Burst Pressures of High Density Polyethylene (HDPE) Pipes Considering the Notch Effect: Testing and Prediction

Xiaotao Zheng[1]* (xiaotaozheng@163.com),
Jiqiang Wang[1] (534906792@qq.com)
Haofeng Chen[2, 3]** (haofeng.chen@strath.ac.uk)

1. Hubei Provincial Key Laboratory of Chemical Equipment Intensification and Intrinsic Safety, Wuhan Institute of Technology, Wuhan 430205, P. R. China

2. Department of Mechanical & Aerospace Engineering, University of Strathclyde, Glasgow G1 1XJ, UK

3. Key Laboratory of Pressure System and Safety, MOE, School of Mechanical Engineering, East China University of Science and Technology, 130 Meilong Street, PO Box 402, Shanghai 200237, PR China

Abstract: This work aims at testing and predicting burst pressures of HDPE pipes with various groove conditions. Four types of notches including U-type, V-type, L-Type (linear type) and R-type (rectangular type) with different depth ratios are discussed. A unified damage model is proposed to predict the damage behaviors of notched HDPE pipes for different notch shapes. Results indicate that the notch shape has an important influence on the burst pressure of HDPE pipe. Generally, the impact extent from high to low in order is the R-type, U-type, V-type, and L-type according to the experimental data. The burst pressure obviously decreases with the increment of the notch depth ratio. However, when the notch depth is less than 0.5mm in this work, the burst pressure reduces

Author to whom correspondence should be addressed;

* Electronic mail: xiaotaozheng@163.com

** Electronic mail: haofeng.chen@strath.ac.uk

slightly compared with that of the virgin pipe due to its good fracture toughness. Moreover, the predicted damage factors by the proposed model agree very well with the experimental data under different groove shapes. This work provides important experimental data and damage assessment approach for various notched HDPE pipes.

Keywords: Notch effect; HDPE pipes; Burst pressure; Damage; Prediction model

1. Introduction

Polymer composites have been investigated in many industries considering the requirements of functionality and structural integrity in recent years [1, 2, 3, 4, 5]. Among these polymers, HDPE is widely applied in chemical and petrochemical engineering, nuclear plant and other industries as pipelines or membranes owing to its good comprehensive performance of light weight, corrosion and wear resistance, mechanical properties and low cost. It is an excellent substitution of steel and concrete in some cases [6]. Although the strength and rigidity of HDPE are significantly lower than those of alloys and concrete, it has excellent fracture toughness and light weight which can partially compensate its strength due to less external mechanical loads applied. Microscopic and macroscopic damage are inevitable during the process of manufacture and long-term application, such as defects or notches, medium abrasion, material degradation due to chemical corrosion or exposure to sun UV rays and so on. Some typical failure modes of HDPE pipes include slow crack growth produced by small defects [7, 8, 9], rapid crack propagation at low temperature due to ductile-fragile transition [10, 11], fatigue fracture [12, 13, 14], burst or buckling due to mechanical loads [15]. Therefore, damage and life prediction are key problems for the integrity assessment of HDPE pipes in practical engineering. Frank, Pinter and Lang [16] investigated the performances of four different pipes used in the gas and water with an age up to 30 years by morphological and fracture mechanics analysis. Results considered that the pipes studied still have very good mechanical properties and maybe adequately safe to use by extrapolated remaining lifetime prediction. Burst pressures of HDPE pipes with R-type groove and without damage were tested systematically by Majid et al. [17, 18]. Several damage models, including a modified version of the stress controlled unified theory, a static damage model using burst pressures, a static damage model using the time to failure and a nonlinear damage-reliability models, were proposed to estimate the performance of HDPE pipes with good accuracy. Nezbedová et al. [19] utilized the Pennsylvania Notch Test and a numerical approach to predict the lifetime of a new generation of PE grades. Guidara et al. [20] researched a defective high density polyethylene pipe with longitudinally disc-shaped groove by burst testing and the J-integral simulation. An obvious gap between the crack initiation pressures of pre-cracked pipe and those of the notched pipe is observed, and it becomes greater when the notch depth is greater than half of the wall thickness. Benhamena et al. [21, 22] investigated the J-integral solution of high density polyethylene pipe with semi-elliptical crack subjected to internal pressure and bending by three finite element simulation [23]. As for the effect of defect shape on the safety of structures, many researchers performed various experimentation and numerical simulation to assess the mechanical integrity of steel materials [24, 25, 26, 27, 28]. However, according to the best knowledge of authors, there are only a few works discussed about the influence of notch shape on the failure behavior of polymer pipes, especially on the burst pressure of HDPE pipes. HDPE pipes are usually used in small and medium-diameter ducts subjected to moderate pressure. It is necessary to investigate the burst pressure and damage evolution of HDPE pipes considering the notch effect. It should be noted that the notch effect of this research means the influence of longitudinal groove shape and size on the burst pressure of HDPE pipes.

In this work, burst pressure and damage behavior of HDPE pipes considering the notch effect are investigated. The experimental procedures and set-up are introduced in the Section 2. Burst pressures of HDPE pipes with various notch shapes, including U-type, V-type, L-type and R-type, with different notch depth ratios are tested and discussed in the Section 3. Moreover, in the Section 4, a unified damage prediction model is proposed, and the predicted results are compared with the tested data in detail. Some important conclusions are summarized finally.

2. Experimental procedures

This work aims to test the burst pressures of HDPE pipes with different notch shapes and sizes. The outer diameter of tested pipes, *Do*, is about 40.2±0.2mm, and the thickness, t, is almost 3.5±0.1mm, as shown in Table 1. Three kinds of notch shapes, namely U-type, V-type and L-type, are prepared. Each notch is machined from the outer surface of HDPE pipe along the longitudinal direction, and four notches are distributed uniformly along the circumferential direction, as illustrated in Fig 1. Each specimen is a 170mm length pipe with four 50mm length longitudinal grooves. Different groove depths h of 0.5mm, 1mm, 1.5mm, 2mm are processed for each notch shape, respectively. Especially, the radius of U-type notch is always 1mm and the angle of V-type groove is 60º for different groove depths. It should be noted that the R-type notched pipes are not machined and tested in this work. The geometrical parameters and burst pressures of R-type notched pipes can be obtained directly from the literature [17] for comparison.

Table1 Outer diameters and deformations of notched HDPE pipes

Notch Type	Notch Depth（mm）	Thickness（mm）	Before Testing Do（mm）	After Testing Do（mm）	Deformation（mm）
smooth	0	3.62	40.37	40.72	0.35
L-type	0.5	3.43	40.30	40.63	0.33
	1.0	3.61	40.32	40.61	0.29
	1.5	3.54	40.38	40.66	0.28
	2.0	3.59	40.37	40.62	0.25
U-type	0.5	3.50	40.31	40.65	0.34
	1.0	3.61	40.36	40.71	0.35
	1.5	3.39	40.38	40.69	0.31
	2.0	3.41	40.35	40.67	0.32
V-type	0.5	3.41	40.24	40.59	0.35
	1.0	3.51	40.27	40.62	0.35
	1.5	3.43	40.37	40.70	0.34
	2.0	3.63	40.12	40.44	0.32

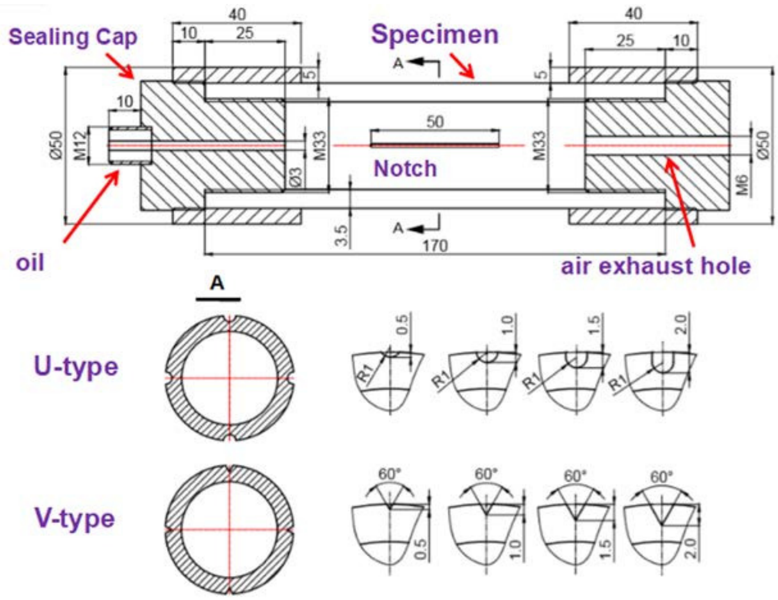

Fig.1 Geometry of specimens and sealing caps (mm)

All the experiments are performed by a general burst testing system, as shown in Fig.2. The test-up equips with oil pump, feeding, internal pressure monitoring and data acquisition system. In order to attain the burst experiments of HDPE specimens in the test-up, two special end caps are designed to promise the sealing and connection capacity. The testing process totally includes two steps. Firstly, we fill the internal space of specimen with oil by the pump and seal the air exhaust hole by a small end cap after the oil spills from the air exhaust hole, as shown in Fig.1 and Fig.2; secondly, the internal pressure increases automatically by the control system and oil pump until the burst behavior takes place. All the experiments are finished in a room temperature condition with the temperature of 22±1℃.

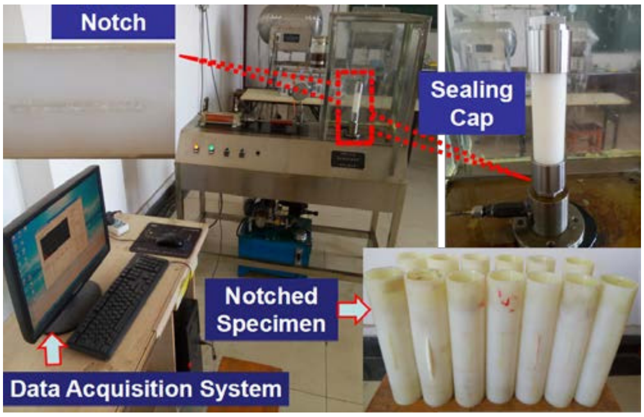

Fig.2 Testing set-up

3. Burst failure of HDPE pipes with various notches

According to the experimental procedures mentioned above, the burst pressures of notched and virgin HDPE pipes are tested. Typical cracking appearances of the virgin and notched HDPE pipes after burst testing are shown in Fig.3. Noting that the depth of each groove in Fig.3 is 2mm for clear illustration. Results show that a clear longitudinal crack occurs for each notched and undamaged HDPE pipe. Especially, obvious plastic deformation is observed for the virgin HDPE pipe. Moreover, the deformation of each notched and original HDPE pipe is measured based on the difference of the outer radius before and after the burst testing, as shown in Table 1. The tested data indicates that the plastic deformation slightly reduces with increasing the groove depth. This may be induced by the constraint effect of pre-machined notches.

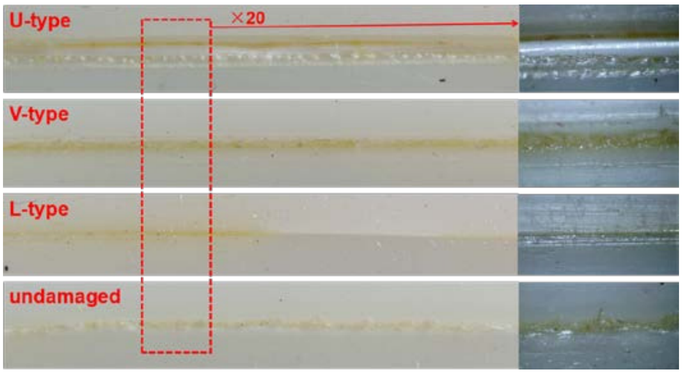

Fig.3 Cracking of HDPE pipes with and without notch after burst testing

The evolutions of internal pressure with time of notched and undamaged HDPE pipes are presented in Fig.4. It is shown that the evolution relationship depends on the groove depth ratio. Noting that the notch depth ratio of this work is defined as the ratio of the notch depth to the thickness of HDPE pipe. Concretely, when the notch depth ratio is equal to and less than 0.14, which corresponds to the groove depth of 0.5mm in this research, the evolution of internal pressure with time has two peaks. The internal pressure enhances slowly due to the swelling of HDPE pipes, and then increases rapidly until to the first peak, which can be considered as the elastic limit pressure of HDPE pipe. After the elastic limit pressure, the plastic deformation takes place, which causes the increase of volume of the HDPE pipe and the decrease of internal pressure. When the plastic deformation approaches to the plastic limit of the HDPE pipe, the burst behavior occurs at the second peak, then the internal pressure decreases promptly. However, only one peak can be observed when the notch depth ratio is equal to and greater than 0.29. It indicates that the internal pressure increases rapidly until to the local plastic limit near the notch root area, and the burst behavior takes place.

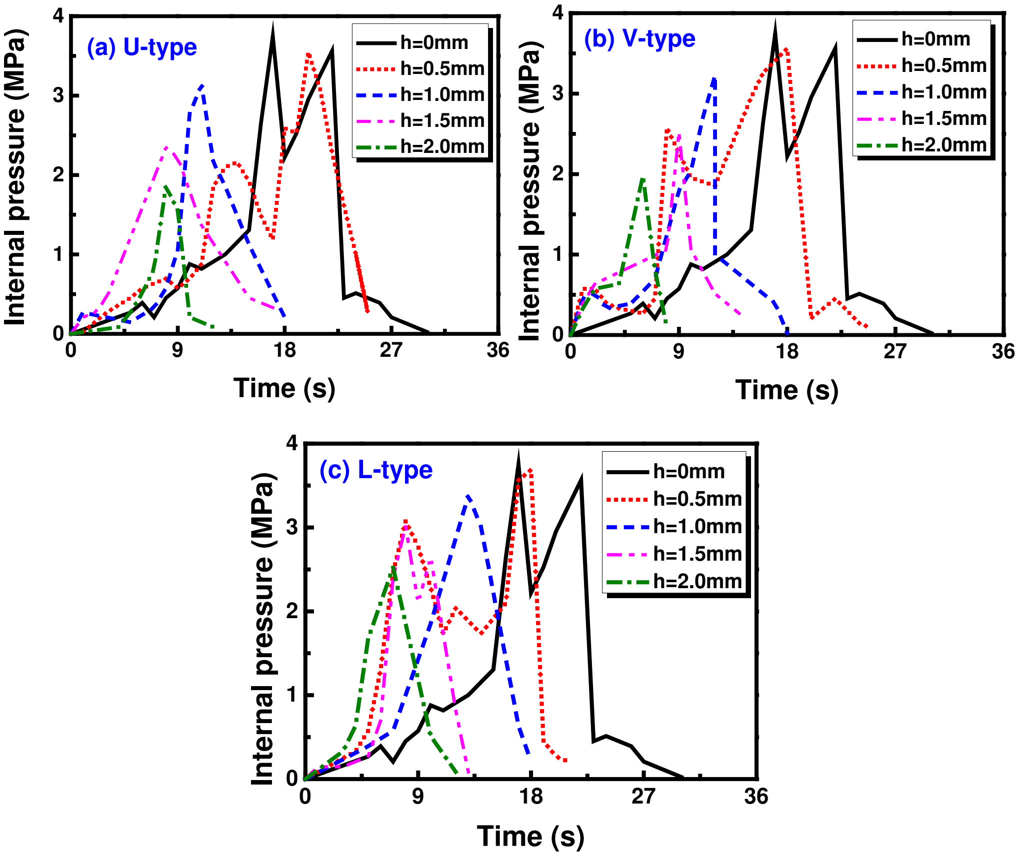

Fig.4 Evolution of internal pressure with time of HDPE pipe with different notch types; (a) U-type, (b) V-type, (c) L-type

The tested burst pressures of virgin and notched HDPE pipes with various groove shapes and depths are illustrated in Fig. 5. As a comparative analysis, the burst pressures of HDPE pipes with the R-type notch from the literature [17] are also superposed in the figure. Noting that all the burst pressures of notched HDPE pipes obtained from experiment and the literature [17] are normalized by that of the corresponding virgin pipe in the following. Results show that the burst pressure obviously decreases with the increment of the notch depth ratio. However, when the notch depth is too shallow comparing with the wall thickness, such as 0.5mm of this work, the burst pressure is slightly less than that of the undamaged pipes. For example, when the groove depth is 0.5mm, the burst pressure decreases by 1.6% for the L-type one, and almost 5% for U-type and V-type notches comparing with that of the virgin pipe. This implies the HDPE material has good fracture toughness. Additionally, the groove shape also influences the burst pressure of HDPE pipe significantly. Based on those general experimental data, the impact extent from low to high in order is the L-type, V-type, U-type and R-type, respectively. It is of great interest that the L-type groove has the least effect on the burst pressure of HDPE pipes, but the R-type notch has the greatest influence on the burst pressure of notched pipes tested. This indicates that the notch with larger volume decreases the burst pressure of HDPE pipes more significantly under the same depth condition. According to the fracture time of HDPE pipes at the burst pressure, the evolution of fracture time with the notch depth ratio is depicted in Fig.6, which presents that the fracture time reduces with increasing the notch depth ratio.

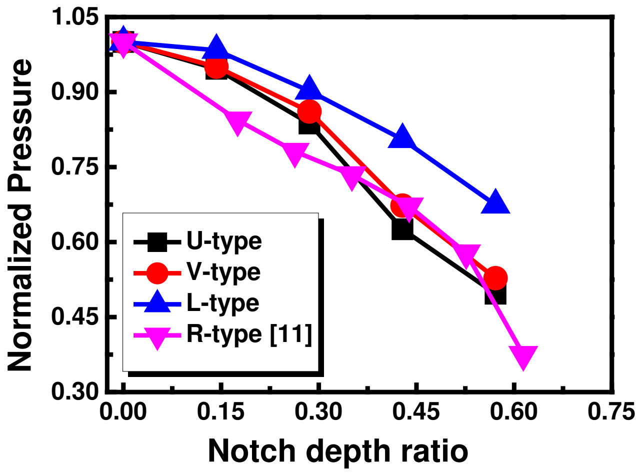

Fig.5 Effect of notch depth on burst pressure of HDPE pipe with notch types

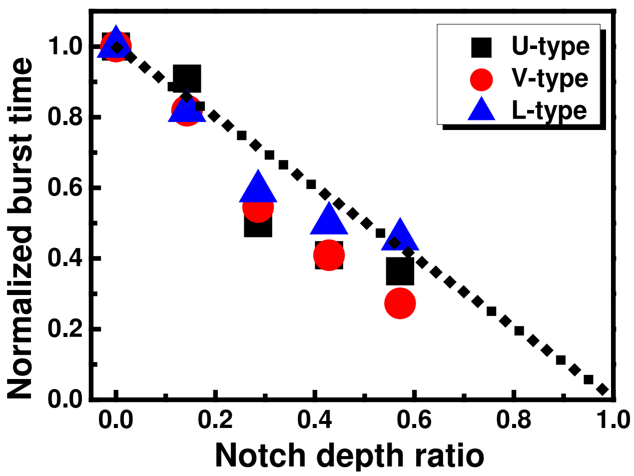

Fig.6 Effect of notch depth on burst time of HDPE pipe with different notch types

4. Damage model of HDPE pipes with various notches

In order to predict the effect of groove shape and size on the burst pressure of notched HDPE pipes, it is necessary to establish a unified damage model considering the notch effect mentioned above. Until now, many damage models of metallic or non-metallic materials have been established in many published works [29, 30, 31, 32, 33, 34]. One of the most famous damage model is the Linear Miner Damage (LMD) model [29], which defines the damage factor as

$$D_L = \sum_{i=1}^{M} \frac{n_i}{N_i} \tag{1}$$

where:

n = the applied number of cycles,

N = the fatigue life, cycles,

M = the number of applied fatigue loads.

The LMD model is adopted by many international design codes for engineering design and safety assessment owing to its simplicity and adaptability without taking account of complex nonlinear factors of materials and structures. It should be noting that the LMD is usually used to estimate the fatigue damage of materials under repeated loads. In this work, the LMD is modified to estimate the linear damage behavior of notched HDPE pipes under internal pressure, as the following:

$$D'_L = 1 - \frac{h}{t} \tag{2}$$

However, the LMD is also considered as a conservative method because the damage factor is usually overestimated for many materials. For the sake of improving the predicted accuracy, some other damage models have been developed by introducing the nonlinear relationship of damage. The unified damage model established by Bui-Quoc et al. [30] is a typical approach to decrease the endurance limit, fatigue life, and material resistance. The damage model is defined as:

$$D_U = \frac{D_L}{D_L + \frac{(1-D_L)}{\gamma - 1}\left[\gamma - \left(\frac{\gamma}{\gamma_u}\right)^m\right]} \tag{3}$$

Where:

$\gamma = {}^{\sigma_e}\!/_{\sigma_0}$,

$\gamma_u = {}^{\sigma_u}\!/_{\sigma_0}$,

σ_e = the instantaneous endurance limit, MPa,

σ_0 = the initial endurance limit, MPa,

σ_u = the ultimate stress, MPa.

To illustrate the damage state of a notched pipe under internal pressure, Majid and Elghorba [17] proposed a modified unified damage model by replacing the LMD factor D_L by $\beta = {}^{h_n}\!/_{h}$, and substituting the stress variables by pressure parameters in the damage model. Where, h_n is the depth of notch, and h is the thickness of HDPE pipe. The modified unified damage model can be expressed as

$$D_U' = \frac{\beta}{\beta + (1-\beta)\left[\dfrac{\dfrac{P_{ur}}{P_o} - \left(\dfrac{P_{ur}}{P_u}\right)^m}{\dfrac{P_{ur}}{P_o} - 1}\right]} \tag{4}$$

where:

P_o = the pressure corresponding to the endurance limit of the undamaged material, MPa,

P_u = the ultimate pressure corresponding to the burst of the undamaged HDPE, MPa,

P_{ur} = the ultimate burst pressure for notched HDPE pipes, MPa.

m = 1 for HDPE material.

The modified unified damage model proposed by Majid et al. can well predict the damage behavior of HDPE with R-type notch [17]. However, the notch effect has not been considered in the modified unified damage model. As shown from the experimental data in Fig.5, the notch shape has important impact on the ultimate burst pressure. Hence, the notch effect should be considered to improve the accuracy of damage model.

Similar to the LMD model, the notch effect can be characterized by the following damage factor because the ultimate burst pressure of notched HDPE pipe P_{ur} is significantly impacted by the geometrical shape and size of notch, namely

$$D_p = 1 - \frac{P_{ur}}{P_u} \tag{5}$$

The damage factor can be calculated based on the experimental data and the damage model in Eq.(4), as shown in Fig.7. To illustrate the accuracy of the modified unified damage model and LMD model mentioned above, the predicted damage factors by these two models are also superposed in Fig.7. Results show that the notch shape and size have important effect on the damage factor defined in Eq.(5). Moreover, the LMD model obviously overestimates those damage factors of HDPE pipes with different notches.

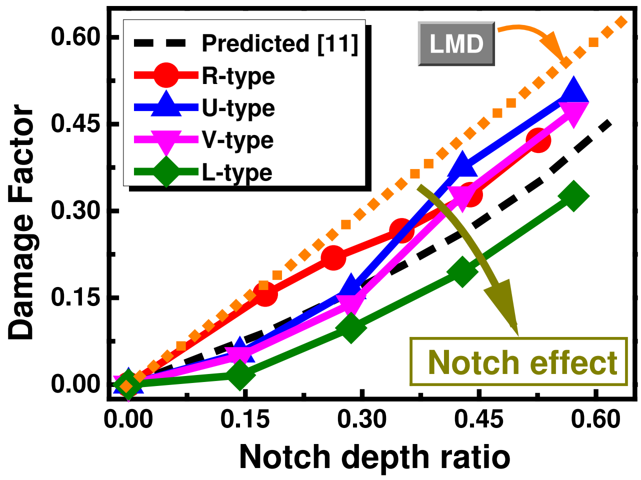

Fig.7 Damage factor of HDPE pipe with different notch types

Comparing with the LMD model, the modified unified damage model has greater precision for notched HDPE pipes. However, the notch effect may be further considered to analyze the damage factors of HDPE pipes with different groove shapes. Therefore, a modified damage model considering the effect of notch effect can be described as

$$D'_U = \frac{\beta}{\beta + (1-\beta)\left(\frac{P_u}{P_{ur}}\right)^s} \tag{6}$$

Where:

s = the shape factor for different grooves.

Based on the experimental data, s is equal to 3 for L-type notch, 1.5 for V-type and 1 for U-type and R-type. According to the damage model in Eq.(6), the evolution of damage factor with the notch depth ratio for U-type, V-type, L-type,and R-type are presented in Fig.8, respectively. The figure clearly shows that the damage evolution with the notch depth ratio is a concave curve, and the concavity of the curve becomes greater with the increasing of the notch depth ratio. This indicates that the proposed model can be described the damage factor with greater accuracy comparing with the LMD. The damage factors of notched HDPE pipe with various groove shapes can be assessed by the characteristic notch depth ratio. Especially, the characteristic notch depth ratio for U-type, V-type and R-type grooves is almost 0.4, and approximately 0.55 for L-type notch. The comparison of those predicted results and experimental data of damaged HDPE pipes with different notches is shown in Fig.9. Results show that the analyzed results are in good agreement with those tested data. This indicates that the proposed model can be well used to predict the damage behavior considering the notch effect. Taking into consideration the important effect of notch geometry on the degradation of HDPE pipes, the shakedown and low fatigue behavior of notched and virgin HDPE pipes will be further tested and evaluated in the following based on the approaches published in previous works [35, 36, 37, 38, 39].

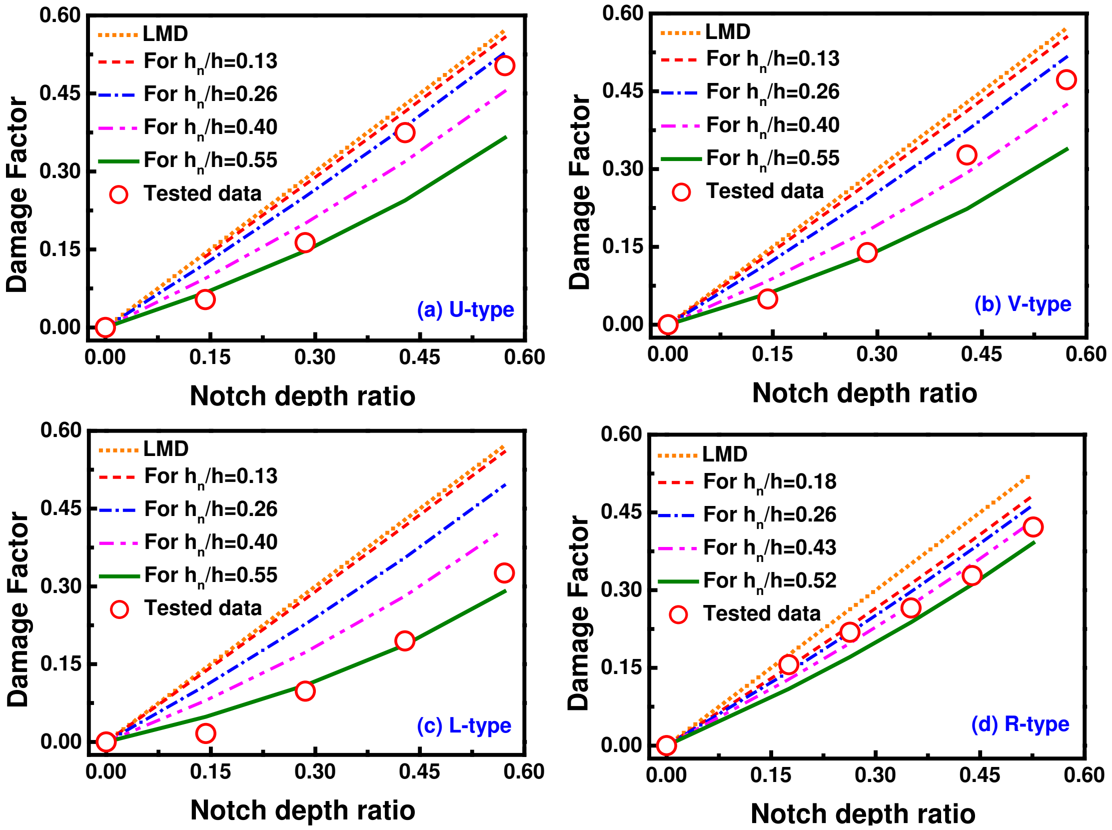

Fig.8 Evolution of the proposed damage model considering notch effect; (a) U-type, (b) V-type, (c) L-type, (d) R-type

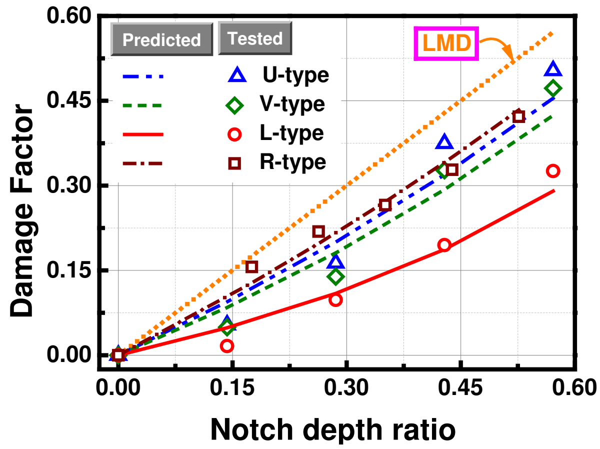

Fig.9 Comparison of damage factors predicted by the proposed model and tested data considering notch effect

5. Conclusions

The work is interested in the burst pressure and damage behavior of notched HDPE pipes with various groove shapes and depths. A unified damage model is proposed to predict the damage factors of notched HDPE pipes. Results indicate that the classical LMD model obviously overestimates those damage factors of notched HDPE pipes. However, the proposed unified damage assessment model can be used to predict the damage behavior of notched HDPE pipes with high accuracy. The groove shape impacts the burst pressures of HDPE pipes significantly. The influence extent from low to high in order is the L-type, V-type, U-type and R-type. This indicates that the groove with the same depth and the larger volume reduces the burst pressure of notched HDPE pipes more obviously. Moreover, the burst pressure remarkably decreases with the increment of the notch depth ratio. However, when the notch depth is less than 0.5mm in this work, the groove has very limited influence on the burst pressure due to the good fracture toughness of HDPE material.

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