The Mechanical Behavior of High-Density Polyethylene under Short-Time Hydraulic Pressure Test

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Received: 2 March 2024 | Revised: 22 March 2024 | Accepted: 30 March 2024

ABSTRACT

This paper provides a synthesis of the results of experimental research and numerical simulations on polyethylene pipes subjected to short-time hydraulic pressure testing. Also, the current paper offers basic information about the engineering behavior of High-Density Polyethylene (HDPE) under the aforementioned test. HDPE presents high levels of technical performance because it has a high-density resin, high molecular weight, and bimodal Molecular Weight Distribution (MWD). HDPE pressure pipelines are used in Drinking Water Distribution Networks (DWDNs) and are component pieces of the thermoplastic piping system. The experimental test was mainly oriented toward the comparative determinations of the burst pressure of both the defect-free pipes and those with a lack of material defects made through mechanical operations. Also, the experimental test establishes the short-time hydraulic failure pressure as well as the determination of the resistance of the polyethylene pipes to hydraulic pressure in a short time period. The numerical simulations were carried out with the purpose of validating the results obtained analytically and experimentally.

Keywords-polyethylene pipe; crack; defect; hoop stress; burst pressure; mechanical behavior

I. INTRODUCTION

A well-known principle of plastic science is that the mechanical properties of plastics are time dependent [1]. To predict the mechanical behavior of a pipe at various times, the loading method, and hoop stress conditions ASTM D1599 [2] can be employed. This test method established the short-time hydraulic failure pressure of thermoplastic pipes. The specific procedure is followed to determine the burst pressure of a tested specimen.

High-Density Polyethylene (HDPE) is extensively deployed in water distribution systems [3]. Each time a polyethylene (PE) pipe is pressurized or subjected to hydraulic transients, its circumference expands and unrestrained length decreases in an elastic manner [4]. Pressurized PE pipes for water distribution have been successfully in service for more than 50 years [5]. Currently, one of the crucial concerns in highly developed pipe line systems is the life and failure prediction of distribution networks [6]. PE is utilized in many industrial fields, such us Drinking Water Distribution Networks (DWDNs) for domestic and industrial use, irrigation, and water management [7].

Nowadays, modern materials with the Minimum Required Strength (MRS) of 10 MPa are available for pipe manufacturing [8]. HDPE has the advantages of low cost, low weight, satisfactory chemical stability, and low moisture and is broadly implemented in pipe production [9]. Despite these advantages, HDPE pipes are vulnerable to external damages, dents, and notches [10, 11].

In [12], HDPE pipes were tested under both constant and cyclic pressure, in thermal-oxidative aging conditions, using air pressure as an internal medium. The results manifested that the lifetime of these pipes obviously decreased under cyclic pressure, being 27.96% shorter than under constant pressure [12]. In [13], the burst pressure of HDPE pipes with various types of notches was predicted and tested. The findings displayed that the burst obviously decreases with the increment of the notch depth ratio whereas notches with the same depth and larger volume reduced the burst pressure of the notched HDPE pipes more profoundly [13]. Pressure testing inside the HDPE pipe certifies that the latter works properly and is correctly installed, providing an overview of how the product behaves. Being considered quality checking of PE pipelines, determination of internal pressure strength was performed in [14, 15], at 20 ℃, for HDPE, under exposure for 100 h and 12.4 MPa.

Inside the pipe, any type of pressure other than the atmospheric one is thought as a loading applied to the system [16]. In normal operation, when the water supply pipes are subjected to internal pressure P_i there is a tendency for them to extend in the longitudinal direction. Hydrostatic testing aims to highlight this phenomenon and assess its consequences. Applying internal pressure has a complex effect [16], inducing additional stresses and strains in the hoop direction, changing and deforming flexible pipes, such as PE pipes. The effects induced by internal pressure on PE pipes [16] may be classified as:

- For PE pipes which show circular cross-section, circumferential induced stresses and strain by the internal pressure will manifest as pure tensile or compression stresses.
- For pipes that do not have circular cross-section and which have been deformed, the applying internal pressure will determine the appearance of bending stress and strains.

The research objectives of this study are:

- The main objective of the research carried out was to determine the time until failure of the tested samples and identify the type of fracture and its position, under the given test conditions (temperature, pressure, and environment) through the short-time hydraulic pressure test.
- Short-time hydraulic pressure test was conducted, also, to discover and understand the effects of this testing on PEHD pipes.
- Studying how the shape, position, and size of surface defects affect stress intensity is the novelty and the main contribution of the current study in the PE mechanical behavior field.
- To predict the damage evolution and failure stress of HDPE pipes, the mechanical behavior of PE pipes under internal pressure was simulated using Finite Element Analysis (FEA). Ansys Workbench was utilized to perform the numerical simulations.
- The strength of the HDPE pipes without and with defects was compared adopting three different methods: the analytical method, experimental tests, and numerical simulations.

II. ANALYTICAL ASSESSMENT

For the analytical assessment of the structural integrity of thin-walled and pressurized pipes, without and with defects, the hoop stress was employed as the principal stress. This choice was made because whatever the pipe radius and thickness are, bursting occurs when the hoop stress reaches a critical value [17].

The time to burst, t_b, in plastic pipe samples subjected to internal hydrostatic pressure, P_i, is generally studied in the laboratory, where for practical reasons, testing cannot be undertaken for longer periods than a couple of years, at best. The hoop stress σ_c is calculated for thin-walled pipes, that are characterized by the ratio between mean radius R and wall thickness s of the shell, which does not exceed 10, according to the Lamé equation [9, 18, 19] using (1). In (1), R_e is the outer radius, R_i is the inner radius, and R is their average.

$$\sigma_c = \frac{R_i^2 \cdot P_i}{R_e^2 - R_i^2}\left(1 + \frac{R_e^2}{R^2}\right) \tag{1}$$

For crack free pipes, when the hoop stress on the mean radius reaches the yield strength limit of the material, the loading can initiate cracking [9].

The crack initiation pressure $P_{\max}$ for a crack free pipe, is calculated starting from the Lamé equation, with (2), where σ_y is the tensile strength at yield.

$$P_{\max} = \sigma_y \frac{\dfrac{R_e^2}{R_i^2} - 1}{1 + \dfrac{4R_e^2}{(R_e + R_i)^2}} \tag{2}$$

For pipes made of modern bimodal HDPE materials, scratches up to 10% depth may be accepted without reduction of the rated pressure [20]. For the calculation of crack initiation pressure for pipes with longitudinal surface defects, with the defect length L width l, and depth a, (3) is used:

$$P_{\text{crack}} = \sigma_y \frac{\dfrac{R_e^2}{R_i^2}-1}{1+\dfrac{4R_e^2}{(R_e+R_i)^2}} \left(1-\sqrt{\frac{a/s}{1+\dfrac{0.3}{L/4R_e}}} \right) \tag{3}$$

A depth of defect a equivalent to 40% of pipe wall thickness, can be considered acceptable [9].

Hydrostatic strength σ_h is the stress on a pipe's wall caused by the fluid pressure inside the pipe, according to ISO 161-1 [21] and DIN 8075 [22]. For a pipe with outer diameter D_e and wall thickness s, the Long-Term Hydrostatic Strength (LTHS) σ_h, caused by the fluid internal pressure P_i is determined by:

$$\sigma_h = \frac{P_i(D_e - s)}{20s} \tag{4}$$

III. EXPERIMENTAL TESTING

A. Test Pieces

The test pieces were taken by HDPE, MRS 10, for potable water supply for underground network, according ISO 4427-1 [23]. The physical-mechanical features of the material of the pipe are demonstrated in Table I [24].

TABLE I. PHYSICAL-MECHANICAL FEATURES OF HDPE

Physical Characteristics	Methods, units, and values		
	Method	**UM**	**Values**
Density 23℃	ISO 1183	g/cm^3	958÷960
Mechanical Characteristics	Method	UM	Values
Young's modulus	ISO 527	MPa	1100
Tensile strength at yield	Tensile test	MPa	26.2
Ultimate tensile strength at 23 °C and 100 mm/min	ISO 527	MPa	30÷36
Tensile elongation at 23℃ and 100 mm/min	ISO 527	%	> 600%
LTHS: 100,000 hours 50 years	Two parameter model in ISO TR9080 software	MPa	 10.6 10.2

The pipes have outer diameter D_e = 90 mm, wall thickness s = 5.4 mm, and 1 m length. For pipes of outside diameter 150 mm or less, the length of the sample between the closure ends shall not be less than five times the outside diameter of the pipe, but in no case less than 300 mm [2]. The pipes have Standard Dimensional Ratio (SDR) equal to 17 and nominal pressure (PN) of 10 bar. In order to identify the influence of defects, such as the lack of material, on the strength of the pipes, defects with variable dimensions made via mechanical operations were practiced on the outer surface, in the middle area of the pipe. A technical drawing of a pipe with longitudinal surface defect is presented in Figure 1. In Table II the dimensions of the defects observed owing to the tested pipes are given.

Section-type specimens of crack free pipes (Pipe I) and section-type specimens with simulate defects of variable dimensions (Pipe II and Pipe III) were made, as noticed in Figure 2-4.

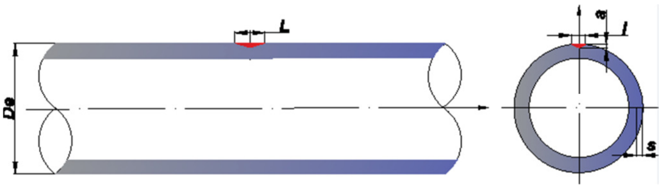


Fig. 1. Technical drawing of a pipe with longitudinal surface defect.

TABLE II. DIMENSIONS OF PIPES AND DEFECTS SHOWN BY THE TESTED PIPES

Tested pipe	D_e [mm]	s [mm]	Defect dimensions		
			L [mm]	**l [mm]**	**a [mm]**
Pipe I	90	5.4	No defect		
Pipe II			50	36	1.2
Pipe III			76	12	1.4

Fig. 2. Crack free pipe (Pipe I).

Fig. 3. Pipe with defect (Pipe II).

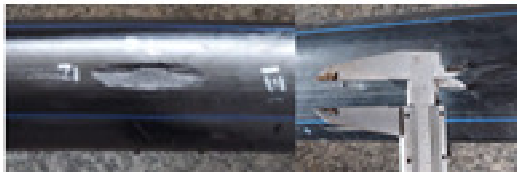


Fig. 4. Pipe with defect (Pipe III).

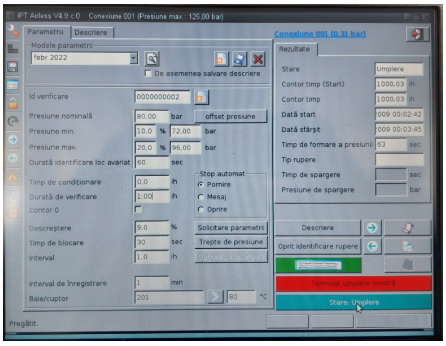
B. Ends of the Tested Specimens

The ends of the tested specimens were secured by assembling the two type A steel ends, according to [11].

C. Experimental Setup for testing Polyethylene Pipes

The installation for testing PE pipes under internal pressure includes a thermal tank in which water is maintained at a constant temperature of 23 ± 2 ℃. This is a pump pressurizing system that applies a continuously increasing internal hydraulic pressure to the tested specimens. The experimental setup has a pressure gauge with a surge protector and a stopwatch. The installation and the tested pipe specimens are observed in Figure 5. The software in the computer connected to the bath adjusts the input data and records the output data. A display of the monitoring process is spotted in Figure 6.

Fig. 5. Testing installation and the pipe samples.



IPT Airless V4.9.c.0 Conexiune 001 (Presiune max.: 125,00 bar)

Modele parametrii: febr 2022

☐ De asemenea salvare descriere

Id verificare: 0000000002

Presiune nominală: 80,00 bar

Presiune min.: 10,0 % 72,00 bar

Presiune max.: 20,0 % 96,00 bar

Durată identificare loc avariat: 60 sec

Timp de condiționare: 0,0 ih

Durată de verificare: 1,00 ih

Contor 0: ☐

Stop automat: ● Pornire ○ Mesaj ○ Oprire

Descreștere: 9,0 %

Timp de blocare: 30 sec

Interval: 1,0 ih

Interval de înregistrare: 1 min

Baie/cuptor: 201 80 °C

Conexiune 001 (0,31 bar)

Rezultate

Stare: Umplere

Contor timp (Start): 1000,03 ih

Contor timp: 1000,03 ih

Dată start: :009 00:02:42

Dată sfârșit: :009 00:03:45

Timp de formare a presiunii: 63 sec

Tip rupere:

Timp de spargere: sec

Presiune de spargere: bar

Terminat umplere mostră

Stare: Umplere

Pregătit.

Fig. 6. Display of monitoring process.

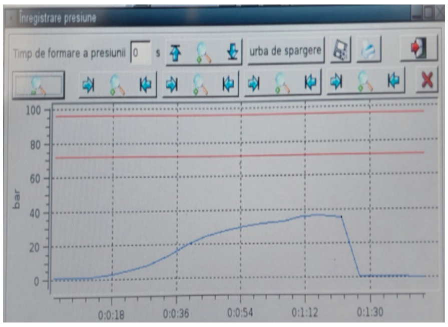
Many thermoplastics give significantly different burst strengths depending on the time to failure. The time to failure for all tested specimens should be between 60 and 70 s, but significant differences were found with failure times of 65 s and 85 s, and the bursting has to occur within a period of two minutes [2]. In general, the ductile failure and brittle fracture occur simultaneously, whereas the ultimate failure depends on which process is faster [25]. When scratches were applied to the PE pipes and they were pressured to burst, brittle fracture appeared instead of ductile fracture [26].

D. Testing

The short-time hydraulic pressure tests were performed according to [2]. Water was used to the pressurized tested specimens. The supply of water under pressure was through one end of the pipe sample. At the opposite end the pressure gauge and the data recording system were mounted. The automatic system ensured protection against shocks by the one-way valve. Testing pressure could be controlled through continuous and uniform increase, both until control pressure (hydrostatic regime), and until failure or fracture of the pipe material (variable pressure). During the test, cracks appeared that led to failure (pressure drop) and leakage.

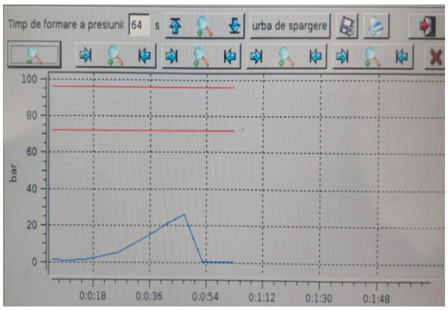
E. Experimental Data Recording

The data recorded by the software of the experimental setup, were displayed in a pressure – time (bar – hh:mm:ss) chart. The charts recorded during tests are depicted in Figures 7- 9. The short-time loading process was applied and the acquired values of the time to failure and the burst are presented in Table III.



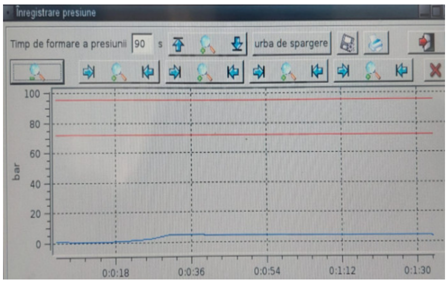
Timp de formare a presiunii 0 s

Fig. 7. Pressure – time charts: Pipe I.



Timp de formare a presiunii 64 s

Fig. 8. Pressure – time charts: Pipe II.



Timp de formare a presiunii 90 s

Fig. 9. Pressure – time charts: Pipe III.

TABLE III. TIME AND PRESSURE RECORDED

Samples	Burst time, t_b, [s]	Burst pressure, P_b, [bar]
Pipe I	77	38
Pipe II	47	28
Pipe III	33	5

IV. NUMERICAL SIMULATIONS

Industrial equipment under applied loads develops in its body stresses that must be below the yield strength limit of the material they are made of [27]. The finite element method, implemented through Ansys, was used to conduct numerical analysis in this study. The primary aim was to assess the in-service performance of HDPE pipes with defects (as portrayed in Table II) oriented longitudinally (worst-case scenario). The analyzed model's geometry was created in Ansys SpaceClaim, which included a central area related to the defect's location under investigation. The pipes have the dimensions observed in Table I. The FEA [28] utilized 917,963 discretization nodes connected in 627,558 SOLID186 finite elements to model the pipeline. The obtained results included the wall thickness distributions in the investigated fault area. The mechanical behavior law introduced in the numerical model precisely reflects the mechanical behavior of both elastic and plastic HDPE [9]. The numerical models, obtained in the Mesh stage, for crack free pipe and for pipe with longitudinal crack are shown in Figures 10-11. The pipe ends were blocked outside the defect area to prevent interference with the stress states. The inner surface of the geometrical model was subjected to the internal pressure value as specified in Table IV.

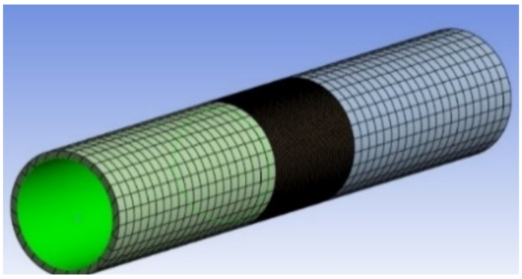


Fig. 10. The numerical model for pipe free crack – Pipe I

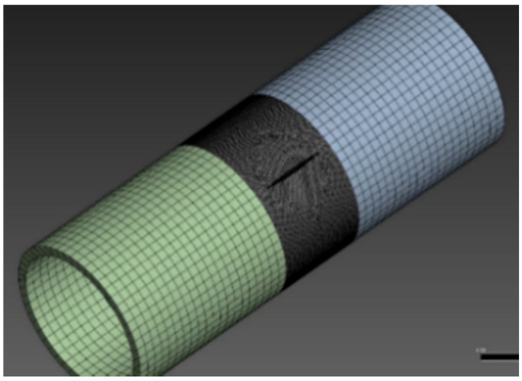


Fig. 11. The numerical model for pipe with defect – Pipe II and Pipe III.

The internal pressure, P_i, as tabular data, is the input in Setup and Stress Intensity [29] is the output in the Solution stage. The utilization of a criterion of crack propagation, based on the linear mechanics of failure imposes the determination of the stress intensity factor [30].

V. RESULTS AND DISCUSSION

A. *Analytical Results*

The value of the hoop stress developed in each of the three tested specimens was calculated with (1). The acquired values are given in Table IV, along with the values of the crack initiation pressure.

TABLE IV. STRESSES AND PRESSURES

Tested pipe	**Hoop stress σ_c [MPa]**	**Maximum crack initiation pressure for free crack pipe P_{max}, [Mpa]**	**Crack initiation pressure in the case of pipes with defect P_{crack} [Mpa]**
Pipe I	$7.3174 \cdot P_i$	3.5805	-
Pipe II	$8.1743 \cdot P_i$	-	1.4712
Pipe III	$8.3385 \cdot P_i$	-	1.3008

B. *Experimental Results and Disscusion*

The dependence between burst pressure and time to failure is illustrated in Figure 12. The burst pressure-hoop stress diagram is exhibited in Figure 13. It can be detected that the dimensions of the defect have a great influence on the hoop stress. The modes of fracture manifestation at the end of the experimental burst test of HDPE samples were:

- Bursting – a rapid loss of pressure, in Pipe I (Figure 14).
- Cracking – a visible passage of fluid through the wall of the specimen, in Pipe II (Figure 15).
- Splitting – a loss of pressure that interrupts the continuous and uniform increase in pressure, Pipe III (Figure 16).

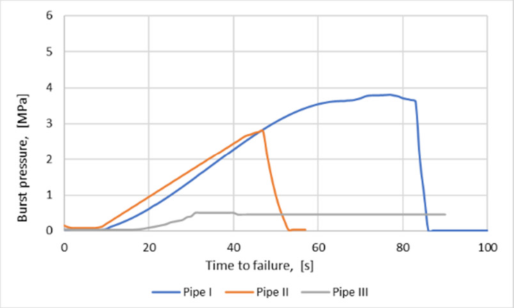


Fig. 12. Dependence between burst pressure and time to failure.

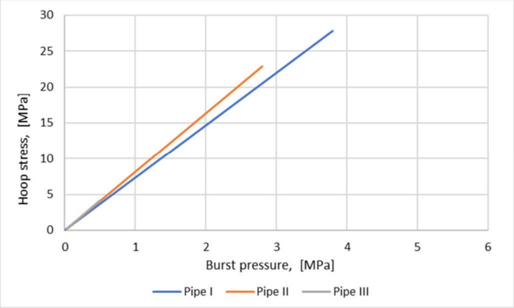


Fig. 13. Burst pressure-hoop stress diagram.

Fig. 14. Bursting in Pipe I.

Fig. 15. Cracking in Pipe II.

Fig. 16. Splitting in Pipe III.

C. Numerical Simulations Results

The results of the FEA are presented in Figure 17. The analytical results are in strong agreement with the experimental data and the numerical models, as can be pinpointed in Table V and Figure 18.

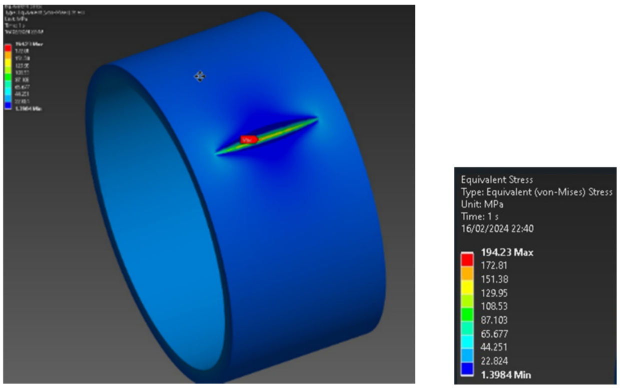


Fig. 17. FEA results.

TABLE V. RESULT COMPARISON

	Pipe I	Pipe II	Pipe III
a [mm]	no defect	1.20	1.40
a/s	no defect	0.222	0.259
L [mm]	no defect	50	76
l [mm]	no defect	36	12
P_{max} and P_{crack} analytical [Mpa]	3.58	1.8906	1.7757
P_i experimental [Mpa]	3.80	2.80	0.50
P_{crack} numerical [Mpa]	3.10	1.66	0.31

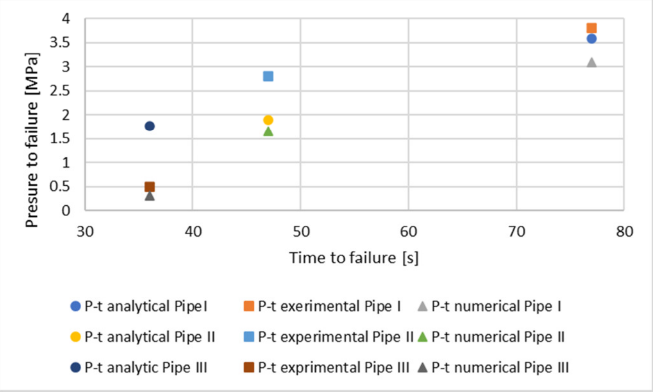


Fig. 18. Result comparison.

VI. CONCLUSIONS

- Both burst pressure and time to failure decrease when the defect depth increases.
- The dependence between burst pressure and time to failure is in good accordance with the diagrams from the technical literature.
- As in [13], the defect shape and dimensions significantly impact the burst pressure of HDPE.
- The depth of the defect was the geometrical characteristic of defect that influenced mainly burst pressure. The other two geometrical characteristics, the longitudinal and circumferential dimensions of the defect, had less contribution on pressure value.
- The kinds of failure, either ductile or brittle, were found by visual examination.
- As in [28], the crack expands more rapidly with increasing internal pressure because the latter induces an increase in the axial equivalent force (see Figures 15 and 17).
- The type of failure, either ductile or brittle, was found by visual examination.
- The modes of fracture manifestation at the end of the experimental burst test of the HDPE samples are different, and were visually ascertained as bursting, cracking, and splitting.
- In the polyethylene pipe subjected to internal pressure stresses that were below the yield strength limit of the material were developed.
- Sensitivity analyses were conducted to determine the optimal size of the finite elements. The finite element size in the area where the defect was modelled was approximately 0.5 mm. This led to conclusive results that are comparable to those experimentally obtained, as shown in Table V.

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