, FEA can be used to predict stress distribution as well as deformation with respect to the pipeline throughout the repair process. According to the study by Zhao *et al.,* [43], FEA modeling can be used to optimize the design of pipeline repair clamps. The study utilized FEA modeling to analyze the deformation and stress distribution with respect to the pipeline throughout the clamping process. The results showed that the FEA modeling approach could provide accurate predictions of the performance of pipeline repair clamps. Moreover, FEA modeling may be employed to predict the pipeline's behavior after a repair has been made, enabling engineers to design repairs that are both safe and cost-effective. FEA modeling can also be used to analyze the effects of different repair materials and techniques on the overall performance of the pipeline. Figure 4 shows schematic diagram the created FE model before analysing.

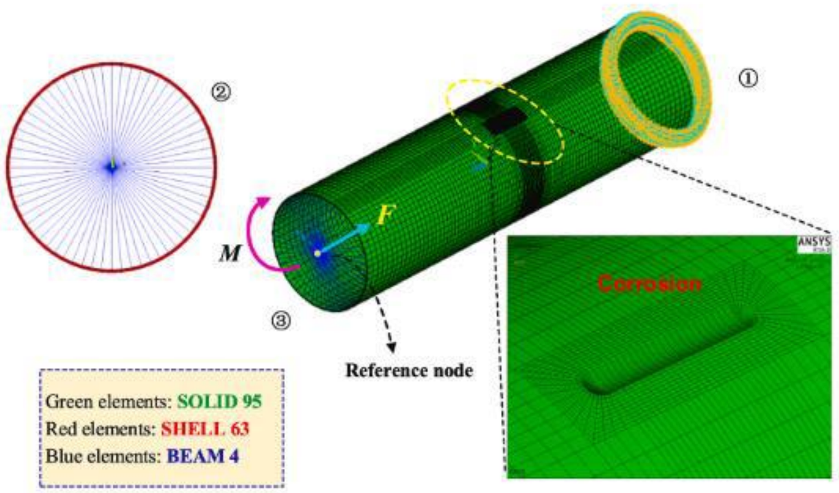

Fig. 4. Schematic diagram of developed finite element model [44]

In another study by Muda *et al.,* [30], FEA modeling was used to analyze the composite wrapping's effect on the subsea pipelines' structural integrity. Here, the study found that FEA modeling can provide an accurate prediction of the performance of composite wrapping in terms of reducing the stress concentration and enhancing the structural integrity of the pipeline. The accuracy of FEA modeling results can be validated through experimental testing. According to the study by Zhao *et al.,* [45], experimental testing can be used to validate the accuracy of FEA modeling results for pipeline repair clamps. The study utilized FEA modeling to analyze the performance of a pipeline repair clamp, and the results were validated through experimental testing. The accuracy of the FEA modeling approach was demonstrated by the experimental and FEA modeling results' strong agreement. Another example of practical implementation is the use of FEA modeling to optimize the design of offshore platforms [46-48]. In this application, FEA modeling can be used to analyze the effects of wind, waves, and currents on the structure, allowing engineers to optimize the design to withstand these loads while minimizing costs. Furthermore, FEA modeling is used in the O&G industry to analyze and design the components' performance, such as valves, risers, and connectors [49,50]. Using FEA modeling, engineers can accurately predict the performance of these components under different loads, allowing them to optimize the design and improve overall reliability [51]. Figure 5 shows a resulting image after applying the numerical technique.

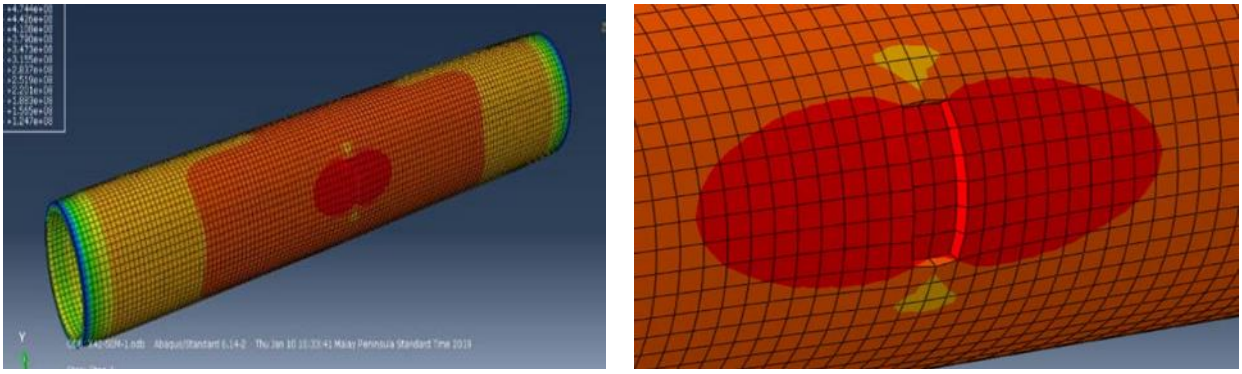

Fig. 5. Finite element visualization of stress output [52]

FEA modeling has some limitations that should be taken into consideration when using this approach for subsea pipeline repair. According to the study by Su *et al.,* [53], FEA modeling is limited by the accuracy of the material properties employed in the model. The study discovered that inaccurate material qualities could cause big mistakes in the predicted performance of pipeline repairs. Therefore, it is important to ensure that the material properties utilized in the FEA model are accurate and representative of the actual pipeline material. Nevertheless, providing insight into the practical implementation of FEA modeling in the O&G industry demands an understanding of the specific challenges faced by engineers in the industry and how FEA can be used to overcome these challenges. By leveraging FEA modeling, engineers can design safer and more efficient structures and components, leading to cost savings and improved performance.

3. Conclusion

FEA modeling is a valuable tool for designing and analyzing subsea O&G pipelines and may be employed to solve problems that are hard to be modeled analytically. FEA has been applied to many O&G applications and has shown reasonable accuracy. The following conclusions were reached after analyzing a few papers on FEA applications in the O&G sector:

i. Accurate prediction of structural behavior: Engineers can optimize the design and guarantee the safety of the structure using FEA modeling, which can precisely anticipate the behavior of subsea pipelines under varied loading conditions.
ii. Cost-effective: FEA modeling can simulate different scenarios and predict the behavior of structures without the need for physical testing, which can be time-consuming and expensive.
iii. Optimization of design: FEA modeling can be used to optimize the design of subsea pipelines by testing different materials, configurations, and dimensions, leading to cost savings and improved performance.
iv. Visual representation of structure: FEA modeling can provide visual representations of the structure under different loading conditions, allowing engineers to identify potential failure modes and develop mitigation strategies.
v. Ability to analyze complex geometries: FEA modeling can be used to analyze complex geometries, such as pipeline bends and irregularities, which can be challenging to analyze using other techniques.

Overall, FEA modeling is a valuable tool, but its limitations need to be carefully considered to ensure accurate and reliable results.

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