Enhancing Functionality and Minimizing Damage of Air Valves in Pipelines Using FRP Sheets

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Abstract:- Pipelines play a vital role in ensuring the efficient and secure transportation of water, making their performance to keep the water continuously going vital. This research explores the influence of air valves on the localized damage and overall functionality of the pipelines. Air valves are critical components that help stabilize pressure and prevent vacuum formation. However, their installation can introduce structural weaknesses in localized areas. The study employs FEM modeling alongside field data from a collapsed bridge to assess the performance and damage in the vicinity of air valves. The findings reveal that strategic redesigns, such as optimizing air valve placement and reinforcing surrounding areas, can significantly enhance performance while mitigating local damage. Additionally, the research highlights the effectiveness of repair methods in increasing pipeline resistance to bending stresses and compares various repair and design approaches, providing new insights into mitigating structural damage in aqueduct bridges. This study addresses a critical gap in the literature, offering a thorough approach to understanding and addressing air valve-related damage in engineering.

Keywords:- *Air Valve, Pipelines, Repair, Numerical Simulation, Structural Failure.*

I. INTRODUCTION

Within the industrial sector, there is an increased appreciation of the role that aqueducts play in water resource distribution; thus, very strict engineering criteria have been established for such systems. The same awareness is evidenced through the growing literature that stipulates operating standards and provides for the durability of water transportation structures. On one hand, the mechanical behavior of the materials adopted in aqueducts has been widely investigated [1]; [2]have set a representative benchmark for general industrial standards with regard to pipeline durability. However, very few studies have been conducted with regard to the actual performance of an aqueduct after structural repair. Common pipeline repair methods include the insertion of steel liners, and this technique has been highly controversially discussed [3]. Other techniques, such as the application of an external steel sleeve, were critically analyzed by [4], referring to their efficiency in different environmental conditions. Nowadays, FRP has been one of the most valid options for conventional steel material replacement because of its efficiency and rapidness in pipeline rehabilitation. A pioneering research by [5] shows that FRP can extend the service life of existing pipelines with little disruption to operation.

The use of FRP composite materials in rehabilitation methodologies does, therefore, hold a great deal of promise for the rehabilitation requirements of underground piping systems. The attractiveness of FRP composites as construction substrates is based on the range of their favorable properties, which include but are not limited to their high specific stiffness, specific strength, corrosion resistance, property tolerability, and improved fatigue life. The present practice in the use of FRP composite materials for pipeline repair proves their efficacy; glass and carbon FRP composites are gaining prominent applications in slip lining and cured-in-place methods on both gravitational and pressurized conduits. Despite these advances, some residual uncertainties remain about long-term performance under rigorous and dynamic environmental exposure. Thus, the mechanical property deviation and thickness in the processes cannot be denied yet; therefore, these need detailed investigations and mitigation strategies to make the FRP composite-based rehabilitation techniques viable and effective for underground piping systems in the long run. This calls for comprehensive research studies to explain the detailed interaction between FRP composite materials and complex operating environments in which they are serving, so that appropriate decision-making can be supported and a sound maintenance strategy could be developed, considering risks and uncertainties associated with such materials. [6], [7]

II. INCIDENT

On October 3, 2021, a partial collapse of the Musota aqueduct bridge over the Ki-nokawa River in Wakayama City occurred as a serious structural event. It was discovered that the reason for the collapse had to do with setting a retrofit member on the hanging member to avoid wind damage. However, when dust, water, and guano built up on the member, it created corrosion that deteriorated the hanging member enough to break. It has also been pointed out that the precise location of the fracture in the hanging member was not ascertainable during the inspection from the control walkway between the pipelines of the aqueduct bridge. It was because the fracture fell into a blind region above the retrofitted members.

Fig 1 Wakayama Aqueduct Bridge Failure

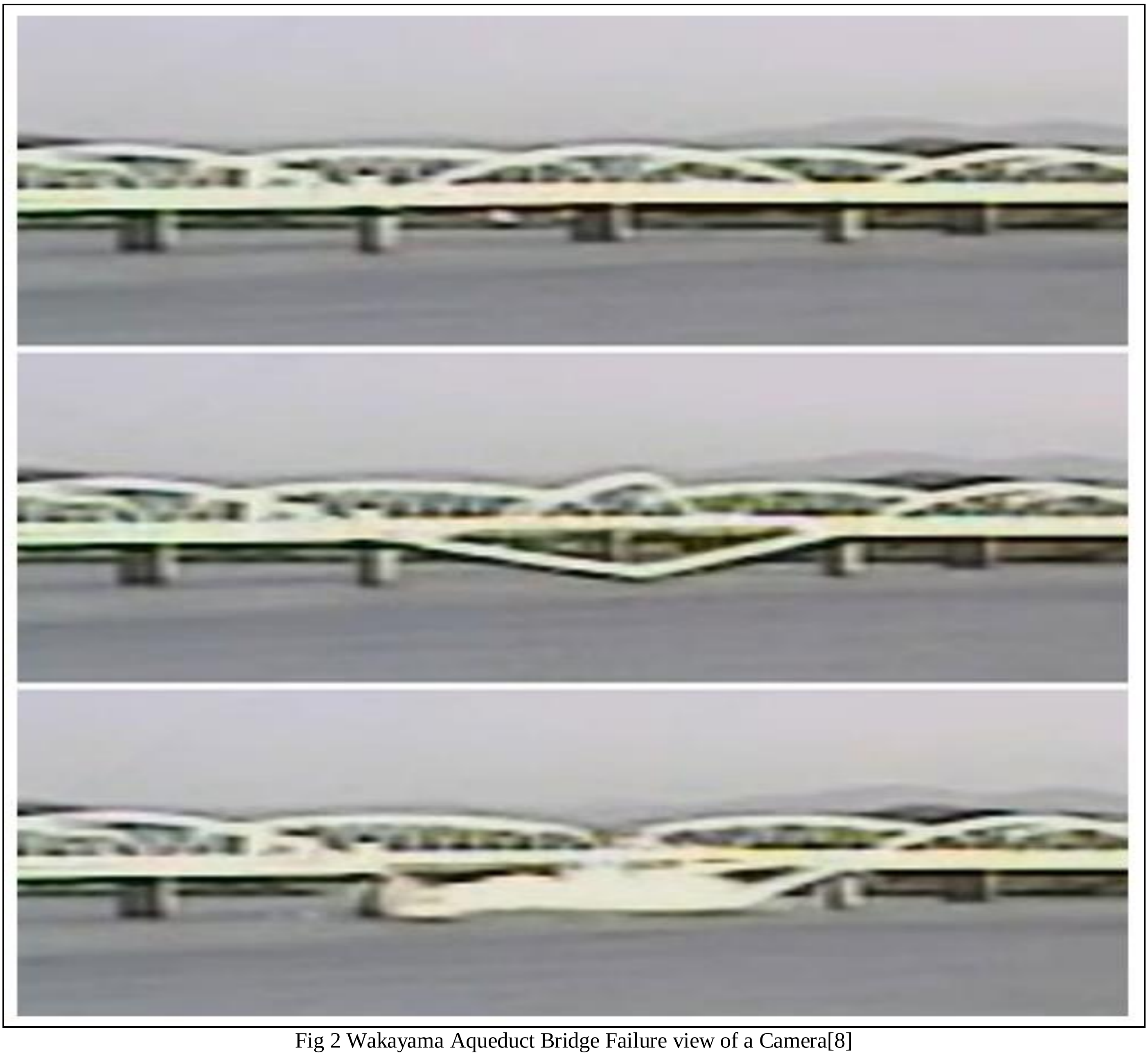

Fig 2 Wakayama Aqueduct Bridge Failure view of a Camera[8]

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III. CHARACTERISTICS OF DAMAGE TO THE PIPE

This has resulted in severe structural damage and disruption of water supply services. The bridge in Wakayama had fitted a number of air valves, which were supposed to regulate pressure surges and prevent the development of vacuum conditions within the water-carrying pipeline. Initial investigations had suggested the local damage at one of these air valves as one of the causative factors leading to collapse. Figure 1 and 2 shows the damaged pipe after the incident.

There was corrosion on the air valve, especially within the metallic elements, which includes but is not limited to the valve body and internal mechanisms. This could weaken the valve by a degree that may cause it to fail in regulating such pressure. In an aqueduct bridge, the plastic damage around an air valve highly depends on the diameter of the valve hole and the weight of the valve. Valve holes for the arch bridges are more significant and, therefore require more accurate cuts during the installation process. Such accuracy in cuts may provide for severe stress concentration at its edge. This may cause plastic deformation at the point of installation. The weight of an air valve will further exert a force on the bridge structure continuously. An increase in the weight of an air valve contributes to more significant application of forces and, therefore, greater plastic deformation in the steel. Therefore, determination of the most appropriate diameter of both the air valve hole and the manhole, along with minimization of the weight of the valve, plays an important role in reducing plastic damage to enhance the durability of the entire aqueduct bridge-especially during construction and maintenance, which would have big impacts on the performance of this bridge.

IV. NUMERICAL MODEL

This paper presents a FEM model that will be further used in the simulation of Pipeline behavior and local damage around air valves. The model incorporates various repair and design modifications to study the effectiveness in the mitigation of stress concentrations, enhancing structural integrity. The model focuses on the middle part of the pipe, where the air valve and manhole are located in the case of plastic damage.

Table 1 Steel Pipe and FRP specification

Steel	
Type	SS400
Young’s Modulus (MPa)	205
Poisson’s Ratio	0.29
Density kg/m^3	7800
Minimum Yield Stress (MPa)	235
Tensile Strength(MPa)	400
Element type	Shell
FRP	
E l (GPa)	55
E2 (GPa)	15.2
E3 (GPa)	15.2
v12	0.254
v13	0.254
v23	0.428
G12 (GPa)	4.7
G13 (GPa)	4.7
G23 (GPa)	3.28
Element type	Shell

Table 2 Cases of the Numerical Model

Case 1	Existing model
Case 2	FRP Sheet
Case 7	FRP Wrapping

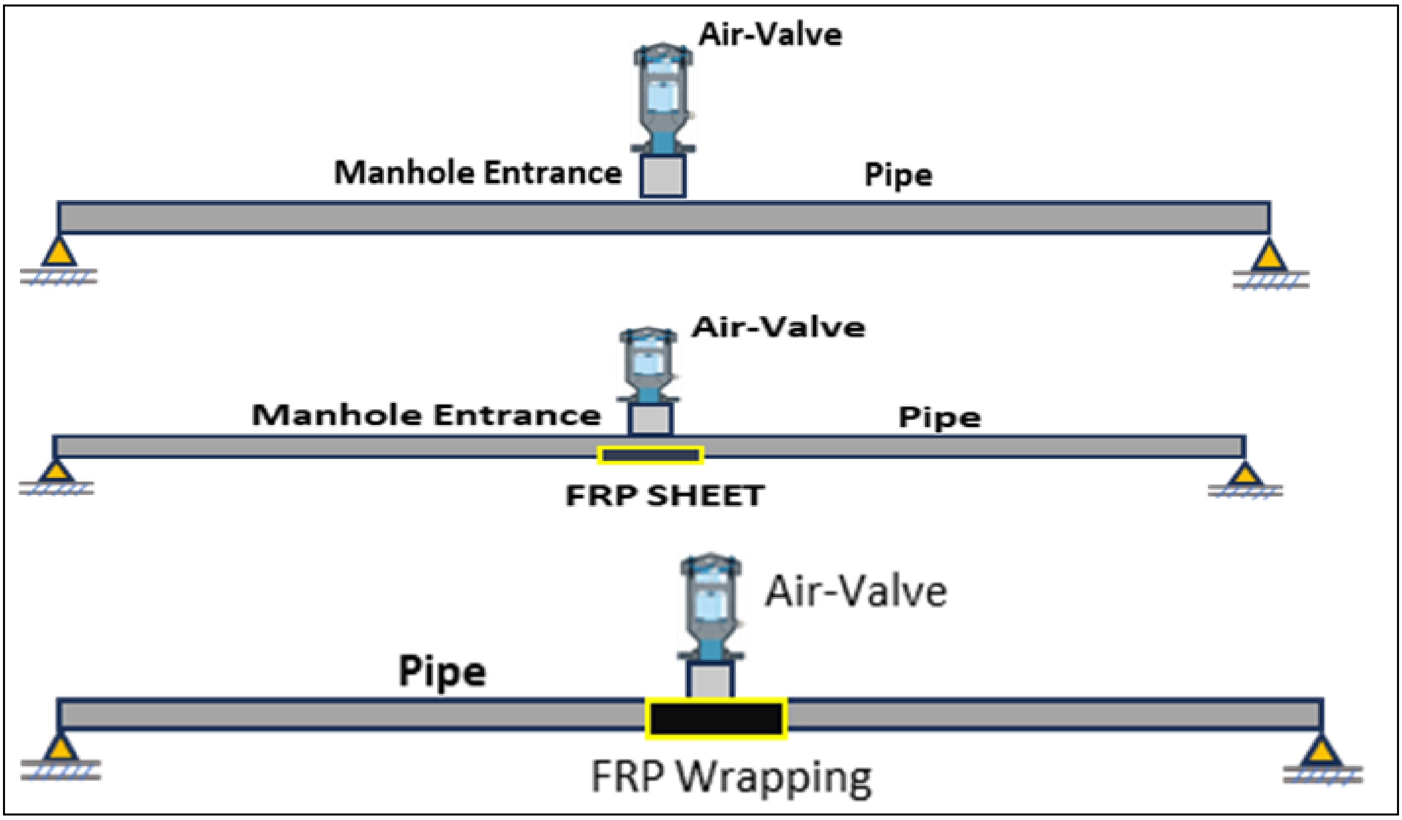

Fig 3 Numerical model Cases

V. ALTERNATIVE DESIGN APPROACHES

Repairs or restorations of piping systems by various design techniques and different composite materials are already an established practice. The technique involves a resin-impregnated liner, which is drawn through an existing pipeline. The permissible live loads and deformations are specified by ASTM F 1743 [9] FRPs can also be incorporated in the liner in CIPP repairs for the instances when the pipe is severely deteriorated and/or when high strength and leakage control are required. Among others, glass and carbon fibers have been used in liners for energy transmission pipeline rehabilitation. The hoop stresses would be counterbalanced while winding the glass fibers in a filament structure in such cases, while axially aligned carbon fibers resist the longitudinal stresses. Apart from the pulled-in-place and direct inversion techniques, some of the other retrofit methods exist and are in standard usage for trenchless piping system rehabilitation. Wet layup techniques with carbon/epoxy composites have been used in large-diameter pipe repairs ; gas pipelines have been wrapped on their exterior with both GFRP and CFRP with the fibers oriented in the circumferential direction. The quality of FRP composites basically depends on the fiber, matrix, and void volume fractions influencing the mechanical performance of the material. FVF can differ based on the fabrication process and conditions during construction. For instance, FRP composites produced by a wet layup technique may have FVFs between 20 and 30% Astrom, 1997, while pultrusion processes are able to produce in a wide range of FVFs between 35 to 60%.

VI. FEM MODEL AND VERIFICATION

The numerical analysis was conducted using the commercial software Abaqus/CAE 2024. The pipe material, as detailed in Table I and II, was consistently applied across all models. Specifically, the pipe used is a Grade SS400 steel pipe, a standard specification for structural steel, with its relevant material properties also outlined. Initially, a complete model of the pipe was developed, with partitions introduced in areas susceptible to defects and damage. This approach leveraged the advantages of double symmetry, effectively reducing the computational time required for the analysis. To achieve a high level of accuracy, very fine meshing was employed using the 8-node linear brick element, C3D8R, available in Abaqus. This meshing method was crucial for accurately simulating the retrofitting scenarios. Figure 4 and Figure 5 illustrate a representative mesh used for this purpose.

VII. RESULTS

The composite layer was incorporated by utilizing the composite layup feature in Abaqus, and applied to the C3D8R solid element to enhance the model's structural integrity. Boundary conditions were established by defining reference points at both ends of the pipe, aligned along the longitudinal axis. These reference nodes were constrained in all directions of translation and rotation, except for the longitudinal translation and the rotational degree of freedom, which were adjusted to account for the applied gravity force. Upon reviewing the deformation results, it is evident that the shape closely resembles the collapse pattern captured in Figure 5, a fixed-point camera image showing the failure of the aqueduct.

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This comparison confirms the reliability of the numerical model in replicating the actual physical behavior observed during the collapse.

At this point, the pipe's stress was as high as 510 MPa on the tensile side and approximately -660 MPa on the compressive side in Figure 6. Consequently, in these conditions where the pipe itself is near failure, with further failure of the suspension components of the bridge, substantial bending occurred and localized damage at mid-span, particularly where the air valve is located. To reduce these effects, the introduction of FRP as reinforcement material was considered, especially for strengthening the pipe in the mid-span region. FRP sheets regulate the performance and recovery that occur in the pipe through the use of tensile properties of FRP material. Moreover, from Figure 3, it can be seen that the application of FRP sheets enables the steel pipe to decrease its stress even at similar displacements given to the mid-span. This again leads to reinforcing the fact that enhanced performance of the pipe is basically associated with reduced stress in the steel material by infusion of composite materials. FRP retrofitting effectively limits the stress exerted on the steel pipe, hence contributing to better durability and performance.

In this study, the behavior of FRP-retrofitted pipes under bending due to gravity conditions is investigated. As expected, in such retrofitting conditions; pipes, in the middle-span region would withstand higher pressures than if the pipe was unrepaired. Strain localization in pipes under bending was prevented, and the FRP sheets increased the limited bending ability and demand of the pipes significantly. Moreover, the strain-based design could be contemplated as a viable alternative for pipes subject to bending. Furthermore, more cases are being, are being currently investigated, and will be reported at a later date. Finally, the influence of combined loading paths, the geometry of the pipe, and the air valve location should also be investigated.

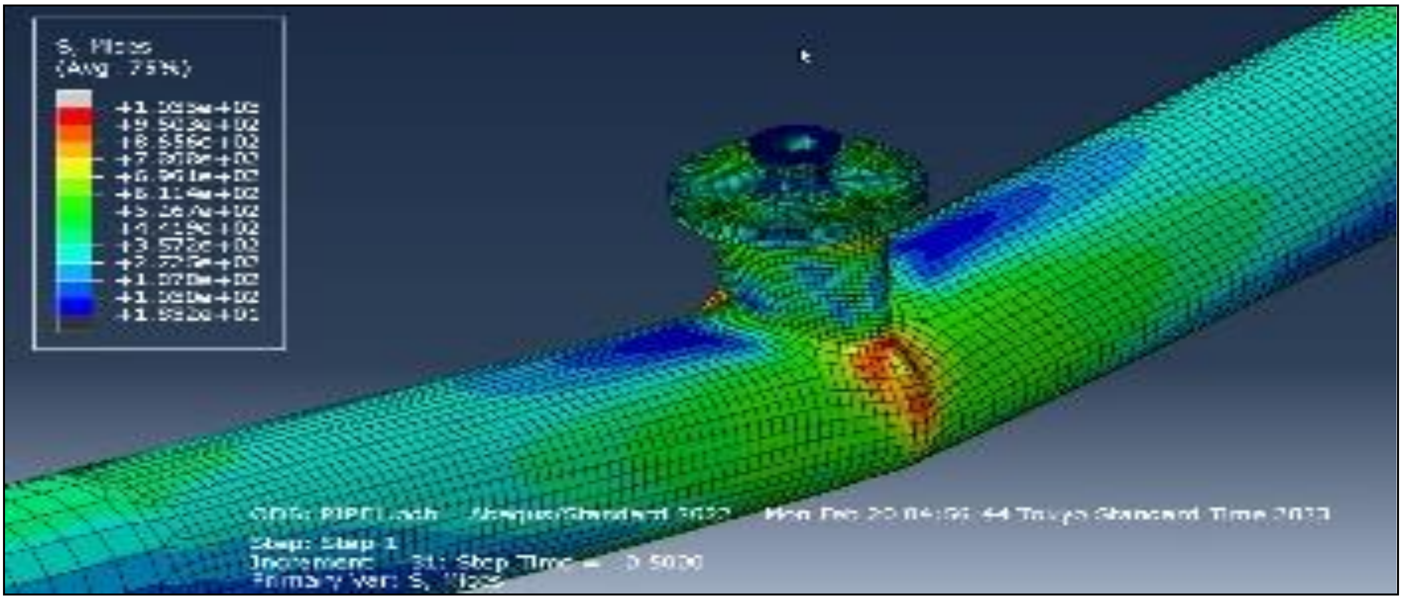

Fig 4 FEM Verification model of the Air-Valve

Fig 5 Damaged Air Valve Located in the Middle of the Span

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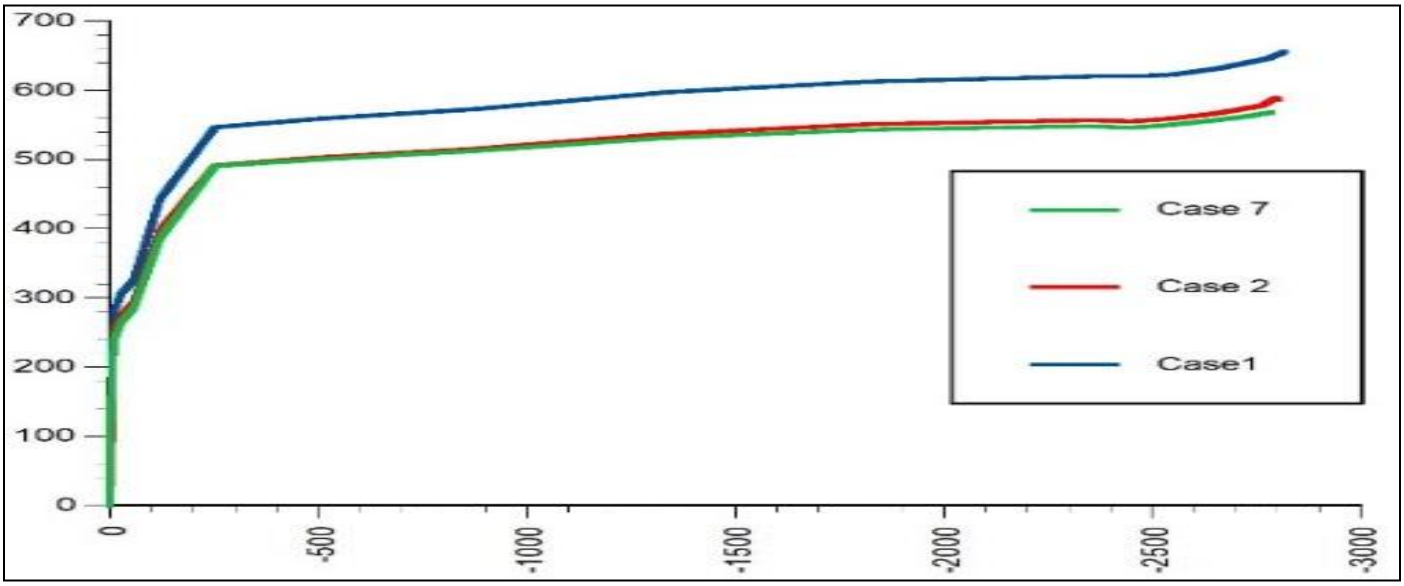

Fig 6 Variation within the Pipe External Region in the Steel, FRP Sheets, and Wrapping and Stress Displacement of Middle Span in the Steel and FRP Cases, Vertical Axis Stress in MPa and Horizontal Axis is Displacement in Millimeters

VIII. CONCLUSIONS

In this research study, we investigate the performance characteristics of pipes that have been strengthened using Fiber Reinforced Polymer (FRP) materials. Our main emphasis is on how these pipes respond to bending stresses caused by gravity forces. Based on existing theories, it was predicted that the sections of the pipes located at the midpoint of their spans would be able to withstand much higher pressure levels under these reinforcement conditions, compared to pipes that had not been repaired or reinforced. The judicious use of FRP sheets was essential in reducing strain concentration inside the pipes during bending, resulting in significant enhancements in both the pipes' ability to withstand bending and their overall structural performance.

Furthermore, the results indicate that a design approach focused on strain criteria emerges as a feasible and efficient option for the engineering of pipes subjected to bending loads. This method has the potential to provide improved performance and dependability in real-world applications where bending forces are a crucial factor. Furthermore, a more thorough set of cases is now under examination, with detailed data and analysis planned for publication in future research.

It is crucial to expand the analysis to include the impacts of combined loading routes, differences in the geometric designs of the pipes, and the strategic positioning of air valves. Gaining an understanding of these elements is essential in order to establish a comprehensive perspective on the behavior of FRP-retrofitted pipes under different operating situations. These further aspects of analysis will enhance a comprehensive and intricate comprehension of the structural soundness and efficiency of reinforced pipe systems in various engineering situations.

REFERENCES

[1]. S.-S. Li, G.-Y. Sang, M.-Y. Xu, and Y. Ye, “Different Aqueduct Structure Make and Design,” Mater. Environ. Eng., pp. 1177–1184, Oct. 2017, doi: 10.1515/9783110516623-115/HTML.

[2]. “API STD 1104: Welding of Pipelines and Related Facilities,” vol. 22, 2021.

[3]. L. K. Sing, S. N. A. Azraai, N. Yahaya, L. Zardasti, and N. Md Noor, “Strength development of epoxy grouts for pipeline rehabilitation,” J. Teknol., vol. 79, no. 1, 2017, doi: 10.11113/jt.v79.9339.

[4]. M. Shamsuddoha, M. M. Islam, T. Aravinthan, A. Manalo, and K. tak Lau, “Effectiveness of using fibre-reinforced polymer composites for underwater steel pipeline repairs,” Composite Structures, vol. 100. 2013. doi: 10.1016/j.compstruct.2012.12.019.

[5]. A. Diniță et al., “Advancements in Fiber-Reinforced Polymer Composites: A Comprehensive Analysis,” Polymers, vol. 16, no. 1. 2024. doi: 10.3390/polym16010002.

[6]. E. Ellobody, “Finite Element Analysis and Design of Steel and Steel-Concrete Composite Bridges,” Finite Elem. Anal. Des. Steel Steel-Concrete Compos. Bridg., pp. 1–676, Jan. 2014, doi: 10.1016/C2013-0-01336-9.

[7]. M. A. Khan, Bridge and Highway Structure Rehabilitation and Repair. McGraw-Hill Education, 2010. Accessed: Sep. 09, 2024. [Online]. Available: https://www.accessengineeringlibrary.com/content/book/9780071545914

[8]. M. of Wakayama Office of River and National Highway and T. and T. Land, Infrastructure, Failure scene of an aqueduct bridge from a fixed-point camera, (2021).

[9]. P. F. Vartanian, “The revised ASTM D-1743 standard test method for corrosion preventive properties of lubricating greases.,” NLGI Spokesm., vol. 52, no. 2, May 1988, 1988.