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Research Paper

Stiffening Weld Repaired Buried Pipes Using Glass/Epoxy Composite Layers to Enhance Buckling Resistance Under External Pressure

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ABSTRACT

Welding is a repair technique to remove discontinuities and damaged areas in buried pipes. Repaired areas should be covered by composite layers for stiffening. The current study focuses on a certain buried drain pipes that is repaired by longitudinal weld and stiffened by glass/epoxy composite. To this end, pipes covered by various numbers of composite layers were modeled in Abaqus and loaded by external lateral pressure to determine buckling behavior. Modeled pipes had a longitudinal dent that represents the weld effect. Results showed the buckling resistance exponentially increases by the number of composite layers. Finally, the reliability and accuracy of numerical simulations were investigated by experimental approach. In this step, three pipes were tested. the differences between numerical simulation and experiment were around 20 percent. This difference is due to composite manufacturing and stiffening procedures and is acceptable.

Keywords: Glass/epoxy composite; Buckling; Abaqus; Composite manufacturing.

1 INTRODUCTION

PIPELINE system are essential in developments in urbanization and industrialization for various applications such as gas and oil transfer [1, 2], water supply systems [3, 4], drainage systems [5, 6], and so on. These pipes are prone to various defect types due to external interference, corrosion effects, or instillation problems. Dent, scratch, cracks, corrosion effect are usually seen in buried pipes after excavation [7, 8, 9].

In the drainage pipes, leakage and rupture, and metal loss in longitudinal direction are common [10, 11, 12]. There have been many attempts to study longitudinal defects in pipes. In this field, for example, Zhou et al. [13] investigated the probability of rupture in pipelines. They proposed a log-logistic model for rupture prediction in steel

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pipelines. Other models are also introduced to evaluate the longitudinal. In another study, Ruggieri and Dotta [14] applied the micromechanics approach to investigate the longitudinal crack type defects in pipeline steel. They employed their model upon a computational cell and CTOA criterion to predict crack propagation. W. Stoppler et al. [15] also employed yield stress, toughness, ligament stress, and plastic criteria in the evaluation of longitudinal flawed pipe made from steel. They could propose equations to predict failure pressure in these flawed pipes. There have been other studies to predict the failure in defected pipes. However, postponing the failure or repairing a failed pipe are other issues that should be focused.

Welding overlay is a technique that is usually used to repair cracked areas, ruptures, and discontinuities in pipes. The main concept of this technique is to cover the defected area by a layer of weld to strengthen the pipe wall. This repair technique is divided into three categories namely half-bead, temper bead welding (TBW), and cold repair. Among them the cold repair is more time-saving, because it does not need any preheating [16]. However, this method causes residual stresses in the pipe wall and can affect the buckling resistance [17, 18].

Various methods are employed to increase the buckling resistance in pipes subjected to external forces. Structural stiffening with steel is one method that effectively improve the buckling stability [19]. Covering the defected area by composite layers is another way to enhance buckling resistance in pipes and repair pipe system [20]. This reinforcement type also increases the corrosion resistance [21]. The applicability of this method has been proven through numerous studies [22]. There have been numerous experimental and numerical studies to investigate effect of composite on damaged steel pipe repair [23]. In recent years, for example, Shafaee Fallah et al [24] experimentaly and numerically studied the effect of adding a glass/epoxy composite patch on a repaired steel pipes under internal pressure. Their results showed the number of layers have a considerable role in the failure resistance. Silva et al [25] studied the effect of composite patch performance in damaged pipes under hydrostatic pressure. All in all, there have been numerous studies on this topic, however, there are many unclear topics that should be focused.

In some cases, the pipe has a longitudinal discontinuity in flow direction that can be fixed by a longitudinal weld. This fixed pipe can also be strengthened by covering a few composite layers around the pipe. This study aims to investigate the effect of a longitudinal weld on the buckling behavior of a special buried pipe that is conventionally used for drain systems. To this end, in the first step, pipes with various layers of composites are modeled and simulated under external loadings using a developed Abaqus plugin. Then, the accuracy of model is experimentally validated. In this phase, one welded pipes without composite stiffener and two welded pipes with 5 and 10 layers of glass/epoxy composite are fabricated and tested to investigate the effect of composite stiffening and validation.

2. METHODOLOGY

2.1. Numerical simulation

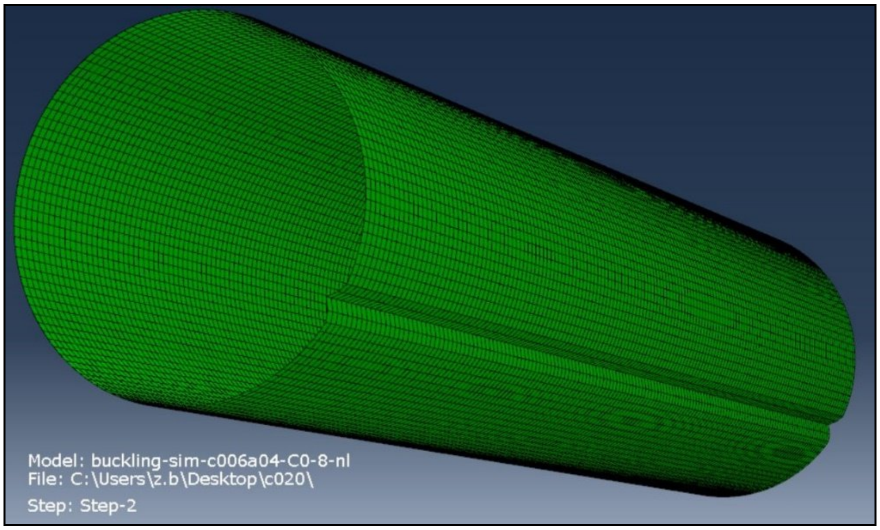
Numerical studies on instability analysis are divided into three categories, namely eigenvalue analysis, Riks method, and quasi-static analysis. The current study employs the Riks method for analysis. This method considers non-linear equations using nonlinear Cauchy strain. The nonlinearity in material properties are also considered. In this method, the amount of the total load is an unknown. The software determines this load giving reference load with a factor called proportionality factor. The following equation shows the equation that determines the total load:

$$P_{total} = P_0 + \lambda\left(P_{ref} - P_0\right)$$

where, P_0 is the initial load at the starting point of the step, P_0 is the reference load. The reference load is the load that is defined in the Riks step and λ is the load proportionality factor. This method is employed in this study to determine the buckling pressure in pipes under external pressure.

In the modeling, a longitudinal dent is employed to model the weld. Fig.1 shows a sample of models with a longitudinal dent that can simulates the weld behavior. Composite layers can also be added to this model. To speed up the modeling procedure, a plugin was developed. The plugin gives the pipes dimension and properties and composite layers and properties, models the pipes, simulates the pressurizing process, and determines the buckling pressure using the Riks model. Fig.2 shows the plugin environment.

In this study, pipes with 250mm diameter, 600 mm length, and 0.6mm thickness were modeled. This geometry is selected according to the drain piping systems. Q235 stainless steel is the material employed for modeling according to the case focused for study. The material selection was also according to the industrial case. Drain pipes are fabricated from this material that has a good resistance to corrosion. These pipes are buried in around 1 m depth. In the first step, a pipe with and without longitudinal dent were modeled to investigate the effect of weld on the buckling behavior. Then, various numbers of composite layers up to 15 layers were added to model to investigate the effect of number of layers. Glass/epoxy was selected as composite stiffener. Even though carbon or kevlar have higher strength, glass is considerably cost effective and more reasonable for this case.



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Model: buckling-sim-c006a04-C0-8-nl
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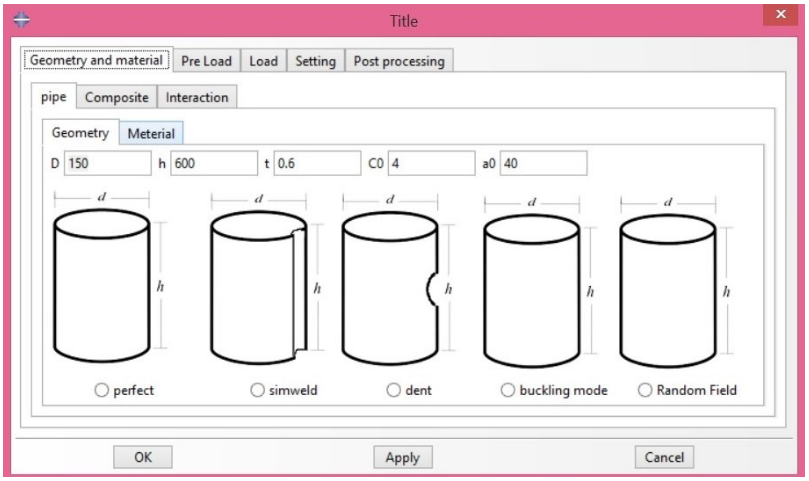
Fig. 1
A sample model of a pipe with longitudinal dent.



D 150
h 600
t 0.6
C0 4
a0 40

Fig. 2
Plug in developed for modeling and simulation.

2.2. Materials and pipe fabrication

Experimental approaches are widely employed for validation of simulations in most of studies. Similarly, a few pipes were fabricated in this study for validation. Q235 pipes were employed to fabricate pipes. Material properties are summarized in Table 1. Fig.3 also shows the fabricated pipes.

For experimental validation, we need to create a defect in the form of a discontinuity that requires repair. To achieve this discontinuity, we can either cut a pipe or roll a sheet; however, cutting a pipe is preferred as it better simulates actual conditions. In the first step, we selected a pipe measuring 600 mm in length and 0.6 mm in thickness. We then made an incision along the length of the pipe, as this direction aligns with common industrial failures. Most failures in these pipes occur due to hoop stress and along the longitudinal direction. In the second step, we repaired the discontinuity using a welding technique. After this, we have a repaired pipe ready for testing. Finally, to assess its resistance under hydrostatic pressure, we weld two circular plates to both ends of the pipe to create a cylinder. This cylinder is then pressurized during the testing phase.

The aim of this study is to determine the effect of composites on the buckling behavior of a longitudinally welded pipe. Pipes stiffened with glass/epoxy composite layers should also be fabricated for validation. To this end, Composite properties should be first determined for modeling. In order to model composite layers a plate of glass/epoxy was fabricated. The hand lay-up method involves several steps. First, a layer of resin is spread evenly on a flat surface. Next, a layer of composite material is added on top of the resin. This is followed by another layer of resin being applied. This process is repeated until the desired number of layers is reached. Finally, the composite sheet is allowed to cure at ambient temperature. Tensile test specimens were then prepared from the cured sheet according to standards using water jet machine. Specimens preparation and tests were done according to D3039 and D3518 standards. To enhance the accuracy of material properties, strain gauges were adhered to specimen in order to achieve exact strains in tensile direction and perpendicular, thereby achieving accurate elasticity modulus and Poison ratios. Use of strain gauges and other experimental stress analysis methods or extensometers are common due the error in displacement measurement in tensile test machines. The composite mechanical properties are summarized in Table 2 and Fig.4 shows the test setup.

Table 1
Mechanical properties of Q235 steel

	Elasticity modulus	Yield stress	Ultimate stress	Poisson ratio
Q235	200 GPa	240 MPa	400 MPa	0.3

Fig. 3
Welded pipes for experimental validation.

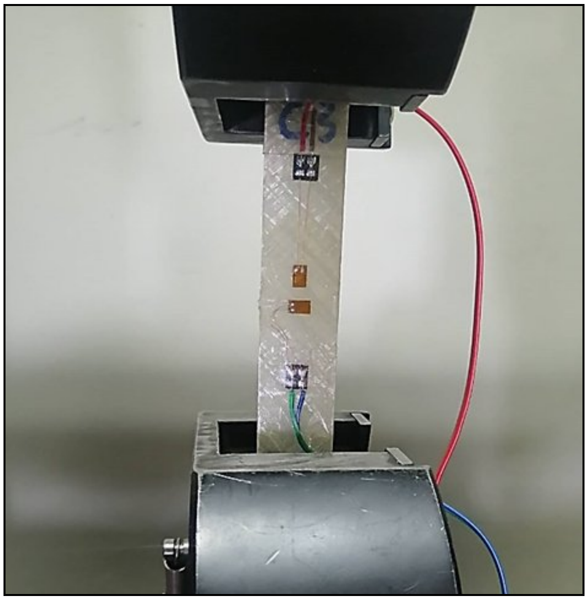


Fig. 4
Glass epoxy composite specimen and adhered strain gauges under tensile test machine to determine mechanical properties.

Table 2
Mechanical properties for Glass woven /Epoxy composite

Et	Ec	G12	Xt=Yc	Xc=Yc	S12	Poisson ratio
20.4 GPa	16.1 GPa	3.61 GPa	294 MPa	160 MPa	56 MPa	0.15

After characterizing the composite, layers of composite were added to the repaired pipes, similar to the previous section. First, a layer of resin was applied to the pipes using an industrial brush. Next, a long strip of woven material was wrapped around the pipes. The length of this layer was determined to ensure an exact number of composite layers were applied. During the wrapping process, additional resin was applied to the pipe with the brush. Finally, the pipe was left to allow the epoxy to cure.

2.3. Experiment

To test fabricated pipes, they are pressurized by water. It is common to put the target specimen in water and increase the water pressure for hydrostatic pressure test. To this end, a bigger chamber is employed that pipes can be put inside of that. The pipe is put in this chamber that has a lid to close it. After that, the water is lightly injected to the chamber that externally pressurizes the pipe. the water pressure is continuously recorded by an accurate pressure gage. The pressure increases until a drop that reveals the buckling. To explain the process, it is clear that when buckling occurs the pipe undergone a harsh deformation, leading to more free space for the water. When the water suddenly finds more space, its pressure decreases and reveals itself in a considerable drop in the pressure curve. Recording the pressure continuously enables us to find the buckling pressure.

To clarify the process, when buckling occurs, the pipe experiences significant deformation, which creates additional space for the water. When the water suddenly has more space, its pressure decreases, resulting in a notable drop in the pressure curve. By continuous pressure recording, we can determine the buckling pressure. Fig.5 shows the test setup.

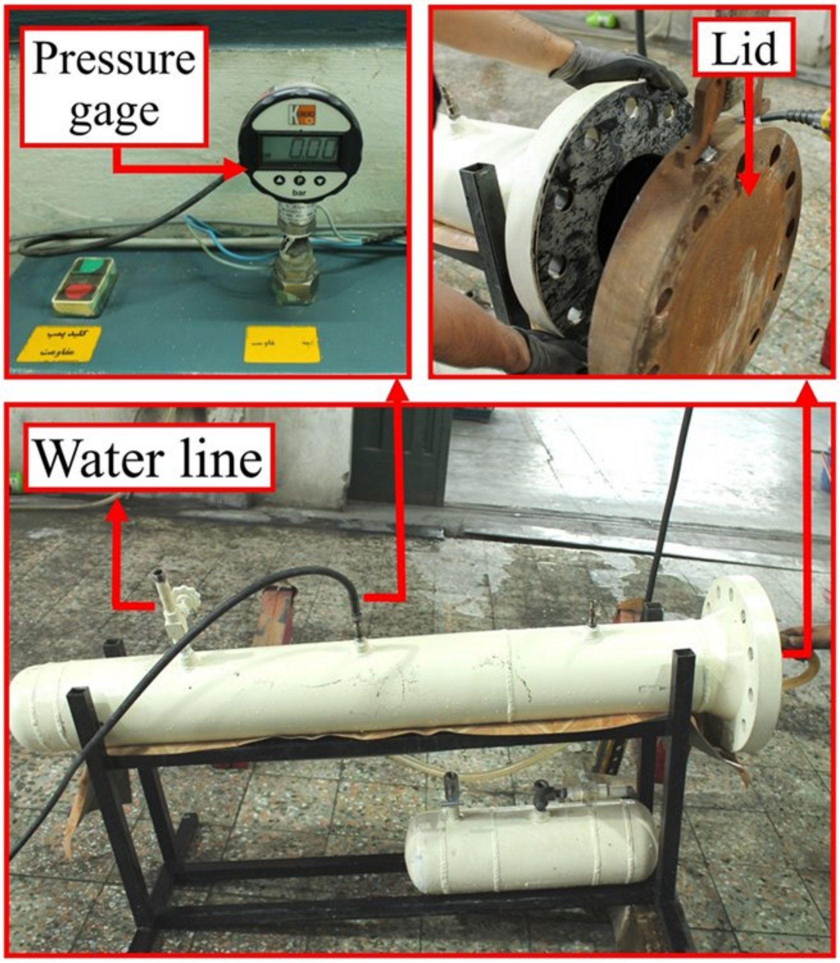


Fig. 5
Test setup.

3. RESULTS AND DISCUSSIONS

3.1. Simulation

In the numerical step of the study, first, two pipes with and without longitudinal went were simulated to investigate the effect of the weld on the buckling behavior. The buckling pressures for two pipes were approximately the same. Thus, the weld did not show any effect in the numerical approach.

In the second step, pipes with longitudinal welds were modeled and simulated using the plugin developed. Buckling pressure for 16 pipes with 250mm diameter and 600 mm length were done. Each modeled pipe had a certain number of composite layers from zero to 15 layers. Fig.6 shows buckling pressures resulted from simulations vs the number of layers. Clearly, the critical pressure exponentially increases by the increase in the number of layers. The period starts by 0.1926 MPa where there is no composite and reaches to 1.6304 MPa where 15 composite layers are added to the pipe.

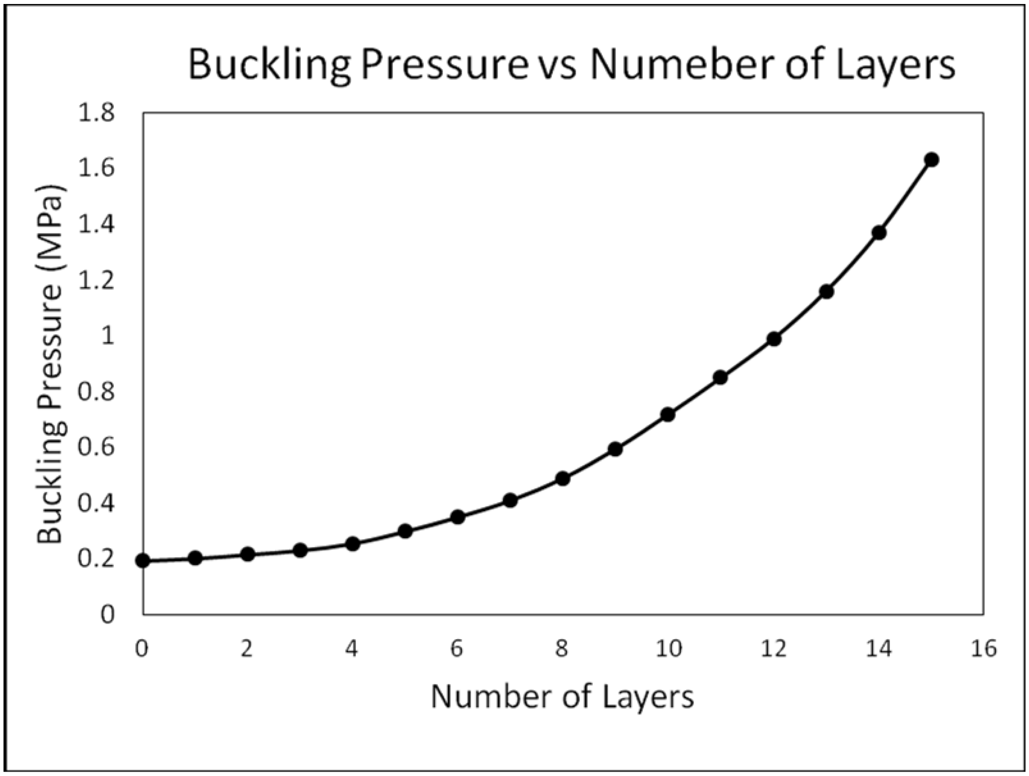


Fig. 6
Numerical results.

3.2. Experimental validation

For experimental validation three welded pipes were tested. The buckling pressure were recorded as what explained. The buckling pressure resulted from numerical simulation and experimental tests are shown in Table 3. According to the table shown, the differences between numerical simulation and experimental results is 11 percent for the unstiffened pipe. For stiffened pipes with 5 and 10 composite layers, the differences are 23 and 20 percent respectively. This differences means that the simulation can be accepted by adding a safety factor.

Fig.7 shows pipes after test. Obviously, the unstiffened pipes did not fail from the weld area. This result matches the numerical result revealing the weld is not the reason of buckling, and the buckling starts from other areas. It is clear that the pipe undergone dramatic change after buckling. However, stiffened pipes resisted severe deformation, meaning that this stiffening can considerably improve the buckling resistance and this technique is effective.

Table 3
Comparison of experimental and numerical results

Shell type	Experimental critical pressure	Numerical critical pressure	Differences
non-stiffened	0.17 MPa	0.1926 MPa	~ 11 %
5 layers stiffened	0.23 MPa	0.2986 MPa	~23 %
10 layers stiffened	0.52 MPa	0.6499 MPa	~20 %

In the stiffened pipes, failure started from the weld area, where the composite layer did not greatly adhere to the pipe surface due to weld bumps. The area near the weld should be completely filled by epoxy to avoid massive voids and this failure. Maybe the high differences between numerical and experimental results is due to this issue. For the stiffened pipe with 5 layer (the middle one), the failure area is clearly disclosed by the color. This area is considerably wider that of the 10 layers. In the pipes stiffened by 10 layers (the downer one) the failure similarly started from the weld area but with smaller areas near the weld. In this case, the high number of layers better resist the buckling.

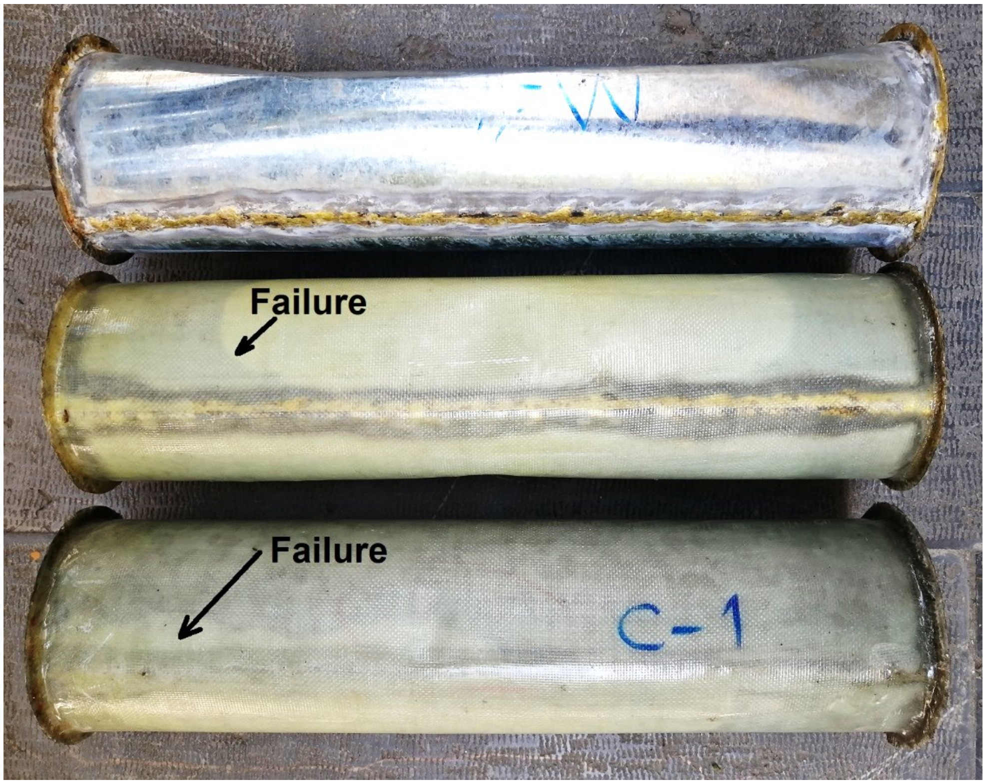


Fig. 7
Failed pipes after test.

The differences between experimental and numerical results are significant and warrant explanation. Firstly, the materials used to produce the cylinder could be of higher quality. The metal utilized often contains numerous imperfections, such as micro-cracks, dislocations, and twinning. These types of imperfections are common in industrial structures, prompting designers to apply a safety factor to mitigate potential issues. In this study, a small safety factor of 1.5 or 2 could help account for these discrepancies. However, due to the complexity and variety of production factors, as well as the challenges in manufacturing, the disparity between theoretical and real-life situations in composite materials is greater than in metals.

Additionally, several factors related to the instruments used can lead to minor differences, which, while small, still contribute to the overall error. In the case of cylinders wrapped in composite layers, a slight gap often exists between the welded area and the composite layer due to the volume of the weld. This gap is the primary cause of these discrepancies. An experiment was conducted to assess the impact of this gap on the results, but it was found to have no significant effect, as the welding was completed to high standards.

In most cases, welding can weaken the structure and the surrounding areas. However, in our situation, the weld did not weaken the structure; instead, it increased its overall resistance. This enhancement is attributed to the thickness of the weld in relation to the tube thickness. The tube had a thickness of 1mm, while the weld was, on average, 5mm thick and spread over a wider area near the cutting line. As a result, the structure's strength in the vicinity of the weld was greater than in other areas.

One point of concern is the gap between the thick weld and the composite layer. This gap can be filled by using resin or composite patches, but machining the welded area to smooth out the bump is not advisable, as it may lead to scratches or other destructive issues during the process. Ideally, welding from the inside of the pipe would be advantageous; however, this method is only feasible for pipes with larger diameters. Additionally, the bump on the inner side can negatively impact fluid flow, which is why welding from the outside is generally preferred.

4. CONCLUSIONS

The effects of covering weld repaired pipes were studied by glass epoxy composite layers in a special buried drain pipe. All topics are listed as:

1. Pipes with 250 mm diameter, 0.6 mm thickness, 600mm length, and Q235 steel properties were modeled in Abaqus and their buckling pressure were determined through simulation under external lateral pressure.
2. Longitudinal dents were added to each model to add the weld effect.
3. For the experimental validation, first, glass/epoxy layers were added to pipes as stiffener. Composite properties were determined through tests on a fabricated composite sheet.
4. Result showed the buckling resistance exponentially increases by the number of stiffening layers.
5. Three pipes with longitudinal welds were fabricated and tested under pressurized water to check the reliability and accuracy of the simulation.
6. The first pipe without any composite layer buckled from other side of the weld, revealing the weld does not have any considerable effect on the buckling. This was also seen in numerical results. However, the pipes experienced a severe deformation. The difference between numerical and experimental results was around 10 percent in this section.
7. In stiffened pipes with 5 and 10 layers the pipes did not severely deformed. However, the differences between numerical and experimental results were around 20 percent.

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