International Journal of Advanced Engineering and Management Research

Vol. 10, No. 01; 2025

ISSN: 2456-3676

Theoretical and Experimental Considerations Regarding the Evaluation of the Mechanical Characteristics of Polyethylene Pipes Under Multiple Loading Conditions

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doi.org/10.51505/ijaemr.2025.1011 URL: http://dx.doi.org/10.51505/ijaemr.2025.1011

Received: Feb 05, 2025 Accepted: Feb 12, 2025 Online Published: Feb 17, 2025

Abstract

Polyethylene pipes are used in most applications for the transport and distribution of drinking water. Pipe systems generally have complex routes that include undercrossings of roads. Consequently, the pipe loads are complex, resulting from: internal fluid pressure, soil loads, traffic pressure. In a test program aimed at evaluating both the axial stress behavior and the mechanical characteristics of polyethylene pipes used in the construction of water distribution piping systems, in the presence of defects, theoretical and experimental research was carried out. The main scope of the research carried out was to determine the behavior of PE100 polyethylene pipes under multiple stress conditions. Thus, a PE100 polyethylene pipe was successively analyzed in analytical evaluation, traffic overpressure simulation, internal pressure test and numerical evaluation. The purpose of performing the multiple stress test of the buried PE100 polyethylene pipe was to evaluate the influence of a defect that can occur on the outer surface of the pipe during installation in the trench, by simulating localized traffic overload and internal pressure, and determining the stress intensity factor, K_I. The present work represents a novelty and it is the main contribution in the buried PE pipe mechanical behavior field. The study addresses how the shape, position, and size of the surface defect could affect the value of the stress intensity factor. By modifying the values of the geometric dimensions of the defect, obtained by imprinting on the outer surface of the pipe with outer diameter, D_e = 90 mm, wall thickness, s = 5.4 mm, and a length, L_{pipe} = 4000 mm, the viscoplastic character of the material was highlighted. The calculated value of stress intensity factor, K_I, is 0.7007 MPa·m$^{1/2}$, and calculated value of the maximum stress is 19.654 MPa. By numerical evaluation, the value of maximum stress developed in the pipe wall was obtained as 19.937 MPa.

Keywords: polyethylene pipe, defect, stress, strain, stress intensity factor, traffic

1. Introduction

1.1 Theoretical considerations regarding the evaluation of the mechanical characteristics of polyethylene pipes under multiple loading conditions

Distribution networks are relatively difficult to operate because they are long, in some segments they are positioned under the road and operate at continuously variable technological parameters (BICA I., 2013).

The mechanical behavior of PE100 polyethylene can be assessed through a basic characteristic, called toughness. Toughness is the ability of a material to withstand large plastic deformations under the action of a high level of loading until it breaks.

In order for the presence of a physical defect not to cause the destruction (rupture) of a resistance element, it is necessary that the value of the toughness characteristic, determined analytically for that defect, be lower than a critical value of the toughness characteristic, called fracture toughness (BRÎNZAN O., 2006).

In the specialized literature, two seemingly similar notions are used, but with different areas of applicability, namely:

a) the toughness of materials specific to materials considered without physical discontinuities (voids, cracks, etc.) and generally assessed based on the surface area under the characteristic tensile curve;

b) the fracture toughness of materials specified for materials (strength elements) that present physical discontinuities (voids, cracks, etc.)

The British standard (EN 1295-1, 1998), through its two component parts, namely: Part 1: General requirements and Part 2: Summary of nationally established design methods, is the normative framework necessary for conducting experimental testing to evaluate the mechanical characteristics of polyethylene pipes under multiple loading conditions.

This standard provides information on the structural design of buried pipelines under various loading conditions. Also, (EN 1295-1, 1998) contains calculation recommendations regarding the stresses and deformations obtained from simultaneous loading. In (EN 1295-1, 1998) there are specifications regarding the effect of pressure on pipe deformation, on pipe buckling under pressure, as well as on longitudinal thrusts and stresses.

The correct and sustainable operation of a water supply system is determined by proper design and execution. Increased attention is currently being paid to advancing the installation of trenchless pipeline installation techniques, as well as guaranteeing their lifespan of more than 50 years.

To determine the solution for laying the pipeline pipes in the trench, the type of retaining walls and the method of filling, it is important to have a good knowledge of the soil lithology and the geotechnical characteristics of the ground.

The loads to be considered refer to:
a) permanent loads, such as ground overburden, asphalt weight (if any) and the self-weight of the pipeline;
b) variable loads, such as the uniformly distributed surface load, the vertical load caused by traffic, the weight of the transported fluid and the load from internal and external pressure, other than atmospheric.

All these loads have an effect on the operational behavior of the buried polyethylene pipe. Under certain conditions, the level of stresses developed in the pipe wall, especially in the presence of defects, can reach the limit state (MANU ID., PETRESCU MG., ZISOPOL DG., NAIM RI., ILINCA CN., 2024).

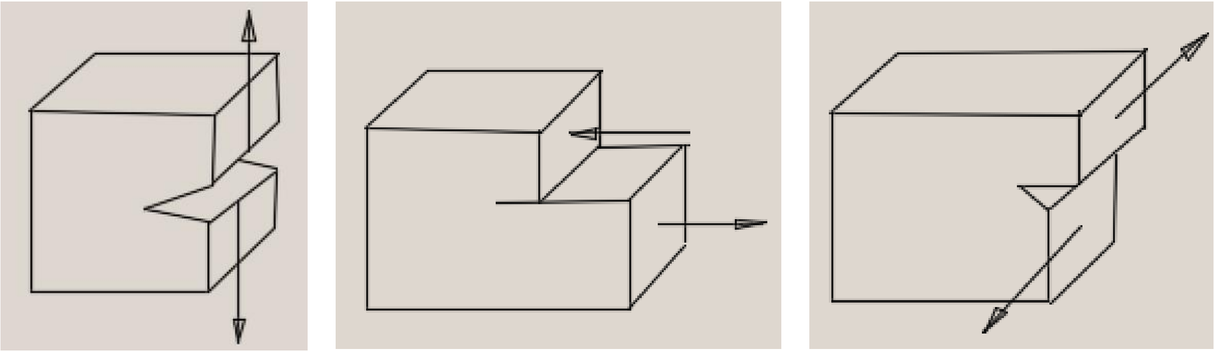
In order to prevent the rupture of pipelines in service that have defects, the allowable stress level of the pipeline, σ_{adm}, can be determined based on the critical stress intensity factor, K_{Ic}, and the dimensions of the defect(s).
The critical stress intensity factor corresponding to the mode I of propagation through the opening of the defect, K_{Ic}, is a material characteristic that is the ability of a body with a defect to resist the stresses acting around the defect and was experimentally determined in (ALUCHI, 2013), obtaining the value $K_{Ic} = 0.743$ MPa·m$^{1/2}$.

The critical stress intensity factor, K_{Ic}, is useful in verifying the condition of non-initiation of the rupture process, given in the relation (1).

$$K_I \le K_{I_c} \qquad (1)$$

where:
K_I – stress intensity factor corresponding to the mode I propagation through the defect opening, [MPa·m$^{1/2}$];
K_{Ic} – critical stress intensity factor, a material's feature of the pipe, [MPa·m$^{1/2}$].

According to Irwin, the edges of a defect can have three independent kinematic motion modes, highlighted in the figure 1a, 1b, and 1c.



a) b) c)

Figure 1. Independent kinematic movement modes of the edges of a defect: a) mode I or tensile opening mode; b) mode II or in-plane sliding opening mode; c) mode III or anti-plane sliding opening mode

Due to analytical difficulties, explicit solutions to the problem of defects in three-dimensional bodies include circular and elliptical defects.
The analytical expression of the stress intensity factor, K_I, for the case of a pipe that presents an unpenetrated semi-elliptical defect on the external surface (figure 2), whose opening is made according to mode I, is given by relation (2).

$$K_I = \sigma_{ech}\sqrt{\pi c \beta(a, L_{pipe})} \qquad (2)$$

where:
σ_{ech} – equivalent stress, [MPa];
c – half-length of the defect, measured in the direction in which the defect extends, [mm];
β – coefficient that depends on the dimensions of the defect and the part it contains;
a – depth of the defect, [mm];
L_{pipe} – length of the pipe containing the defect, [mm].

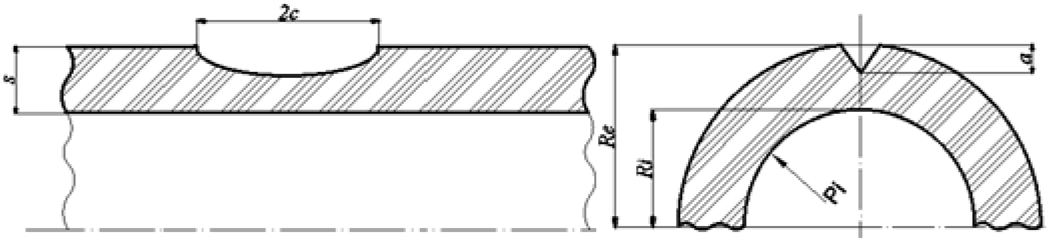


Figure 2. Section in a PE100 pipe with unpenetrated semi-elliptical defect

To determine the value of the stress intensity factor, K_I, in the case of an unpenetrated semi-elliptical defect, shown in figure 2, at a depth $a < s$, the relation (3) is used, according to (ULMANU, V., ZECHERU Gh., 1994).

$$K_I = \left[M_F + \left(\Phi\sqrt{\frac{c}{a}} - M_F \right) \cdot \left(\frac{a}{s} \right)^8 \right] \cdot \frac{\sigma\sqrt{\pi \cdot a}}{\Phi} \cdot M_{TM} \qquad (3)$$

where:
M_F - factor that depends on the geometry of the defect (a/c), which is determined by relation (4).

$$M_F = \sqrt{1 - \left(\frac{a}{c} \right)^2} \qquad (4)$$

Φ – the complete elliptic integral of the second degree, which is determined by relation (5).

$$\Phi = \int_0^{\pi/2} \sqrt{1 - e_f^2 \cdot \sin^2 \varphi} \cdot d\varphi \qquad (5)$$

e_f – elliptic modulus or eccentricity; $e_f = \tan\varphi$

φ – defect angle; [°]; $\varphi = \cos^{-1}\left(\frac{a}{c}\right)$

M_{TM} – correction factor that takes into account the increase in stress due to radial deformation in the vicinity of the defect and which is determined with the relation (6).

$$M_{TM} = \frac{1-\frac{a/s}{M_T}}{1-\frac{a}{s}} \qquad (6)$$

M_T – Folias correction factor, for the ratio λ < 1, $M_T = \sqrt{1+1{,}61\lambda^2}$;

λ – ratio, $\lambda = \frac{c}{\sqrt{R_m \cdot s}}$, where c – half-length of the defect, R_m – average radius and s – wall thickness.

1.2 Experimental considerations regarding the evaluation of the mechanical characteristics of polyethylene pipes under multiple loading conditions

2. Materials and methodology

1) Materials used in the multiple stress test of buried PE100 polyethylene pipe
(a) Pipe
The PE100 polyethylene pipe used for the multiple stress test (Figure 3) had the following dimensional and material characteristics: pipe outer diameter, D_e = 90 [mm]; wall thickness, s = 5.4 [mm], pipe length, L_{pipe} = 4000 [mm]; pipe material density, ρ_{PE100} = 960 [kg/m^3].

Figure 3. The PE100 polyethylene pipe used for the multiple stress test

(b) The filling material
The pipe was laid in an irregular trench, without supervision, with soil with stones or rocks for which n_2 - coefficient that takes into account the type of terrain is n_2 = 6, being unsettled terrain. The pipe bedding, made of the filling material, is shown in Figure 4a. The backfill material used in the experiment is shown in Figure 4b.

a) b)

Figure 4. Aspects of laying a PE100 polyethylene pipe in a trench:
a) pipe bedding; b) backfill material

The metal tubes, two in number, were used to simulate the load due to street traffic, P_t. Thus, the experiment used the additional load produced by the weight of the two metal tubes, shown in Figure 5, having: tube outer diameter, D_{tube} = 250 mm, tube wall thickness, s_{tube} = 11.3 mm, tube length, L_{tube} = 1840 mm, and tube material density, $\rho_{steel} = 7.85 \cdot 10^3$ [kg/m^3].

Figure 5. Metal tubes used to simulate the load due to street traffic

(c) Used equipment
In the multiple stress test of the buried PE100 polyethylene pipe, the Rems Push manual pressure test pump (Figure 6a), with a maximum pressure of 160 bar (Figure 6b), the Shangli CPCD30 diesel forklift (Figure 7) and the experimental facility used for testing of polyethylene pipes were used.

a) b)

Figure 6. The Rems Push manual pressure test pump: a) general view; b) detail

Figure 7. Shangli CPCD30 diesel forklift

2) Methodology used in the multiple stress test of buried PE100 polyethylene pipe

PE100 polyethylene pipes and fittings must be buried according to (ASTM D2774, 2012) and (PE Pipe, 2006) for pressure systems.

The installation of polyethylene pipes can be carried out, according to (BAI Q., BAI Y., RUAN W., 2017) and with an open trench with/without sand bed, by the plowing method - DVGW GW 324. As a rule, the trench has a width of 50 cm + De (cm), according to (NE 035-06, 2006).

The pipe material is chosen depending on the water quality and soil aggressiveness. Corrosion resistance of the pipe material and not of the subsequent wall protection is preferred, according (NE 035-06, 2006). For this reason, the pipe made of PE100 polyethylene material was chosen.

The PE100 polyethylene pipe used in the experimental test had caps applied to ensure sealing of the ends (Figure 8). Type A steel caps were installed with threaded connections, shown in figure 9, according to ISO 1167-1.

Figure 8. Pipe with type A caps mounted at its ends

a) b)

Figure 9. Type A steel caps: a) graphic representation; b) real appearance

Subsequently, the pipe was positioned on the workbench to create a graphic representation of the marks on its surface in order to identify the exact position of the defects produced during the trench installation phase.

The distance between two consecutive circumferential marks - along the length of the pipe - was 30 mm (Figure 10a), and the distance between two consecutive horizontal marks - along the circumference of the pipe - was 40 mm (Figure 10b). Circumferential markers from 1 to 50 and horizontal markers from A to H were drawn (Figure 10c).

a) b)

c)

Figure 10. Creating a graphic representation of the marks on the surface of the PE100 pipe: a) drawing the circumferential marks; b) drawing the horizontal marks; c) the final appearance of the graphic representation of the marks drawn on the outer surface of the PE100 pipe

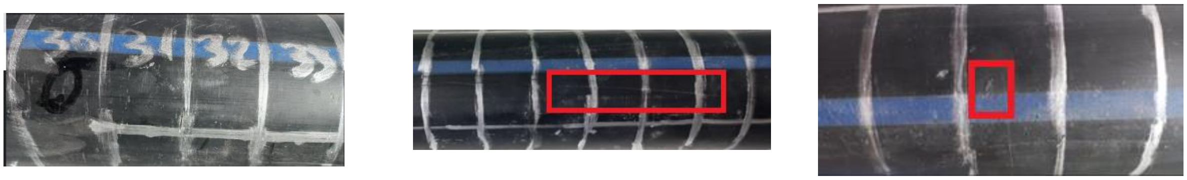
For the multiple stress testing of the polyethylene pipe, the following steps were carried out:
a) mechanized digging of the trench with length, L = 5000 mm, width, l = 600 mm and depth, h = 500 mm;
b) creation of the foundation bed, using the filling material shown in figure 11;
c) positioning the test pipe on the foundation bed;
d) connecting the pipe through the hole in one of the two covers to the Rems Push pump;
e) introducing water to obtain internal pressure;
f) overlapping metal pipes to simulate traffic overpressure;
g) identification of defects made on the outer surface of the pipe during the stressing stage;
h) analysis of the identified defects;
i) stressing the pipe to internal pressure until it bursts;
j) identification of the defect that caused the pipe to burst.
Pipe is shown in the preliminary stage of installation in the trench in the figure 11.

Figure 11. Pipe in the preliminary stage of installation in the trench

Figure 12 shows the overlapping of metal tubes over PE100 polyethylene pipe for the purpose of simulating traffic overload.

Figure 12. Applying an external load (122.3963 kg) to the defect area to simulate localized traffic overload

After performing the traffic overload simulation stage, non-destructive examination of the PE100 polyethylene pipe was performed, carried out by visual inspection. During the visual inspection, defects of type lack of material were identified, such as imprint (figure 13a), scratch (figure 13b) and microcrack (figure 13c), positioned on the outer surface of the pipe.



a) b) c)

Figure 13. Defects of type lack of material identified on the outer surface of the PE polyethylene pipe: a) imprint, b) scratch; c) microcrack

After internal pressure testing of the pipe (figure 14), it was found that the defect identified in the form of a scratch, shown in figure 13c, was the defect that caused the pipe to burst.

Figure 14. Internal pressure testing of the pipe

The location and description of the defect are requirements in writing an experimental test report. In this regard, the defect was positioned in the GH 23-26 space (figure 15) and had the appearance of a scratch, 9 mm long and 1.2 mm deep (MANU ID. – PhD Thesis, 2024).

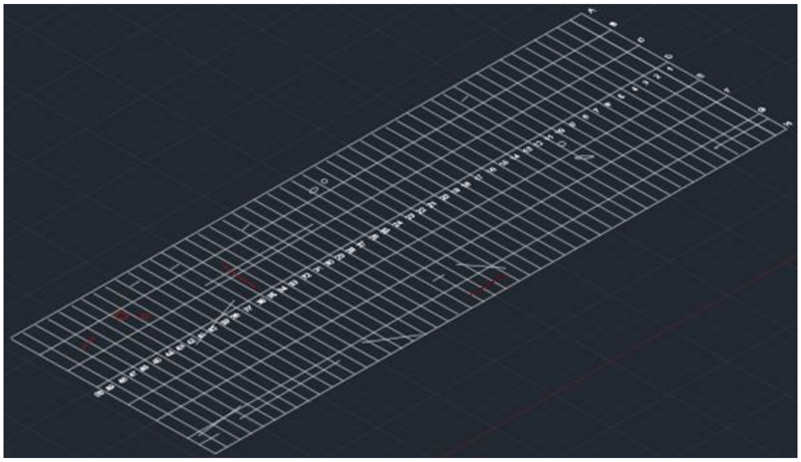


Figure 15. Positioning of defects identified on the outer surface of the PE100 polyethylene pipe after traffic overload simulation

The PE100 polyethylene pipe subjected to multiple stress testing was numerically evaluated through a study conducted in the Ansys program.

The purpose of the numerical evaluation was to evaluate the influence of the identified defect on the strength of the tested pipe. For this purpose, the defect depth values were consecutively increased from 10% to 70% of the wall thickness, *s*. The same procedure was applied to the length of the defect, which was consecutively increased from 10% to 70% of the pipe length, L_p.

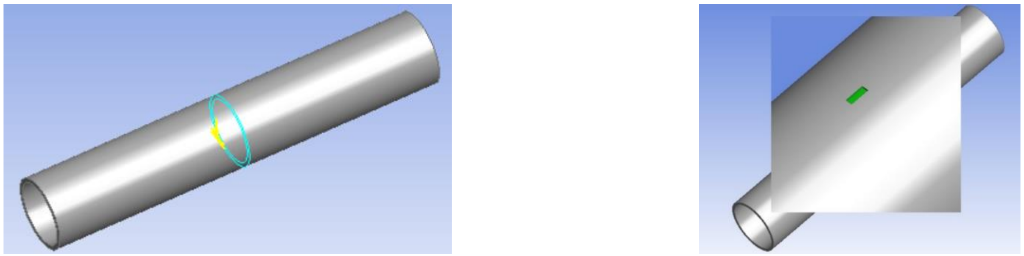
For the tested pipe, in the ENGINEERING DATA stage, the same characteristics of the PE100 polyethylene materials presented in the table 1 were used.

Table 1. Material characteristics of PE100 polyethylene

Material characteristic	Symbol	Material characteristic value	Unit of measurement
Density	ρ	960	[kg/m^3]
Young's modulus	*E*	1100	[MPa]
Poisson's ratio	μ	0.45	-

Since the structure of the pipe under analysis presents both longitudinal and transverse symmetry, in order to improve computational efficiency, a model with a length of 500 mm was adopted.

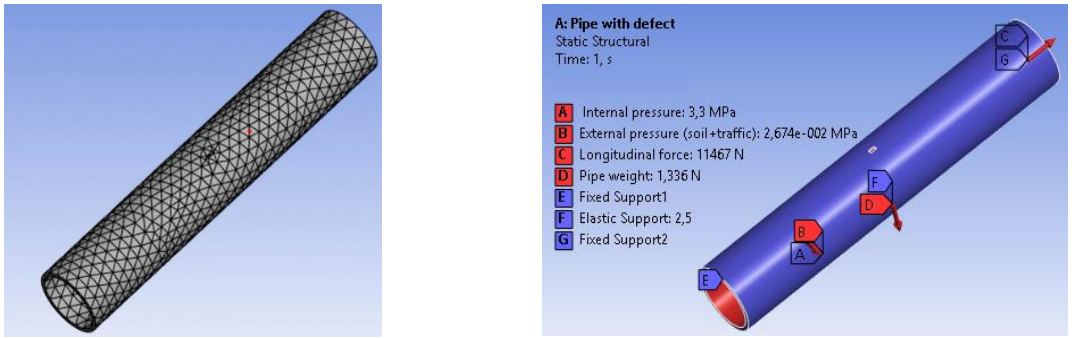
In the GEOMETRY stage, the geometry of the PE100 pipe was create (Figure 16a). The scratch-type defect, 9 mm long and 1.2 mm deep, was created and its appearance is shown in the figure 16b.



a) b)

Figure 16. Geometric models: a) of the PE100 pipe; b) of the defect

In the MODEL and SETUP stages of the numerical analysis, the pipe discretization was performed and the loads acting on the pipe were introduced and positioned (figure 17).



A: Pipe with defect
Static Structural
Time: 1, s

A Internal pressure: 3,3 MPa
B External pressure (soil+traffic): 2,674e-002 MPa
C Longitudinal force: 11467 N
D Pipe weight: 1,336 N
E Fixed Support1
F Elastic Support: 2,5
G Fixed Support2

a) b)

Figure 17. MODEL and SETUP stages of the numerical analysis:

a) the pipe discretization; b) loads acting on the pipe

3. Results

The results obtained in the evaluation of the polyethylene pipe under multiple stress conditions and their interpretation are presented in tables 2, 3 and 4 and in figures 18, 19, 20, 21, 22, 23 and 24.

For evaluating the polyethylene pipe under multiple stress conditions, for the stress intensity factor, K_I, the value presented in table 2 was obtained by using the calculation relations (3), (4), (5) and (6).

Table 2. The stress intensity factor, K_I, for polyethylene pipe evaluated under multiple stress conditions

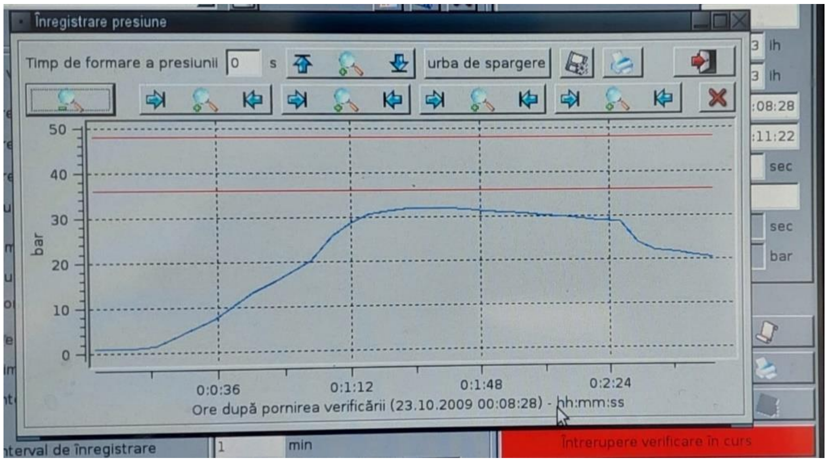
Average pipe diameter	Defect depth	Defect length	Half of defect length	Average radius	Wall thickness	Report	Folias correction factor
D_m	a	L_{defect}	c	R_m	s	λ	M_T
[m]	[m]	[m]	[m]	[m]	[m]	[-]	[-]
0.0846	0.00012	0.009	0.0045	0.0423	0.0054	0.2977	1.069
	Correction factor	Defect angle	Elliptic modulus or eccentricity	Complete elliptic integral of the second degree	Factor depends on the defect geometry	Maximum stress	Stress intensity factor
	M_{TM}	φ	e_f	Φ	M_F	σ	K_I
	[-]	[º]	[-]	[-]	[-]	[MPa]	[MPa·m$^{1/2}$]
	1.0184	1.0366	1.6906	1.6904	0.9638	19.654	0.7007

During the traffic overload simulation phase, defects such as imprints, scratches and microcracks were observed on the external surface of the pipe. The scratch defect, 9 mm long and 1.2 mm deep (representing 22.22% of the pipe wall thickness), was the cause of the pipe bursting.

The polyethylene pipe bursting occurred through local swelling around the defect identified as being located in the GH 23-26 space, concomitant with wall thinning until failure (Figure 18). The length of the portion of the pipe affected by the rupture was 35 mm.

Figure 18. PE100 polyethylene pipe failure evaluated under multiple stress conditions

The burst pressure values and burst time values recorded for the PE100 polyethylene pipe evaluated under multiple stress conditions are presented under the pressure-time (bar-s) diagram, shown in Figure 19 and Table 3.



Timp de formare a presiunii 0 s

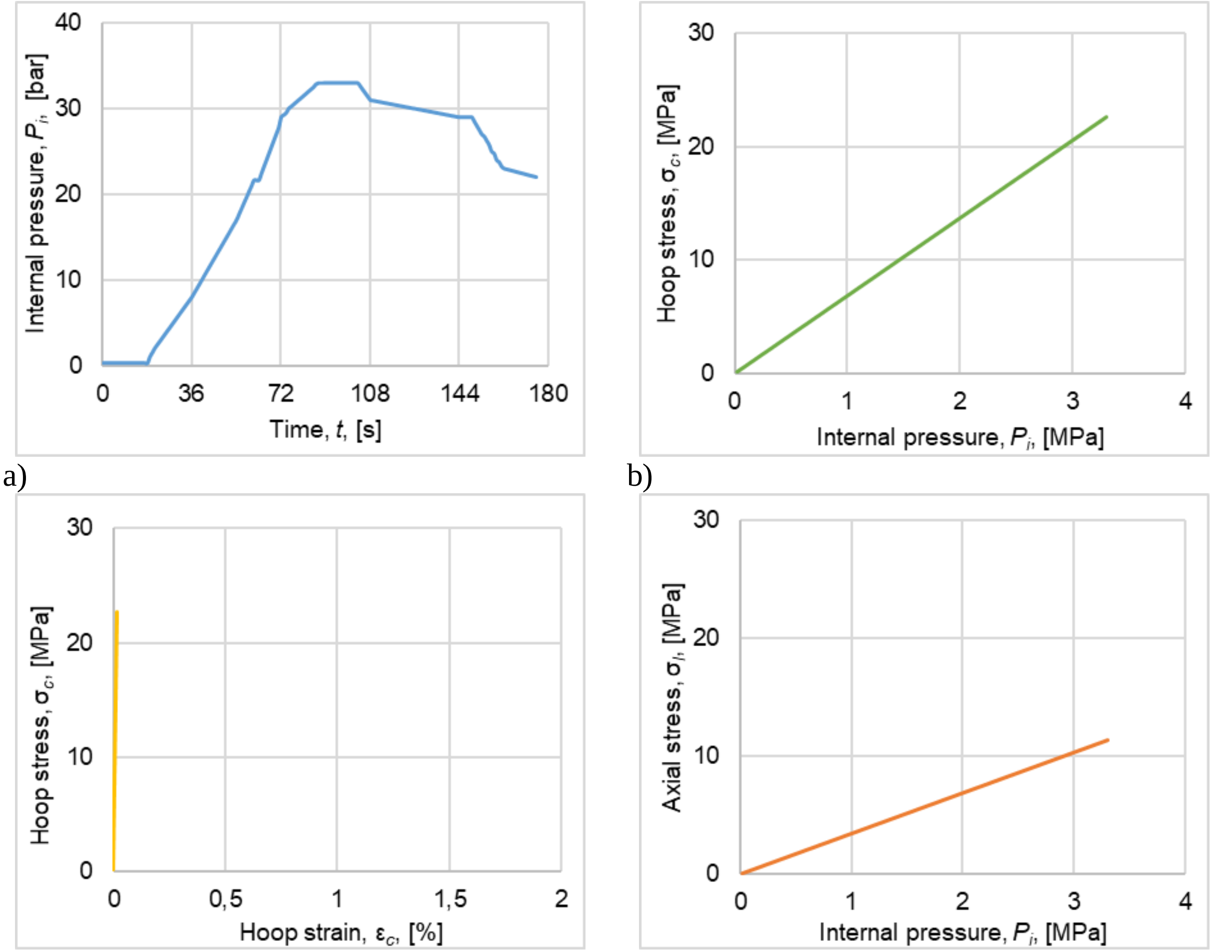
nterval de înregistrare 1 min

Figure 19. Pressure-time diagram (bar – s) for PE100 polyethylene pipe evaluated under internal pressure test stage

Table 3. Results recorded to testing PE100 pipe evaluated under internal pressure test stage

Testing pipe	Burst pressure	Burst time
	P_i, [bar]	t, [s]
PE100 polyethylene pipe evaluated under multiple stress conditions	33	149

To study the behavior of the PE100 polyethylene pipe evaluated under multiple stress conditions, the following diagrams were drawn: internal pressure - time, hoop stress - internal pressure, hoop stress - hoop deformation and axial stress - internal pressure (Figure 20).

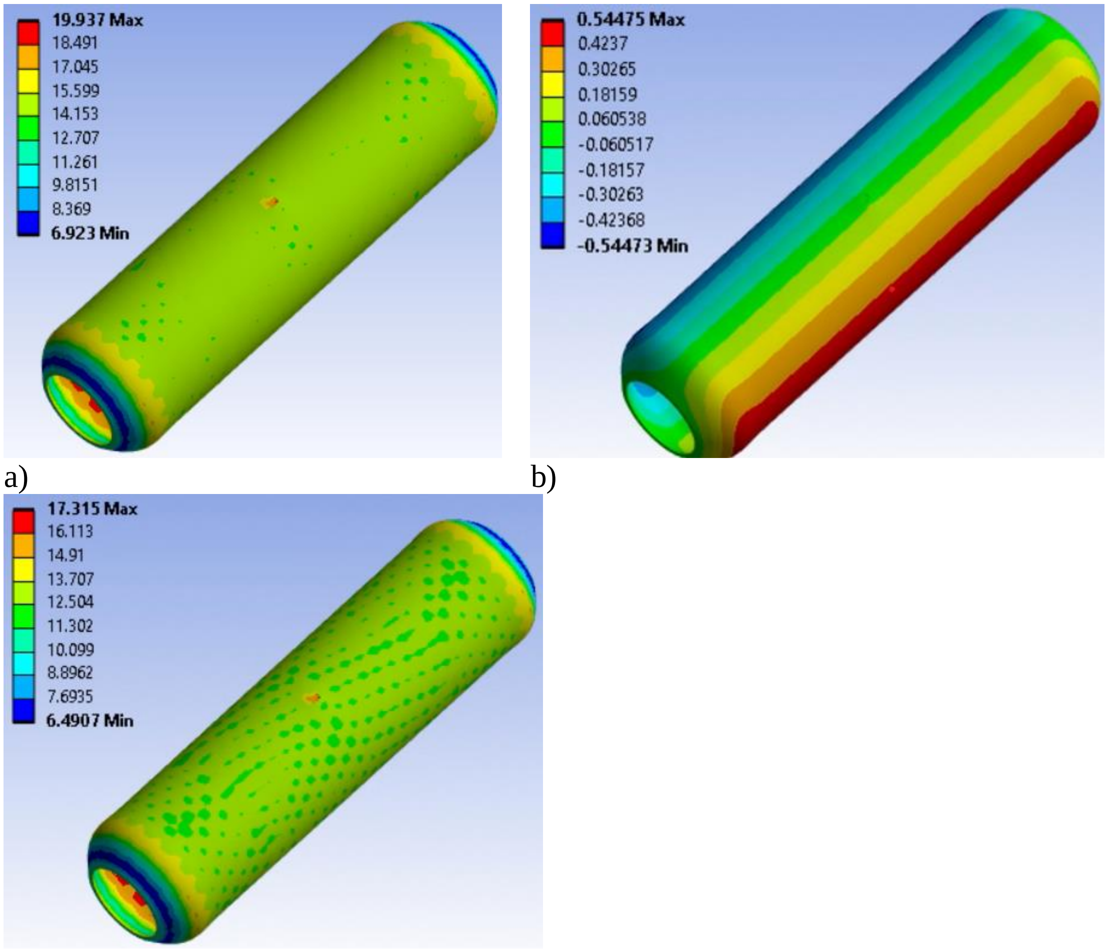


a) b)

c) d)

Figure 20. Diagrams for PE100 polyethylene pipe evaluated under internal pressure test stage: a) $P_i - t$; b) $\sigma_c - P_i$; c) $\sigma_c - \varepsilon_c$; d) $\sigma_l - P_i$

In the numerical analysis, in the SOLUTION stage, results were obtained in the form of stresses, strains and equivalent stresses, presented in Figure 21.



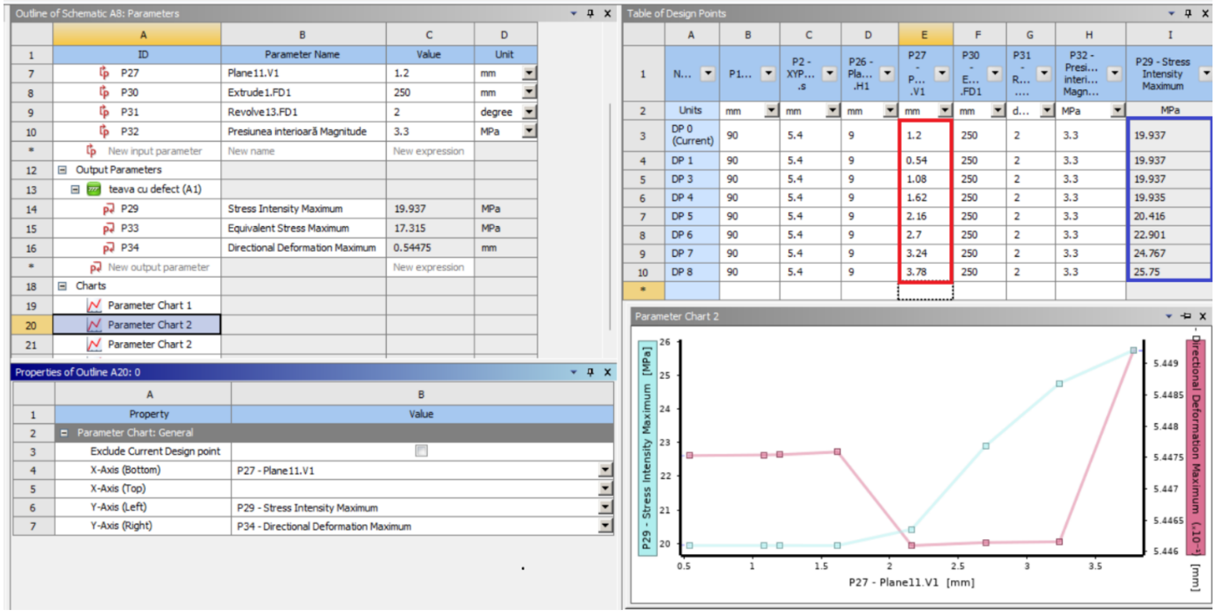
a)

b)

c)

Figure 21. Results obtained in SOLUTION stage of numerical analysis: a) strength values; b) strains values; c) equivalent stress values

To present the maximum values of the Stress Intensity, Equivalent Stress, Directional Deformation parameters and analyze the influence of defects on the mechanical strength of the PE100 pipe, printscreens are shown with the modified values of the defect depth, *a*, (Figure 22), and with the modified values of the defect length, 2*c*, (Figure 23) and, implicitly, the modified values of the Stress Intensity parameter.

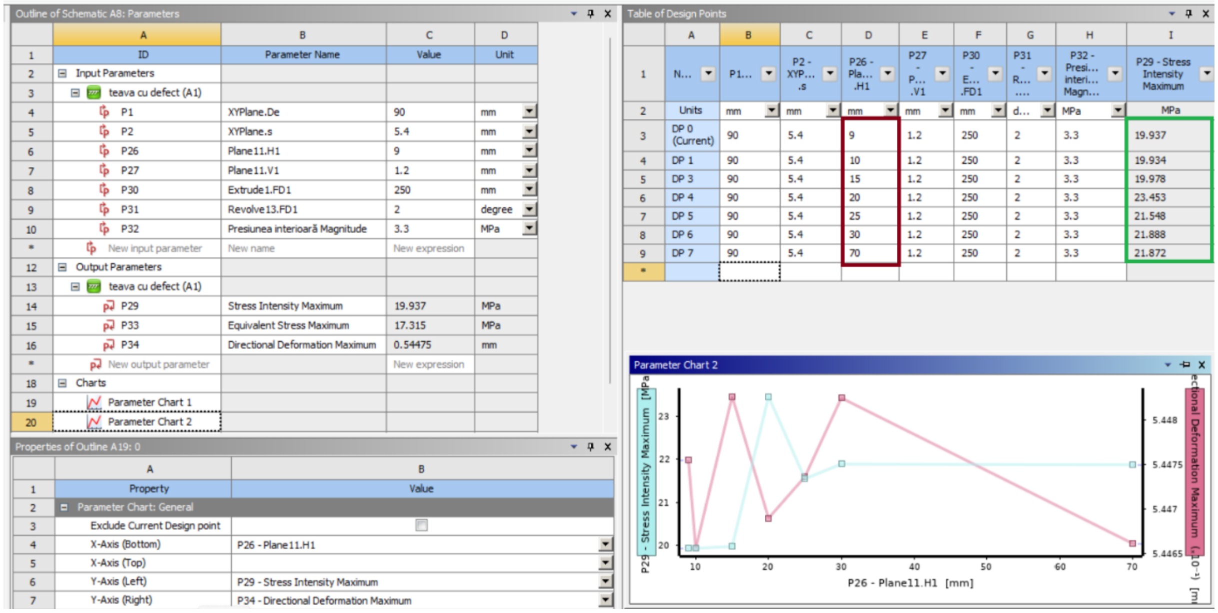


	A	B	C	D
1	ID	Parameter Name	Value	Unit
7	P27	Plane11.V1	1.2	mm
8	P30	Extrude1.FD1	250	mm
9	P31	Revolve13.FD1	2	degree
10	P32	Presiunea interioară Magnitude	3.3	MPa
*	New input parameter	New name	New expression	
12	⊟ Output Parameters			
13	⊟ teava cu defect (A1)			
14	P29	Stress Intensity Maximum	19.937	MPa
15	P33	Equivalent Stress Maximum	17.315	MPa
16	P34	Directional Deformation Maximum	0.54475	mm
*	New output parameter		New expression	
18	⊟ Charts			
19	Parameter Chart 1			
20	Parameter Chart 2			
21	Parameter Chart 2			

	A	B
1	Property	Value
2	⊟ Parameter Chart: General	
3	Exclude Current Design point	☐
4	X-Axis (Bottom)	P27 - Plane11.V1
5	X-Axis (Top)	
6	Y-Axis (Left)	P29 - Stress Intensity Maximum
7	Y-Axis (Right)	P34 - Directional Deformation Maximum

	A	B	C	D	E	F	G	H	I
1	N...	P1...	P2 - XYP... .s	P26 - Pla... .H1	P27 - P... .V1	P30 - E... .FD1	P31 - R...	P32 - Presi... interi... Magn...	P29 - Stress Intensity Maximum
2	Units	mm	mm	mm	mm	mm	d...	MPa	MPa
3	DP 0 (Current)	90	5.4	9	1.2	250	2	3.3	19.937
4	DP 1	90	5.4	9	0.54	250	2	3.3	19.937
5	DP 3	90	5.4	9	1.08	250	2	3.3	19.937
6	DP 4	90	5.4	9	1.62	250	2	3.3	19.935
7	DP 5	90	5.4	9	2.16	250	2	3.3	20.416
8	DP 6	90	5.4	9	2.7	250	2	3.3	22.901
9	DP 7	90	5.4	9	3.24	250	2	3.3	24.767
10	DP 8	90	5.4	9	3.78	250	2	3.3	25.75
*									

Figure 22. Parameter analysis - change in defect depth



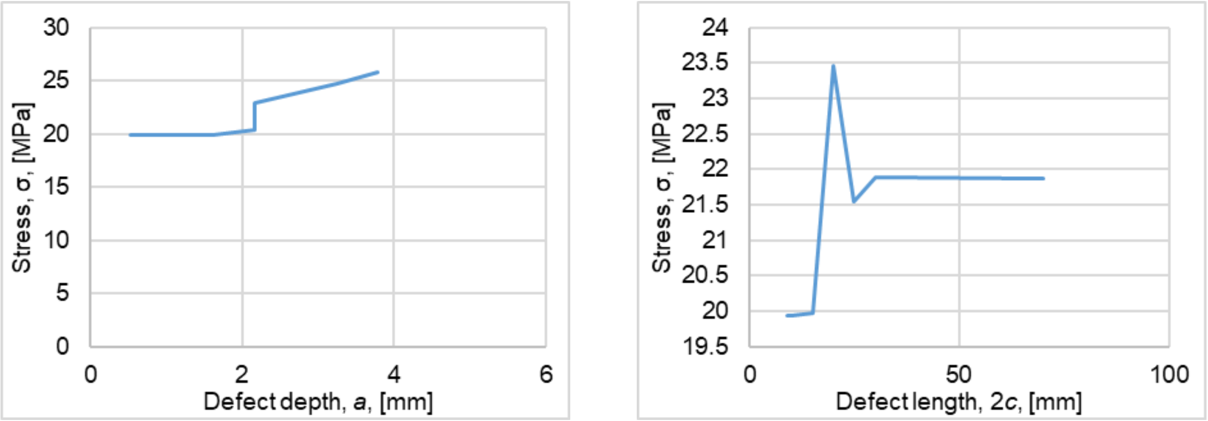
	A	B	C	D
1	ID	Parameter Name	Value	Unit
2	⊟ Input Parameters			
3	⊟ teava cu defect (A1)			
4	P1	XYPlane.De	90	mm
5	P2	XYPlane.s	5.4	mm
6	P26	Plane11.H1	9	mm
7	P27	Plane11.V1	1.2	mm
8	P30	Extrude1.FD1	250	mm
9	P31	Revolve13.FD1	2	degree
10	P32	Presiunea interioară Magnitude	3.3	MPa
*	New input parameter	New name	New expression	
12	⊟ Output Parameters			
13	⊟ teava cu defect (A1)			
14	P29	Stress Intensity Maximum	19.937	MPa
15	P33	Equivalent Stress Maximum	17.315	MPa
16	P34	Directional Deformation Maximum	0.54475	mm
*	New output parameter		New expression	
18	⊟ Charts			
19	Parameter Chart 1			
20	Parameter Chart 2			

	A	B
1	Property	Value
2	⊟ Parameter Chart: General	
3	Exclude Current Design point	☐
4	X-Axis (Bottom)	P26 - Plane11.H1
5	X-Axis (Top)	
6	Y-Axis (Left)	P29 - Stress Intensity Maximum
7	Y-Axis (Right)	P34 - Directional Deformation Maximum

	A	B	C	D	E	F	G	H	I
1	N...	P1...	P2 - XYP... .s	P26 - Pla... .H1	P27 - P... .V1	P30 - E... .FD1	P31 - R...	P32 - Presi... interi... Magn...	P29 - Stress Intensity Maximum
2	Units	mm	mm	mm	mm	mm	d...	MPa	MPa
3	DP 0 (Current)	90	5.4	9	1.2	250	2	3.3	19.937
4	DP 1	90	5.4	10	1.2	250	2	3.3	19.934
5	DP 3	90	5.4	15	1.2	250	2	3.3	19.978
6	DP 4	90	5.4	20	1.2	250	2	3.3	23.453
7	DP 5	90	5.4	25	1.2	250	2	3.3	21.548
8	DP 6	90	5.4	30	1.2	250	2	3.3	21.888
9	DP 7	90	5.4	70	1.2	250	2	3.3	21.872
*									

Figure 23. Parameter analysis - change in defect length

Also, the influence of the geometric dimensions of the defect on the strength of the PE100 polyethylene pipe evaluated under multiple stress conditions is shown in Figure 24.



a) b)

Figure 24. The influence of the geometric dimensions of the defect on the strength of the PE100 polyethylene pipe evaluated under multiple stress conditions is shown in Figure 24.

4. Discussion

The determined value of the stress intensity factor, in the case of polyethylene pipe evaluated under multiple stress conditions, is given in Table 2, namely K_I = 0.7007 MPa·m$^{1/2}$. This value is lower than the critical value determined by (ALUCHI, 2013), namely K_{Ic} = 0.743 MPa·m$^{1/2}$. In this case, relation (1) is fulfilled.

The maximum value of the internal pressure recorded during the internal pressure stress of the PE100 pipe was $P_{i,max}$ = 33 bar. This was the value at which the pipe depressurization began – corresponding to the bursting time of 149 s – test fluid leaks occurred or the process of water leakage from inside the pipe was initiated.

The pipe failure was ductile, also known as “parrot beak” (figure 18).
By numerical evaluation, for the scratch-type defect, positioned in the GH 23-26 space, with 9 mm long and 1.2 mm deep, the strength value of the pipe (maximum stress developed in the pipe wall) was obtained as 19.937 MPa.

By successively changing the values of the depth and length of the defect, in percentages from 10% to 70% of the geometric dimensions of the pipe, it was found that the resistance has a nonlinear variation (figures 22 and figures 23), which can be explained by the viscoelastic behavior of the material.

Experimental and numerical results show that surface defects, such as scratches and microcracks, can significantly reduce the mechanical strength of PE100 polyethylene pipes. Preliminary experimental and numerical findings indicate that surface imperfections, including scratches and microcracks, can substantially diminish the mechanical strength of PE100 polyethylene pipes. A scratch-type defect, with a depth of just 1.2 mm (22.22% of the wall thickness), was sufficient to induce pipe rupture under internal pressure. This underscores the necessity for robust pipeline protection methods during installation and the establishment of more stringent standards for assessing the quality of these before utilization.

5. Conclusions

The tests and results obtained in the evaluation of the polyethylene pipe under multiple stress conditions are shown in summary table 4.

Table 4. Centralizer of tests and results obtained in the evaluation of the polyethylene pipe under multiple stress conditions

Test name	Results obtained, symbol and unit of measurement	Description/values						
Analytical evaluation	Stress intensity factor, K_I, [MPa·m$^{1/2}$]	0.7007						
Traffic overload simulation	Identification of the defect in the form of a scratch	9 mm long and 1.2 mm deep positioned in the GH 23-26 space						
Internal pressure test	Burst pressure, P_i, [bar]	33						
	Burst time, t, [s]	149						
Numerical evaluation	Defect depth, a, [mm]	1.2	0.54	1.8	1.62	2.16	2.7	3.24
	Strength, σ, [MPa]	19.937	19.937	19.937	19.935	20.419	22.901	24.767
	Defect length, $2c$, [mm]	9	10	15	20	25	30	70
	Strength, σ, [MPa]	19.937	19.934	19.978	23.453	21.548	21.888	21.872

The study demonstrated that numerical modelling plays a crucial role in assessing the performance of PE100 polyethylene pipelines. It was found that numerical models can reduce the time necessary for conducting physical experiments and optimize the utilization of resources. Furthermore, the numerical results indicated that the depth and extent of defects significantly influence the mechanical behavior of the pipe, a finding corroborated by experimental evaluations.

Numerical modelling facilitates the simulation of multiple stress scenarios on pipelines by leveraging data from physical tests to optimize the identification of critical defect points, thereby reducing the need for extensive, costly, and time-consuming experimental tests, while the use of ANSYS software enables a rapid assessment of defect impact on pipeline strength and allows for the practical evaluation of multiple scenarios.

The use of hybrid approaches, integrating experimental testing with numerical simulations, can contribute to the development of more precise standards for the design and maintenance of underground pipelines.

This study emphasized the necessity for robust pipeline protection measures during installation and stricter standardized quality assessments to prevent premature failure and future work should focus on advanced monitoring techniques and protective coatings to enhance pipeline longevity and reliability.

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