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Laboratory Investigation of Fracture Resistance of uPVC Pipes

M.B. Ali[1], F. Ahmed[2], A. H. Akhi[3]

[1]*Student, Department of Civil Engineering, RUET, Bangladesh (muazbinali100@gmail.com)*
[2]*Student, Department of Civil Engineering, RUET, Bangladesh (farihaahmedfa2017@gmail.com)*
[3]*Lecturer, Department of Civil Engineering, RUET, Bangladesh (atika2012cen@gmail.com)*

Abstract

The Unplasticized Polyvinyl Chloride (uPVC) pipes are extensively used in Bangladesh for transporting water due to their durability, corrosion resistivity, and low maintenance requirements. Fracture is one of the major causes of the failure of these pipelines. It is crucial to determine the remaining strength of the pipes for maintaining them economically. The concepts of fracture mechanics are successfully employed for determining the remaining strength. Most of the studies are concerned with the stress threshold of crack growth or fracture initiation. This study aims to evaluate fracture toughness of uPVC pipe i.e., its resistance before the propagation of flaw. The uPVC pipe is collected from the laboratory of the Rajshahi University of Engineering & Technology (RUET) for the examination of the fracture toughness. In the laboratory test, crack propagation with respect to load and the fracture toughness were assessed using Single-Edge Notched Bending (SENB) specimens.

Keywords: uPVC pipe; Cracking; Fracture toughness; Single-Edge Notched Bending.

1 Introduction

Fracture toughness determines structural integrity and serviceability of a material (Milović et al., 2007). Fracture toughness refers to brittle materials' resistance to flaw propagation under an applied stress, and it makes the assumption that the longer the flaw, the lower the stress required to cause fracture. Musraty et al. establish the external loading criteria for ductile fracture. In this study, a newly developed testing method uses new pipe-ring notch specimens for bending (PRNB) to measure the fracture toughness on defects in the axial direction (Musraty et al., 2017). Gubeljak et al. determined fracture toughness of pipe by using a modified non-standard specimen in their research. Standard (Single-Edge Notched Bending and Compact Tension) specimens and pipe-ring specimens have been compared in order to validate the new technique and specimen (Gubeljak et al., 2014). EL-Bagory and Younan (2017) utilized the linear elastic fracture mechanics theory to assess the plane strain fracture toughness of Plasticized Polyvinyl Chloride (PVC) pipes under a number of operating situations. They also determined stress intensity factor (K_Q) surrounding the crack tip by Finite Element Method (FEM).

The stress intensity factor was contrasted with the result of a theoretical equation (EL-Bagory and Younan, 2017). Numerous techniques, such as uniaxial tensile strength, notched C-ring, critical work of fracture, strain energy release rate, fracture toughness, and impact tests, were done in another study to determine strength and toughness of each modified PVC pipes, with different concentrations of chlorinated polyethylene (Whittle et al., 2001). Seldén used accelerated ageing tests in air to examine the impact of thermo-oxidative deterioration on the fracture toughness qualities of Unplasticized Polyvinyl Chloride (uPVC) pipes (Seldén, 1987). Nowadays, uPVC pipes are most commonly used for water supply in Bangladesh. The pipes may be cracked due to many reasons. The replacement of these pipes because of a minor crack is not economical and viable. This study aims to establish the fracture toughness i.e., the maximum load that the previously cracked pipe can withstand before failure so that catastrophic failure can be prevented and safe supply of water will be ensured. As a result, the pipe with a tiny crack will be usable for an extended period of time. SENB testing has been used in this research in accordance with ASTM E399-90 (ASTM, 1997). This investigation also determines some uPVC pipe characteristics, including density, elastic modulus, and yield strength.

2 Methodology

A long uPVC pipe of outer diameter, d_o= 22 mm, inner diameter, d_i= 19.45 mm, and thickness 12.75 mm was collected from the strength of materials laboratory in the Department of Civil Engineering at Rajshahi University of Engineering & Technology. At first SENB specimens from the long pipe were prepared according to the specifications outlined in ASTM E399-90. These specimens are typically rectangular, with a fatigue pre-crack created at the center of one of the narrow faces. In this test the length (L), clear span (S), width (W) and thickness (B) of the test specimens were 117 mm, 96 mm, 25.5 mm, and 12.75 mm, respectively as shown in figure 1. The width-to-thickness ratio (W/B) for the specimens was kept at 2. A pre-cracked notch (Figure 2) of length 12.75 mm was done at the middle of each specimen along its length, as shown in Figure 1.

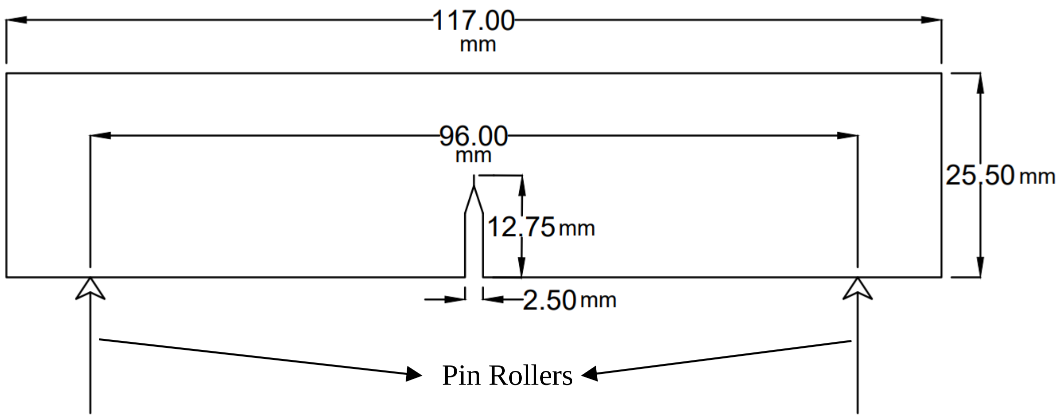

Figure 1. Test Specimen

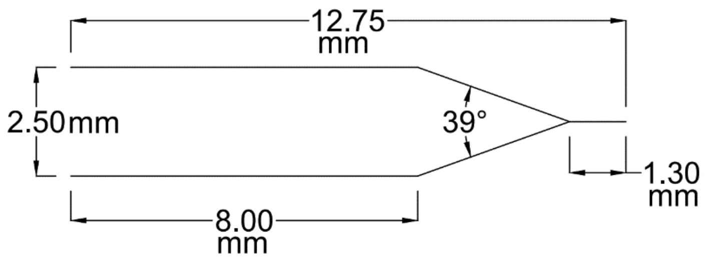

Figure 2. Notch

The test apparatus was set up as shown in Figure 3. The test specimens were placed into the testing machine so that proper alignment and contact with the loading fixtures was ensured. The specimens were set up over 25 mm pin rollers, and three-point loading was applied so that the specimens' pre-cracked notch at the middle fell exactly beneath the load. The load was given and increasing at the same rate for each specimen and failure load was noted.

When the failure load (P) was known, the fracture toughness K_Q in MPa$\sqrt{m}$ was determined using equation (1) followed by ASTM E399-90 (ASTM, 1997).

$$K_Q = \left[\frac{P\,S}{BW^{3/2}}\right] f(a/W) \tag{1}$$

Where:

$$f\left(\frac{a}{W}\right) = \frac{3\left(\frac{a}{W}\right)^{1/2}\left[1.99-\left(\frac{a}{W}\right)\left(1-\frac{a}{W}\right)\left(2.15-3.93\left(\frac{a}{W}\right)+2.7\left(\frac{a}{W}\right)^2\right)\right]}{2\left(1+2\frac{a}{W}\right)\left(1-\frac{a}{W}\right)^{3/2}}$$

B is the specimen thickness (cm),
P is the ultimate load (kN),

S is the clear span (cm),
W is the specimen width (cm),
a is the crack length (cm).

Figure 3. Test setup

3. Result

3.1. Modulus of Elasticity and Yield Strength

The tensile strength test was carried out according to ASTM D638-14. Three stages were noticed during this test. During the first stage of loading, up to stress 30, 26, and 25 MPa, the specimen 1, 2, and 3 respectively behaves elastically. In this zone, stress and strain have a linear relationship that is consistent with Hooke's Law. The next stage is plastic zone. In this stage, the stress increases very little or not at all while the strain grows. The graph indicates that specimens 1, 2, and 3's respective plastic zones lie along the strain between 0.01-0.029, 0.01-0.026, and 0.01-0.027, approximately. The third stage is fracture point, also known as the maximum point of the stress-strain curve. At this point, the specimen fails catastrophically as a result of the stress being applied. According to the graph specimens 1, 2, and 3 are capable of withstanding stresses of approximately 38, 35, and 37 MPa, respectively.

By choosing two points on the elastic zone of the stress-strain curve, and then calculating the ratio of the stress difference to the strain difference of those two points, the modulus of elasticity is determined. The yield strength is determined by drawing yield line that is horizontally displaced by 0.2% strain while remaining parallel to the linear elastic zone. The stress value at the stress-strain curve's intersection denotes the yield strength.

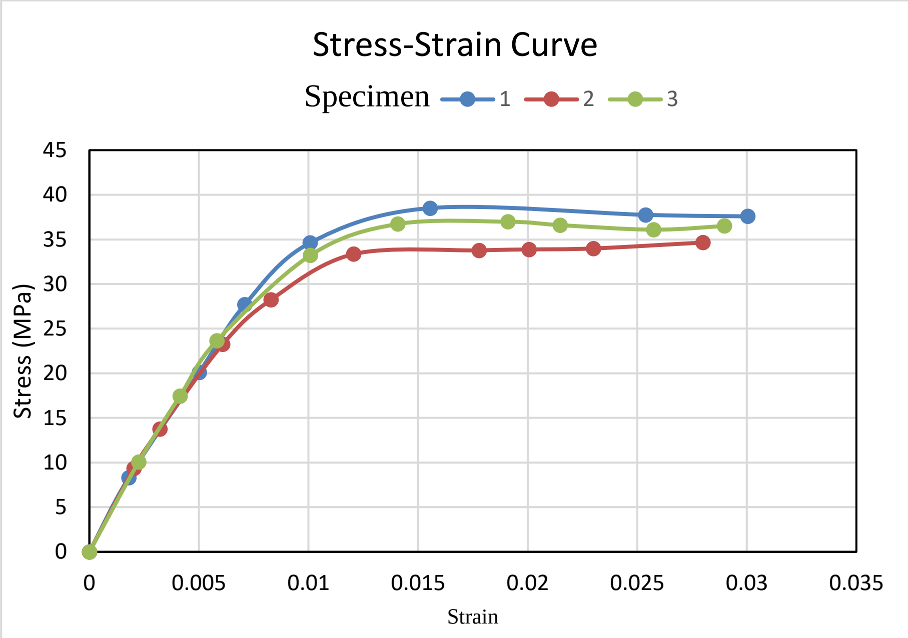

Figure 4. Stress-strain curve for specimen 1, 2 and 3.

Table 1. Material Parameters

Material Properties	Specimen			Average
	1	2	3	
Density (g/cm^3)	1.44	1.52	1.50	1.49
Modulus of Elasticity (GPa)	3.46	3.38	3.27	3.37
Yield Strength (MPa)	37	34	36	35.67

3.2 Fracture Toughness

From equation (1), $K_Q = [\frac{P\,S}{BW^{3/2}}]\ f(a/W)$

Here,

$$f(\frac{a}{W}) = \frac{3(\frac{a}{W})^{1/2}\ [1.99-(\frac{a}{W})(1-\frac{a}{W})(2.15-3.93\left(\frac{a}{W}\right)+2.7\left(\frac{a}{W}\right)^2)]}{2(1+2\frac{a}{W})(1-\frac{a}{W})^{3/2}}$$ = 2.6627, which is same for all the specimens as the ratio of crack length to specimen width $(\frac{a}{W})$ was kept 0.5 for the specimens.

Table 2. Results obtained from SENB test

Specimen	Failure Load, P (KN)	K_Q (MPa$\sqrt{m}$)
1	0.8491	4.22
2	0.9704	4.82
3	0.92188	4.58

The values of K_Q is determined by using equation (1). It is seen from the equation that the value of K_Q is proportional to the failure load P as all the dimensions of the specimens 1, 2, and 3 are kept same in the SENB tests. But each specimen has got different failure load, which causes variations in $K_Q$values. K_Q for specimen 1, 2, and 3 are 4.22, 4.82, and 4.58 MPa$\sqrt{m}$ respectively. The average K_Q for the uPVC pipe is 4.54 MPa$\sqrt{m}$. The value of K_Q determined is valid by comparing the values with the findings of Rodolfo (2021) and EL-Bagory and Younan (2017). Rodolfo used ISO/CD 6259-2 for the test while EL-Bagory and Younan employed curved three point bend (CTPB) and C-shaped tension (CST) specimens according to E399–12e3. (EL-Bagory and Younan, 2017; Rodolfo et al., 2021).

4. Conclusion

The replacement of a pipe with a minor crack is not economical and viable solution for any country. This study assesses the failure load of the cracked pipe using SENB test in the laboratory. Fracture toughness, K_Q, of the pipe with crack was evaluated using failure load. The values of K_Q lies between 4-5 in this study and found to be identical with previous studies. This fracture parameters enable engineers to have a service life of the cracked pipe and prevent catastrophic breakdowns. On the other hand, some properties like modulus of elasticity, yield strength, density are also figured out. This information will be usable for further researches when the value of fracture toughness obtained from the laboratory test in this experiment will be compared with numerical analysis by ABAQUS.

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