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Strength Investigation on Butt Welded Polymer Tubes

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Abstract

The purpose of this study is to examine instances in which pipes and butt welds are subjected to unintended stresses, resulting in fractures or full destruction. The behavior of radial force (perpendicular to the OX axis) in two circumstances is seen, and we conclude which of the two examples has more flaws. The two circumstances will be examined from an analytical, theoretical, and experimental standpoint, leading to some key findings of this type of incident. The analytical component involves a rigorous investigation of the structural design, material properties, and stress distribution within the given contexts. This is complemented by a theoretical exploration, wherein mathematical models and simulations are employed to predict the response of pipes and butt welds to various stress scenarios. Experimental analyses are conducted to validate the theoretical predictions and provide real-world insights into the behavior of these components under unexpected stress conditions.

Keywords: Finite element, Polyethylene, Butt weld, Polymer tube, Welding, axial strength, compressive strength.

INTRODUCTION

Polyethylene Pipes

Natural resources such as cellulose, resins, oil, and natural gas are used to make plastics. The primary basic material is oil. Crude oil is separated into various factions at refineries. There are numerous stages of distillation depending on the range of boiling temperatures: gas, gasoline, kerosene, black oil, and bitumen as leftovers. All of these components are made up of hydrocarbons with just minor differences in molecule size and shape [9]. Straight-run gasoline is the most significant component in plastics production. A thermal cracking process (vapor cracking) divides and converts this gasoline into ethylene, propylene, butene, and other hydrocarbons. The component combinations of plastics, known as monomers or monomer molecules of the same sort, are formed from hydrocarbons, which make up the majority of plastics. There are instances where an external force acts on the accidentally buried polyethylene pipe, either on the pipe or on the welding region.

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Various Forces in the Polyethylene Pipes

A three-dimensional stress occurs when an internal pressure Pi and an exterior pressure Pe (Figure 1) act on a tubular pipe. The pipe's wall is subjected to three different types of stress [1]:

A circumferential stress:

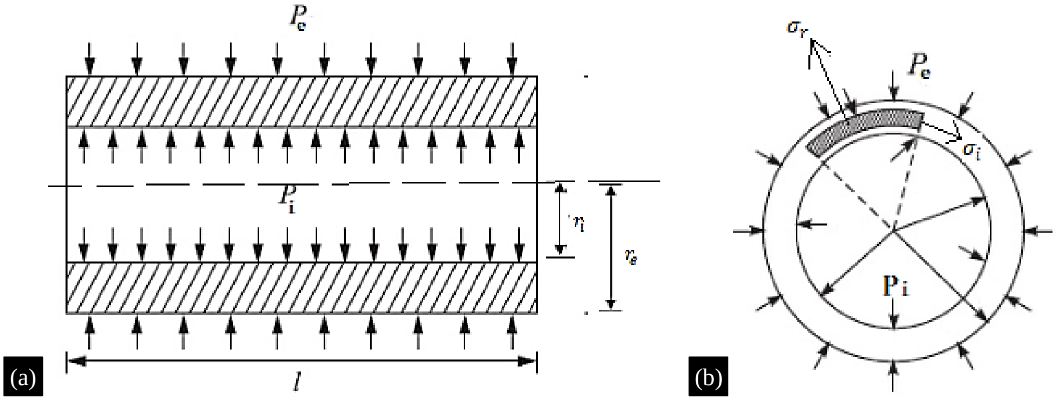

Figure 1. (a, b). Stress distribution on the polyethylene pipe based on exterior and interior pressures

$$\sigma_i = \frac{1}{r_e^2 - r_i^2}\left[p_i r_i^2 - p_e r_e^2 + (p_e - p_i)\frac{r_e^2 r_i^2}{r^2}\right] \quad (1)$$

A tangential stress:

$$\sigma_i = \frac{1}{r_e^2 - r_i^2}\left[p_i r_i^2 - p_e r_e^2 - (p_e - p_i)\frac{r_e^2 r_i^2}{r^2}\right] \quad (2)$$

Direct stress:

$$\sigma_{ax} = \frac{p_i r_i^2 - p_e r_e^2}{r_e^2 - r_i^2} \quad (3)$$

The external radius of the pipe is re=D/2, and the interior radius is ri=d/2 in the previous relations. We can see that for r = ri, the radial tension is:

$$\sigma_r = -p_i \quad (4)$$

The radial stress will have the following value when r = r_e, then

$$\sigma_r = -p_e \quad (5)$$

If r = r_i, the following formula gives the circumferential stress.

$$\sigma_i = \frac{r_e^2 + r_i^2}{r_e^2 - r_i^2} p_i - \frac{2r_e^2}{r_e^2 - r_i^2} p_e \quad (6)$$

and if r = r_e, we get the relationship:

$$\sigma_i = \frac{2r_i^2}{r_e^2 - r_i^2} p_i - \frac{r_e^2 + r_i^2}{r_e^2 - r_i^2} p_e \quad (7)$$

These formulas can alternatively be written as follows:

$$\sigma_i = \frac{D^2 + d^2}{D^2 - d^2} p_i - \frac{2D^2}{D^2 - d^2} p_e \quad (8)$$

External stress σ_e, is an example of this is:

$$\sigma_i = \frac{2d^2}{D^2 - d^2} p_i - \frac{D^2 - d^2}{D^2 + d^2} p_e \quad (9)$$

The pipe's exterior and internal radii, respectively, are D and d.

The fluid flowing through the polyethylene pipe creates internal pressure. If $p_{e=0}$ is used, the formula for radial stress (relation 2.1) is

$$\sigma_r = \frac{r_i^2}{r_e^2 - r_i^2}\left(1 - \frac{r_e^2}{r^2}\right) \quad (10)$$

where p = p_i.

If $r = r_i$, σ_r retains the relationship's value (2.4), and if r = r_e, then $\sigma_r = o$.

In a similar vein, the tangential stress formula is:

$$\sigma_i = \frac{r_i^2}{r_e^2 - r_i^2}\left(1 + \frac{r_e^2}{r^2}\right) \tag{11}$$

For $r = r_i$, stress reaches its maximum value, which may be estimated using the formula below:

$$\sigma_i = \frac{r_e^2 + r_i^2}{r_e^2 - r_i^2} \tag{12}$$

or

$$\sigma_i = \frac{D^2 + d^2}{D^2 - d^2} \tag{13}$$

owing to the fact that it is a direct consequence of the relationship (5.8).

If we replace $D = d + e_n$, (en being the thickness of the pipe's wall) in the formula (5.13) and leave off the term that contains e_n^2, we get:

$$\sigma_i = \frac{p * D}{2e_n} \tag{14}$$

If e_n^2 is not present in a phrase.

Because the tangential stress is the most relevant, the previous formula is frequently used to calculate size.

Following the same calculation technique in terms of axial stress, it gets

$$\sigma_{ax} = \frac{r_i^2}{r_e^2 - r_i^2} p \tag{15}$$

Or is:

$$\sigma_{ax} = \frac{d^2}{D^2 - d^2} p \tag{16}$$

We may deduce the axial stress using the same estimate on e_n^2

$$\sigma_{ax} = \frac{pd}{4e_n} \tag{17}$$

MATERIALS AND METHODOLY

Computation of Polyethylene Pipe and Polyethylene Welding Behavior

Ansys Workbench was chosen as the software program for modeling (numerical simulation) of the radial compression of polyethylene pipes because of its capacity to characterize and consider all three types of nonlinearities (material nonlinearities, geometric nonlinearities, and boundary conditions nonlinearities). To replicate this radial compressive test, the Ansys program supplies the user with a unique module called Workbench transient structural, which allows users to perform both explicit and implicit dynamic assessments [5]. After completing the static analysis, the input file for the nonlinear analysis (compression pipe k) is created, which is required when using the Workbench solver. After this file has been created, the analysis can proceed. Then, on the screen, a dialogue box displays the results from the analysis and the number of time increments covered. A study of the type illustrated above can take many hours to complete, depending on the processor speed, the amount of RAM available, and the frequency with which the results are written to the results files. After the analysis, one of two types of processors can be used: Ansys' General Postprocessor or a custom program named Transient Structural, which can be found in the directory containing all of Ansys.3's executables [2]. Examining the structure, a pipe is a slender, tubular form that can extend significantly in length.

While beams may share a tubular structure, they are primarily employed for their strength, often as columns. In contrast, pipes are predominantly designed for fluid and gas transportation, encompassing applications involving high temperatures, elevated pressures, and viscous substances. To minimize pipe thickness to conserve materials without compromising compliance with strength, temperature, and pressure specifications. The choice of element shapes—whether one, two, or three-dimensional—depends on the nature of the problem at hand. When examining the temperature distribution in a pipe or the deformation of a pipe under axial tension, the geometry, material properties, and field variables can be represented using a single spatial coordinate, a one-dimensional (line) element shape. The accuracy of problem-solving is influenced by the desired precision level, which, akin to element size, depends on the number of elements employed. While greater numbers of elements contribute to more accurate solutions, there reaches a point where increasing the count has negligible impact on result accuracy. Within the Ansys software, three distinct elements are at our disposal: PIPE288, PIPE289, and ELBOW290. Both PIPE288 and PIPE289 are versatile, accommodating thin-walled and thick-walled (including solid circular) cross-sections. When opting for the thick-walled configuration, a comprehensive 3D stress state is applied. The current analysis was carried out on a PE100 SDR 11 pipe with a diameter of 90 mm and a wall thickness of 8.2 mm (identical to the one used in the experimental experiments in this study), and the findings were seen and saved using the program proposed. The goal was to figure out the stresses (represented by the von Mises stress and the main stress on the force direction), the strains (represented by the primary, secondary, and equivalent von Mises strains) [3,4], the displacement in the two radial directions of the pipe, and the variation of the compression force during the deformation process. Figure 2 depicts the finite element mesh of the upper bar, pipe, and lower bar assembly, while Figure 3 depicts the graph of the compressive force fluctuation at the upper bar level. The maximal value of this force is estimated to be roughly 860 [N].

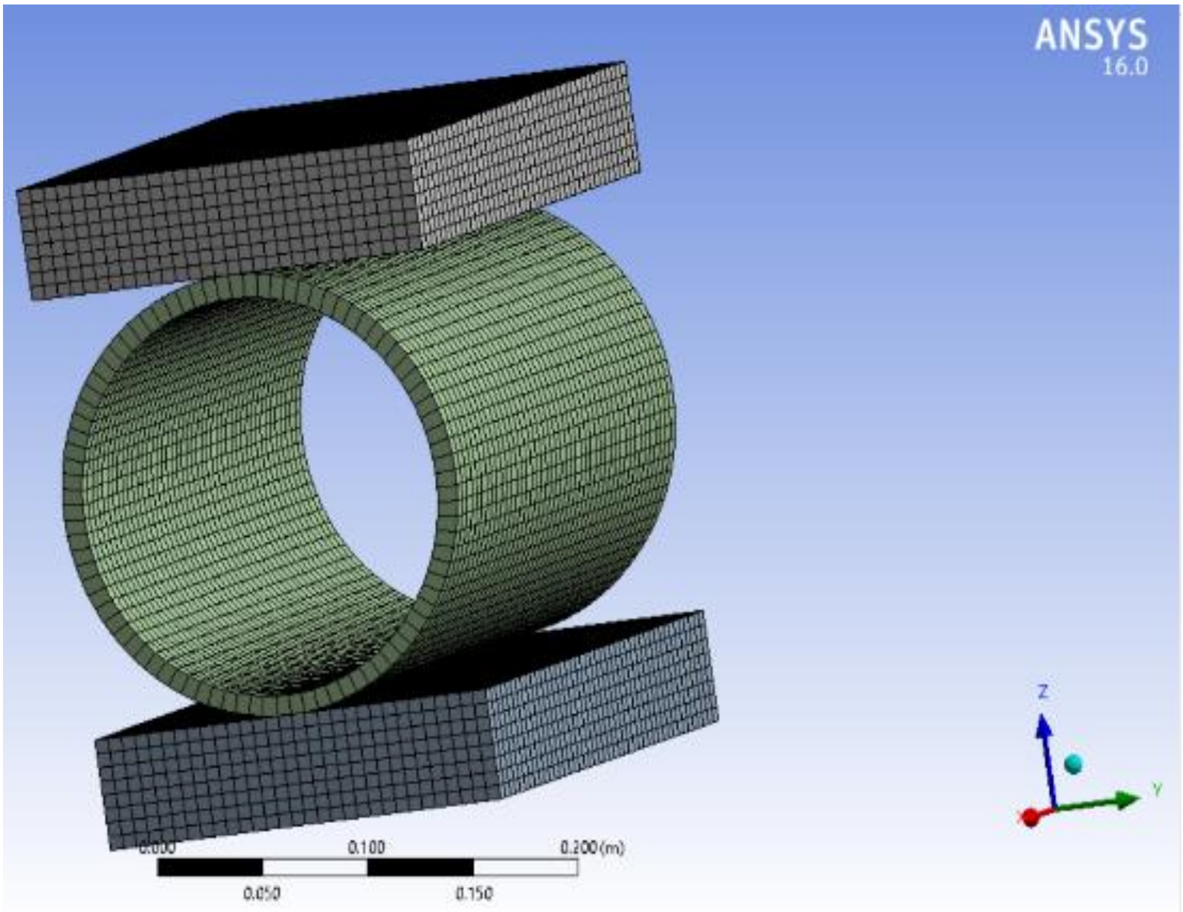

Figure 2. Meshed Upper bar – pipe – lower bar are the components of the assembly

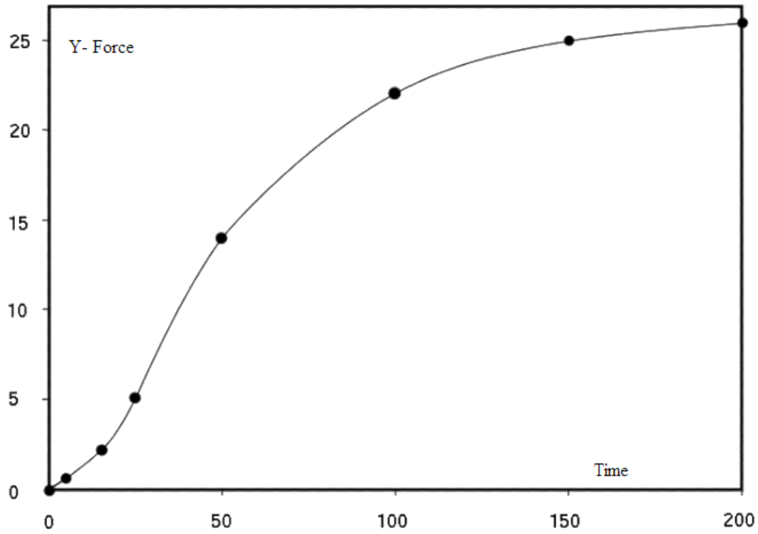

Figure 3. Compression force variation at the upper bar.

The figures 4 below depict how the pipe's material moves in the radial direction Oy at increment (analytical step) 0.3.

At increment (step of the analysis) 0.3, Figure 7 illustrates the distribution map of the equivalent von Mises stresses that arise in the pipe's material.

Different findings were achieved for different sizes of polyethylene pipes when the same simulations were run for butt welding. In addition to the types of data shown above, the program can calculate a variety of other values, such as energy consumption, mechanical effort used, friction energy consumed, tension and strain on various fibers (external, internal, median) [6], and so on. These nonlinear dynamic studies are becoming more widely used because they can forecast how a polyethylene pipe will behave over time while also lowering maintenance expenses.

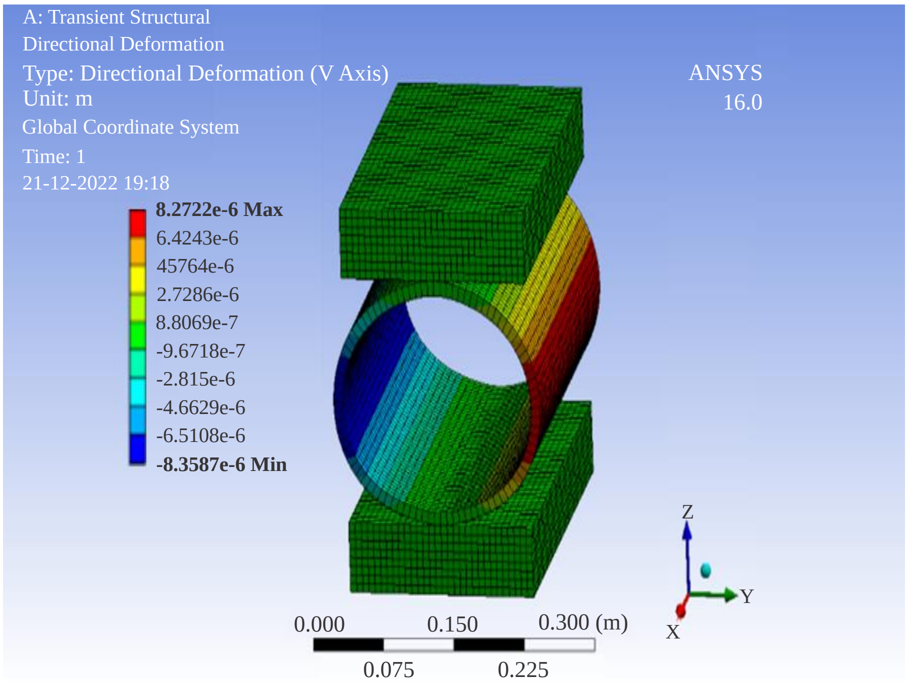

Figure 4. Radial displacement of the pipe material Oy at increments of 0.3.

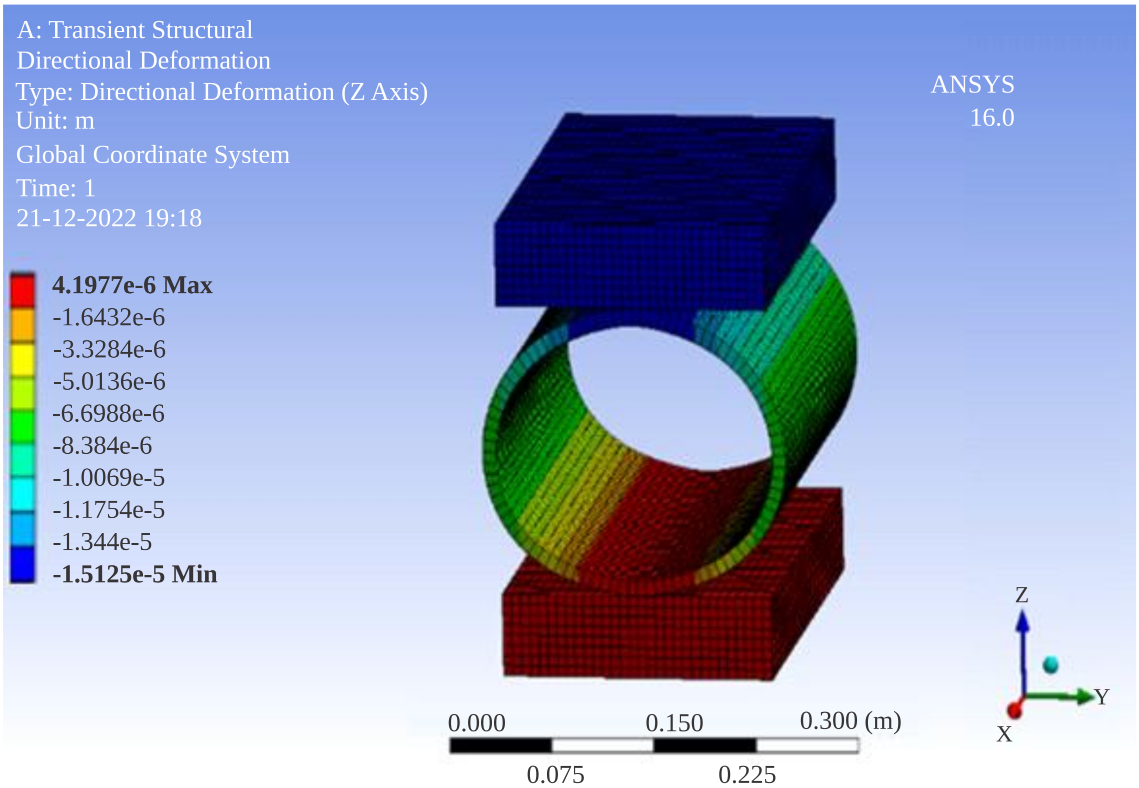

Figure 5. The material displacement in the radial direction of the pipe Oz at increment 0.3.

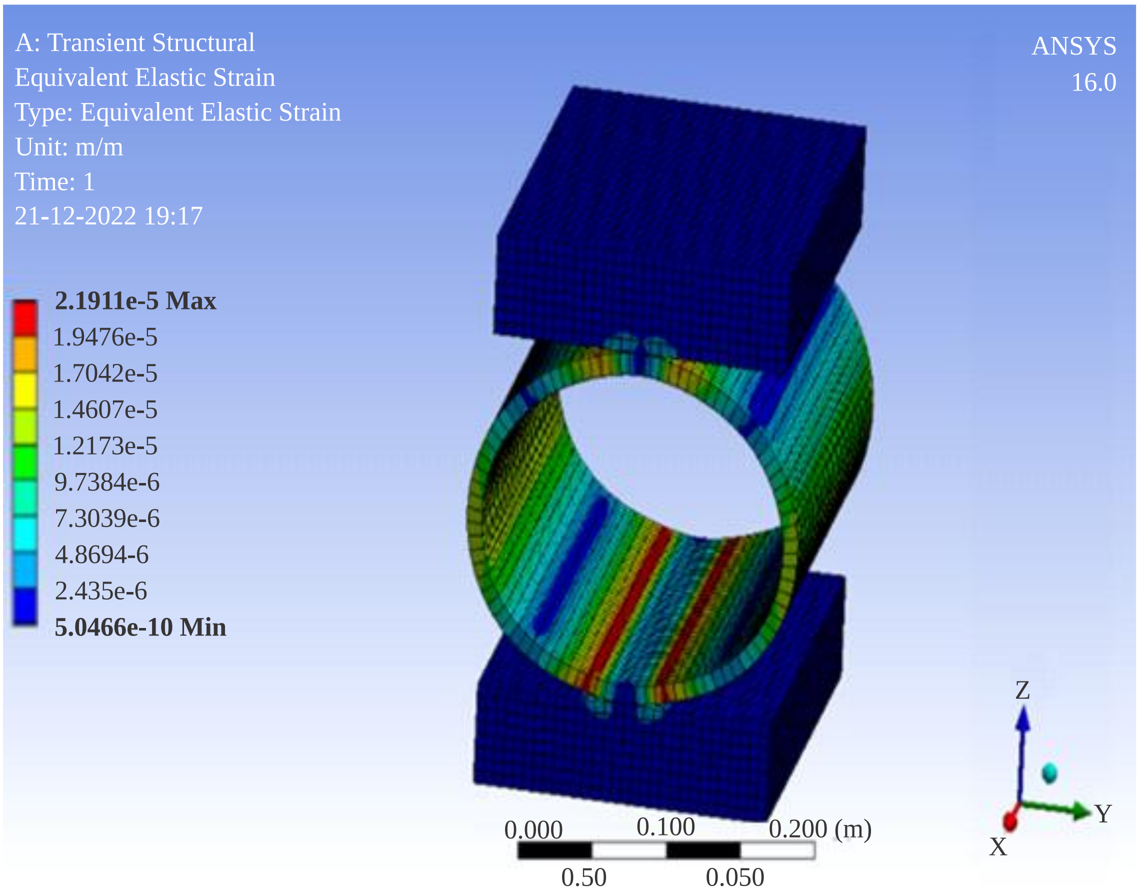

Figure 6. At increments of 0.3, the main unit strain in the pipe's material is distributed.

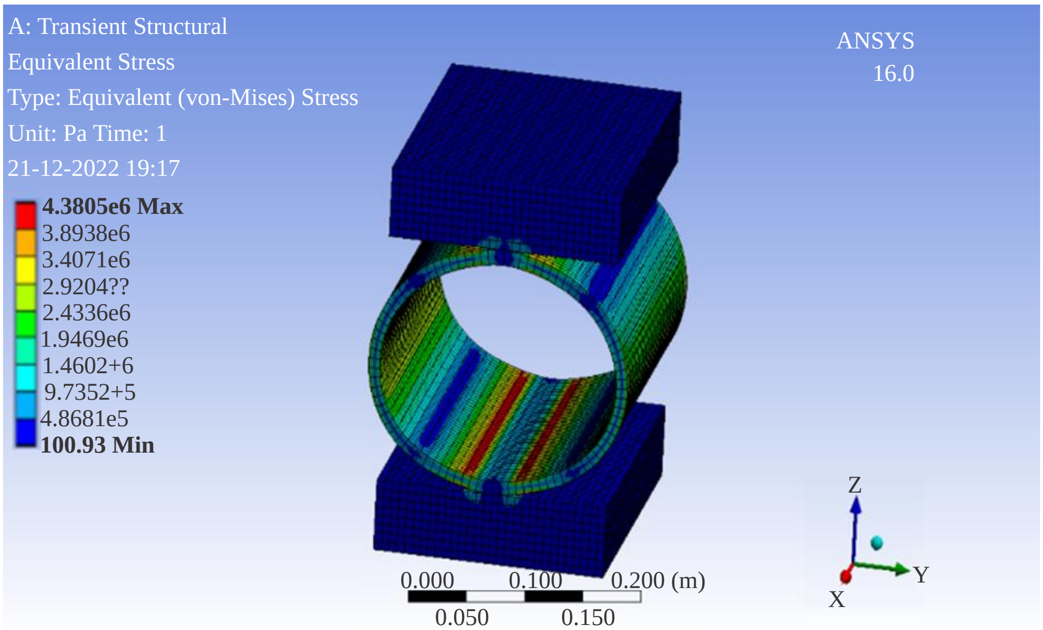

Figure 7. At increment 0.3, the distribution of von Mises stresses is found in the pipe's material.

Setting up the Welding Installation

The butt fusion welding machine should be checked before welding pipes together to ensure that it functions silently and smoothly, and that it is programmed according to the material of the pipe to be welded. The use of the proper vices or bushes, as well as tightening all of the mounts, will limit the chance of misalignments during the axial movement [7]. After the stabilization time of 20 minutes, the suitable temperature of the platen for the material to be welded must be confirmed in many locations using a contact thermocouple and a digital thermometer. In order to reduce contamination of the surfaces and heat losses, the platen should be covered with an insulating bag in between welding. To avoid slipping/back slashing during rotation, check that the cutters used to cut and straighten the ends of the pipes are sharp, undamaged, and firmly attached to the cutting tool. To ensure smooth operation, all moving parts must be examined, and leakproof hoses and fittings must be installed on hydraulic machinery. Special care must be used when preparing the pipes to be welded. To obtain the correct length after the welding operation, we must take into account the shortenings that must be done during the straightening phase, as well as the fact that the pipes shorten when they melt. The components to be welded must first be axially straightened before being fixed in the welding machine's bars [8]. Before inserting the pipe into the machine, inspect the ends for any uneven edges, damages, or sand/grit embedded in or adhered to the surfaces. The irregularity's maximum depth cannot exceed 10% of the pipe's wall thickness. It is necessary to remove any pipes that are broken or have deep notches in them. Wipe the pipe's ends with a lint-free cloth on both the interior and exterior surfaces of the pipe to remove any minor contamination. The pipes must be secured in the welding equipment's fixtures once they have been cleaned. (See Figure 8) Fixing the pipes in such a way that their markings are aligned is recommended to align them. If necessary, it also aids in later identification.

After the pipes have been clamped in the vise, the ends can be brought into contact with a rotary tube straightener (Figure 8) and cut continually until both ends are straightened. Straightening the ends prepares them for a precise weld. The cuttings must be carefully removed so that they do not come into contact with the treated ends. As a result, we ensure that the pipe surface is free of grease or dirt from our hands. The alignment of the pipes should be double-checked, and if necessary, changes to the vice should be made to ensure that the diameter is not misaligned. Before the welding phase, [10] we must choose the heating and cooling durations and the welding pressure, based on the pipe diameter, and record them in the primary evidence sheets during the welding cycle.

Figure 8. Butt welding with the polyethylene welding machine.

Some machines have all of the essential tables with these characteristics according to the dimensions of the pipe to be welded stored in their internal memory. Others lack this capability, and the user will be required to use a timer or a clock to accurately time the settings. Remove the insulating bag from the platen and verify the temperature with a digital thermometer and a contact thermocouple. Before executing the actual weld, a test welded connection is usually created. [12] By doing so, we ensure that the surface of the platen that comes into touch with the pipe ends is completely clean and devoid of any dust or other particles that could contaminate the coupling.

The platen is then inserted between the pipe ends in the next technological phase of the process, and the operator must ensure that it is perpendicular to the pipe surface. The pipes are pushed until they come into contact with the hot platen, and then an axial force is applied to form a softened material seam around the pipe. On both sides of the platen, the seam should encompass the pipe's whole diameter. Depending on the type of equipment, the force is applied in various ways. The force is applied mechanically with a spring loading mechanism in some welding equipment, and the force is maintained by screw locking. Hydraulic pistons are employed in other types of equipment, and the pressure is maintained through the hydraulic circuit's switching valves.

The pressure is lowered for the heat melting phase once the required seam is attained. The pipes stay in touch with the hot plate, allowing the heat to enter the material and limiting the chance of "cold welding". Because the length of the melting phase varies depending on the pipe diameter and wall thickness, the manufacturer's specified time must be followed [13]. After this step is completed, the pipes are gently removed from the platen to ensure that the melted seam does not stick to the platen's surface, and the platen is quickly removed. The pipes are then forced together as smoothly as possible, yet as quickly as possible as shown in Figure 9, to reduce the risk of temperatures dropping and to avoid exceeding the force required. When the needed force is obtained, the cooling phase of the weld begins. The welding force should be maintained throughout this phase to ensure the welded coupling's maximal resistance.

The pressure can be decreased to zero and the pipe can be withdrawn from the fittings after the cooling time has passed. The final weld can now be visually tested for uniformity and alignment, and if these are found to be satisfactory, it will be subjected to additional non-destructive tests (using the ultrasound or the penetrating radiation method).

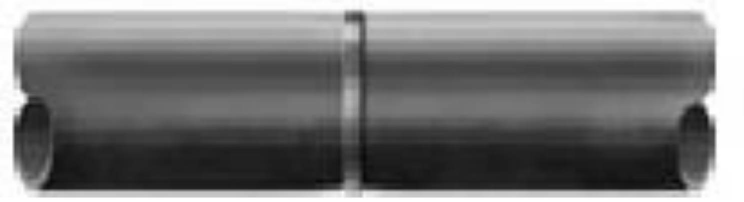

Figure 9. The 90 mm diameter pipes were butt welded.

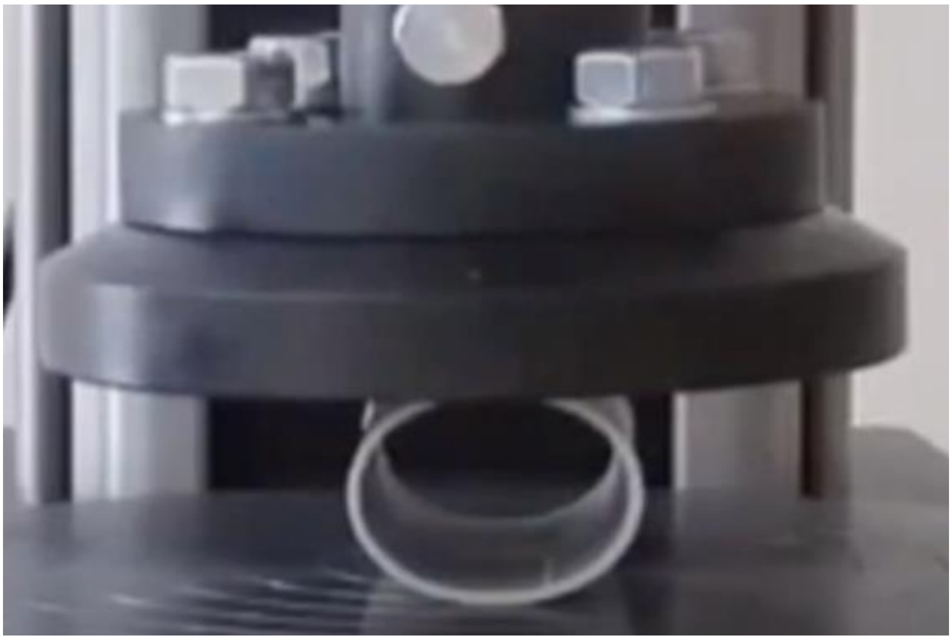

Figure 10. The universal testing machine to fix the pipe.

Radial Compression of Polyethylene Pipes And Butt Weld Test

Experimental tests were carried out using a tensile, compression, and buckling testing machine Instron 5587 to measure the crushing strength of polyethylene pipes used for natural gas transportation, with samples cut in 250 mm sections from various diameter pipes [11]. These experiments were carried out in order to determine the deformation of a sample, the elastic recovery, and the strains and stresses that occur in such structures. In addition to the Instron machine software, an optical approach utilizing Aramis 2M equipment was used for these experimental determinations [14].

We used 90 mm diameter (PE100) polyethylene pipes for the experiment. According to ASTM D 2412, a pipe's flexural stiffness can be computed using the following equation:

$$SN = \frac{E \cdot I}{D^3}, \tag{18}$$

where SN is the flexural rigidity, E is the pipe material's elastic modulus (E = 1.2 GPa for PE100 pipe), and I is the section's moment of inertia derived using the equation: I = t3/12, where t is the pipe thickness and D is the pipe's median diameter.Pieces of around 250 mm in length were cut for the research samples, which were then compressed radially (Figure 10).

The portions of the pipe were painted in a rapid drying adherent matte white paint before being compressed for optical data collecting using the Aramis 2M system. The portions exposed to the imaging equipment were then sprayed with a graphite powder. The polyethylene pipes were compressed at a maximum force of 7,500 N with a 10 mm/min upload speed, allowing data on pipe deformation to be collected using the Aramis 2M system and data on compression behaviour to be collected using the Instron 5587 machine's software at the same time.

Figure 11. Testing equipment for polyethylene pipes.

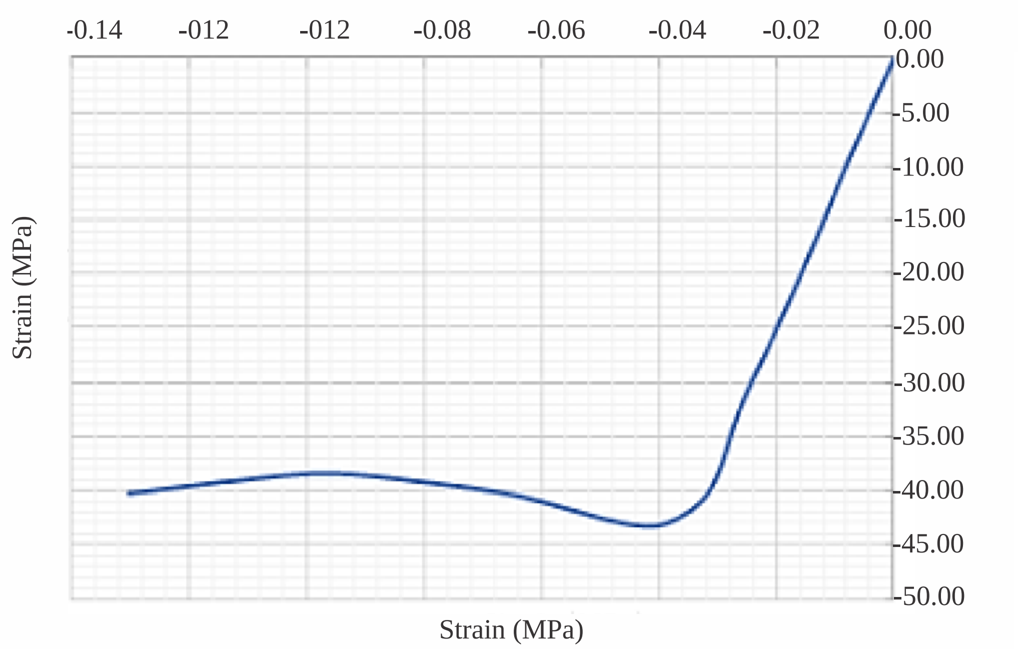

Figure 12. Stress-Strain experimental curves for the Dn90 pipe.

The full assembly used for the experimental determinations is shown in Figure 11: Universal testing machine Instron 5587, polyethylene pipe, high-speed cameras, data acquisition computer. The force-deformation curves for the 90 mm diameter and PE100 materials are shown in the Figure 12. The graph below shows how the maximum deformation (equivalent to a force of 7,500 N) varies depending on the diameter and material of the pipe (PE100).

RESULT AND CONCLUSIONS

Following theoretical studies on polyethylene pipes and fittings, the following conclusions and observations are made, which largely confirm the questionnaire's findings:

- The calculation elements of the forces that appear in welded polyethylene assemblies confirm that the fracture zone of the polyethylene pipe is the butt welded area, where the initial cut and filler material welding are performed.
- The largest stress was recorded in the middle portion of an assembled Dn 90 element when it was radially subjected to an unintentional force.
- We introduced polyethylene fracture elements-fundamental theoretical conceptions-that are critical for preparing the practical study that will follow.
- Accidental components, such as those that can degrade polyethylene pipe and fittings, have also been noted.
- Because the contact surface between the pipe and the fitting is substantially larger, we propose using polyethylene fittings and electro fusion welding.
- After situating the polyethylene pipe, the butt weld can be further protected with a protective polyethylene tube, which will safeguard the weld in the event of an unintentional collision.

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