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Influence of Plastic Deformation Capacity on Failure Behaviour of Pipelines

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Abstract. Plastic deformation capacity parameters affect the deformability of steel in the plastic stage, and then affect the limit pressure of pipelines. This paper investigates the influence of plastic deformation capacity parameters on the limit bearing capacity of pipelines. These parameters include yield to tensile ratio (σ_y/σ_u), percentage uniform elongation (δ) and strain hardening exponent (n). Based on the Swift strain hardening model, the relational expression of the plastic deformation capacity parameters is theoretically deduced. 95 groups of material tensile test datum have been collected. Based on these test data, the variation tendency of the plastic deformation capacity parameters have been analyzed statistically, and the empirical formula of the key parameters have been fitted numerically. 20 groups of finite element examples are designed to analysis the influence of yield to tensile ratio and uniform elongation to limit pressure of pipeline. Results show that, with the improvement of strength grade of steel, the plastic deformability of steel decreases; the recommended of critical plastic deformation capacity indexes are: ① pipeline steel below X65, σ_y/σ_u≤0.85 and δ≥10%; ② pipeline steel for X70-X80, σ_y/σ_u≤0.93 and δ≥8%.

1. Introduction

It is well known that the plastic deformation capacity can significantly affect failure behavior of pipelines. As such, yield to tensile ratio, uniform elongation and strain hardening exponent have been recognized as important parameters in material specification and selection, structural design and integrity assessment [1]. The reasonable critical plastic deformation capacity index is of great significance to the construction and operation of pipelines [2].

At present, the plastic deformation capacity research mainly focuses on yield to tensile ratio. Progress made in the manufacturing of pipeline steels in recent years has led to increased yield stress without a corresponding increase in the ultimate tensile stress. As a result, modern pipeline steels tend to have a higher yield to tensile ratio. A considerable amount of research has been conducted to evaluate the significance of the yield to tensile ratio in hydrostatic testing, operating stress level, and plastic flow behavior for pipeline steels [3]. Recently, Bannister et al. [1] investigated the implications of the yield to tensile ratio to the ductile fracture failure assessment, while Sloterdijk [4, 5] compiled a literature survey.

Table 1 [6-10] is the provision to the plastic deformation capacity index in the criterion, and can show that, the requirements for plastic deformation capacity index vary in different country criterion and different famous petroleum company norms. The research on the influence of plastic deformation capacity to the failure of pipelines is still in the preliminary exploring stage.

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Nomenclature

σ_y	yield stress
σ'	engineering stress
σ_y'	engineering yield stress
σ_u	ultimate tensile stress
σ_u'	engineering ultimate tensile stress
ε	strain
ε'	engineering strain
ε_y	yield strain
ε_y'	engineering yield strain
σ_y/σ_u	yield to tensile ratio
δ	percentage uniform elongation
δ_y	percentage uniform elongation, when $\sigma = \sigma_y$
δ_u	percentage uniform elongation, when $\sigma = \sigma_u$
δ_b	percentage elongation after fracture
Ψ	percentage reduction of area
Ψ_y	percentage reduction of area, when $\sigma = \sigma_y$
Ψ_u	percentage reduction of area, when $\sigma = \sigma_u$
n	strain hardening exponent
K	strain hardening coefficient
A_0	original sectional area
A	fracture sectional area
l_0	original length
l	fracture length
P_{Limit}	limit pressure

Table 1.The provision to the plastic deformation capacity index in the criterion

criterion	p provision
API Spec 5L-2009/GB 9711-2011	PSL2 pipe:for equal or below X80: σ_y/σ_u≤0.93, for X90: σ_y/σ_u≤0.95; for X100: σ_y/σ_u≤0.97; for X120: σ_y/σ_u≤0.99.
ANSI/ASME B31.8-2010	σ_y/σ_u≤0.85.
ISO 3183-2	for X42～X52: σ_y/σ_u≤0.85,for X60～X80: σ_y/σ_u≤0.90.
ISO 3183-3	for X42～X52: σ_y/σ_u≤0.90,for X60～X80: σ_y/σ_u≤0.92.
TransCanada P-04	δ≥10％
SHELL GROUP L-3-2/3	σ_y/σ_u≤0.90
NRF-001-PEMEX-2007(Mexico)	for X52～X65: σ_y/σ_u≤0.93
DNV	for expanded pipe: σ_y/σ_u≤0.90; for general pipe: σ_y/σ_u≤0.85
Russia 75-86	for X65: σ_y/σ_u≤0.90

2. Physical Significance of the Plastic Deformation Capacity Index

The strain hardening exponent, yield to tensile ratio, percentage uniform elongation and percentage reduction of area are known collectively as the plastic deformation capacity index in the uniform deformation stage of material. These indexes do not exist independently, and have a great influence on the failure behavior of pipelines. The uniform deformation stage of material is the process from the material stress reaching the yield stress to ultimate tensile stress. The material stress and strain changes mildly in the stage.

2.1. Yield to Tensile Ratio
The yield to tensile ratio is the ratio of yield stress and ultimate tensile stress, and is dimensionless. The yield to tensile ratio does not have any physical significance unless combined with the yield stress. Its physical significance is the ability of bearing the overload margin when the material stress reaches the yield stress in the uniform deformation stage of material.

2.2. Uniform Deformation
The uniform deformation is characterized by percentage reduction of area or the percentage uniform elongation [11]. Its physical significance is the material deformability when it bears the limit pressure. The greater the value of Ψ or δ is, the stronger the plastic deformation capacity is. [12]

2.3. The Strain Hardening Exponent
The strain hardening exponent represents the deformation hardening ability in the uniform deformation stage of material. There are many strain hardening models, such as, Ramberg-Osgood model [13], Hollomon model [14], Swift model [15] and Ludwick model [16].

In order to research the effect of the plastic deformation capacity on the ultimate bearing capacity of pipeline, the first thing is to find out the relation of the plastic deformation capacity index. Use the theoretical derivation method to find the relationship of yield to tensile ratio, percentage uniform elongation and percentage reduction of area, and the basis of derivation is the Swift model.

Swift model is based on the Hollomon model, which is defined as Eq. (1). The stress-strain curve is divided into two parts, which are linear elastic part and plastic part. These researches focus on material's uniform deformation stage, so the linear elastic part of stress-strain curve can be ignored.

$$\sigma = \mathrm{K}\left(\varepsilon_y + \varepsilon\right)^n \tag{1}$$

After removing the elastic part, the function expression can be defined as Eq. (2):

$$\sigma = \Phi(\varepsilon_y + \varepsilon) \tag{2}$$

The form of the function is based on Hollomon model, and Swift model expression is obtained, the function relation between δ and Ψ is as follows:

$$\Psi = \frac{\delta}{1+\delta}, \text{ or } \delta = \frac{\Psi}{1-\Psi} \tag{3}$$

When $\sigma = \sigma_u$,

$$\Psi_u = 1 - \Psi_y - \frac{1}{e^n} \tag{4}$$

Then we can obtain:

$$\frac{\sigma_y'}{\sigma_u'} = \frac{1-\Psi_y}{e^{-n}+\Psi_y}\left[\frac{ln\left(\frac{1}{1-\Psi_y}\right)}{n}\right]^n \tag{5}$$

Substituting Eq. (3) and Eq. (4) into Eq. (5), we obtain the relationship of the plastic deformation capacity index

$$\begin{cases} \dfrac{\sigma_y'}{\sigma_u'} = M \cdot \left[\dfrac{ln\left(\frac{1+\delta_u}{M}\right)}{n}\right]^n \\ M = \delta_u + (1+\delta_u) \cdot e^{-n} \end{cases} \tag{6}$$

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3. The Statistical Analysis of the Plastic Deformation Capacity Index

In the previous section, we obtain the function relationship of the plastic deformation capacity index through theoretical derivation method, and the presupposition is that true stress and strain relations meet the Swift model.

In order to analyze the relationship between the plastic deformation capacity index of the pipeline, and research on the influence of index on the limit bearing capacity of pipeline, this section uses the statistical analysis and mathematical fitting methods. We collected the tensile performance test results of three strength grades steel (X65, X70 and X80) [17-21].

3.1. Change Trend Analysis

We adopt the statistical regression analysis method to analyze the change trend of deformation capacity index. Figs.1 shows that: strain hardening exponent and percentage uniform elongation decrease as the strength grade (yield stress) increases. It indicates that the deformation capacity of material in the plastic stage is reduced with the increase of steel strength grade.

Fig.2 shows that: the change trend of strain hardening exponent and percentage uniform elongation is consistent. This shows that in uniform deformation stage the stronger the strain hardening capacity, the stronger the deformability of material, namely the greater the plastic deformation allowance of material. This indirectly proves that the two deformation capacity indexes affect the deformation capacity of material in the plastic stage, and also affect the limit bearing capacity of the material in the plastic stage.

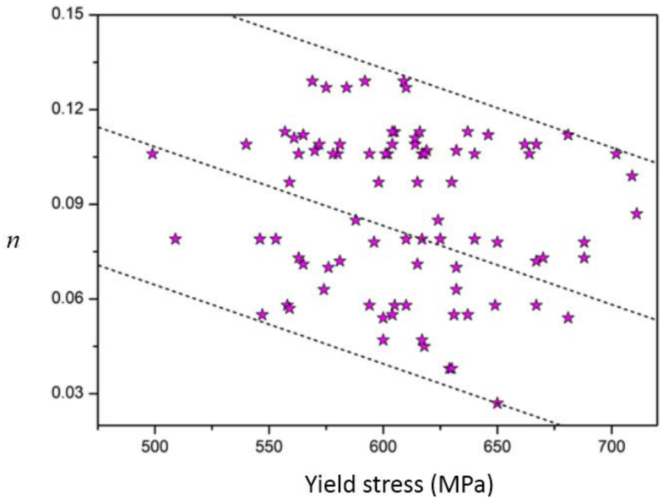

Figure 1. The relationship between the yield strength and the strain hardening exponent

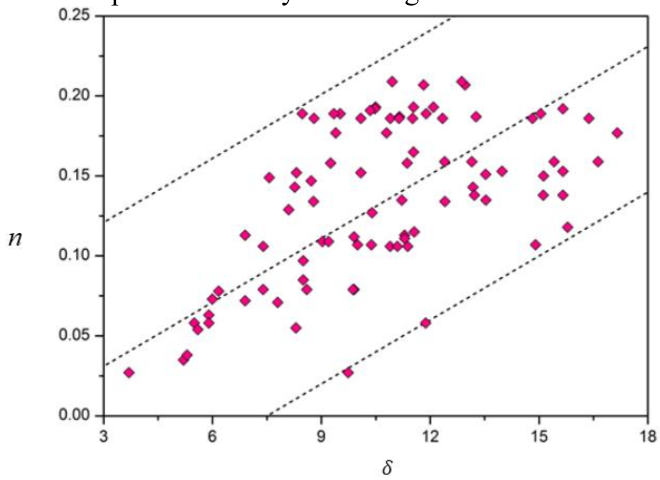

Figure 2. The relationship between the uniform elongation and the strain hardening exponent

3.2. The Empirical Formula

In engineering Application, the plastic deformation capacity indexes are often incomplete due to various reasons such as limited actual operation conditions, and it causes inconvenience to pipeline estimators. The experience formulas of two key indexes (σ_y/σ_u and δ) with other plastic deformation capacity indexes are obtained, which use statistical analysis and mathematical fitting methods. The experience formulas can provide a reference basis to estimators.

3.2.1. The empirical formula about δ. In the material tensile test, δ_b the percentage elongation after fracture, often can be measured by calculating the relative elongation of test specimen after fracture. In order to obtain the percentage uniform elongation (δ), we need to get the relationship between δ and δ_b. Figs.3 and 4 show the relationship between δ, δ_b and δ/δ_b. Using the mathematical fitting method, we can obtain

$$\delta = 0.5894 \cdot \delta_b - 5.771 \tag{7}$$

$$\delta = 0.02612 \cdot \delta/\delta_b + 0.1286 \tag{8}$$

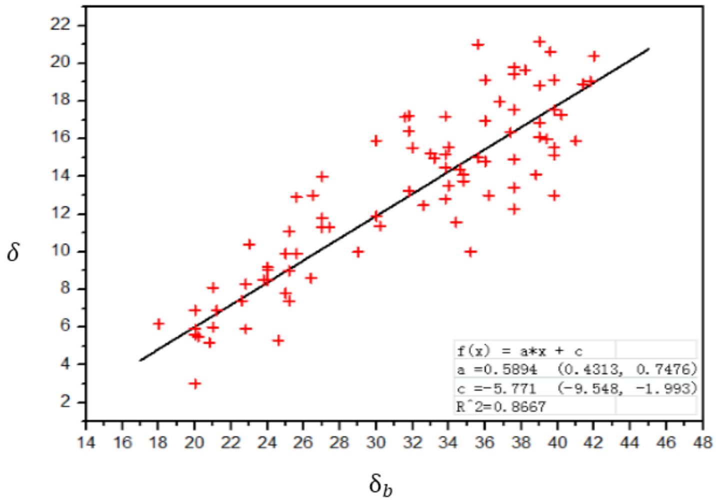

Figure 3 . The relationship between δ and δ_b

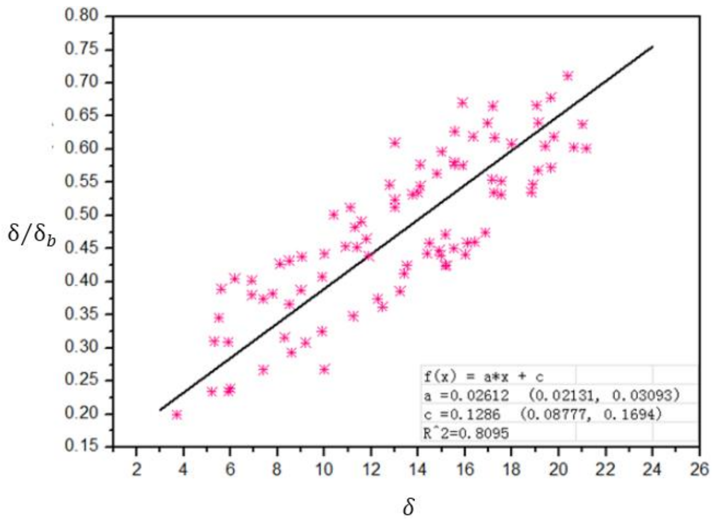

Figure 4. The relationship between δ and δ/δ_b

When δ and δ_b can be measured, in order to obtain the strain hardening exponent (n), we need to get the relationship between δ, δ_b.and n. Fig.5 shows the relationship between n and δ/δ_b. Using the mathematical fitting method, we can obtain

$$n = 0.3502 \cdot \delta/\delta_b - 0.0353 \tag{9}$$

It follows that,

$$\delta/\delta_b = 2.856 \cdot n + 0.1008 \tag{10}$$

Substituting Eq. (10) into Eq. (8), we obtain the relationship between n and δ

$$\delta = 0.0746 \cdot n + 0.1312 \tag{11}$$

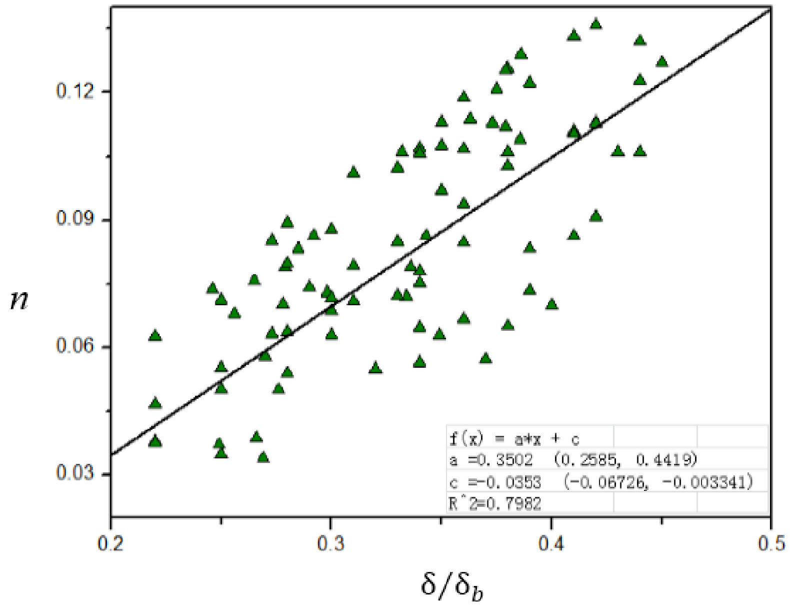

Figure 5. The relationship between n and δ/δ_b

3.2.2. The empirical formula about σ_y/σ_u. δ/δ_b is the proportion of the uniform elongation in the total elongation. δ/δ_b and n are the indexes which indicate the deformability of the material in the plastic stage. Figs.6 and 7 show the relationship between σ_y/σ_u , δ/δ_b and n. Using the mathematical fitting method, we can obtain

$$n = -12.88 \cdot (\sigma_y/\sigma_u)^3 + 30.45(\sigma_y/\sigma_u)^2 - 24.12(\sigma_y/\sigma_u) + 6.517 \tag{12}$$

$$\delta/\delta_b = \frac{10.182}{1+exp(20 \cdot \sigma_y/\sigma_u - 23.2)} - 9.786 \tag{13}$$

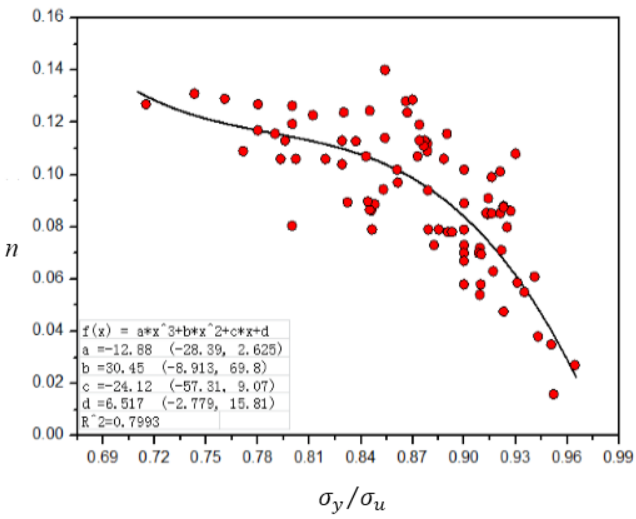

Figure 6. The relationship between σ_y/σ_u and n

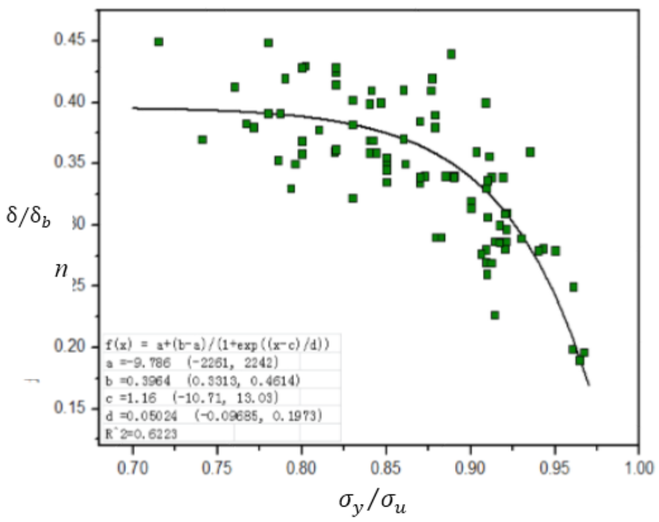

Figure 7. The relationship between σ_y/σ_u *and* δ/δ_b

In Figs.6 and 7, we can see that: after σ_y/σ_u reaches 0.85, δ/δ_b and n are falling faster. When σ_y/σ_u reaches 0.93, n is only 0.06, and δ/δ_b is less than 30%. It can be concluded that when σ_y/σ_u reaches 0.93, the plastic deformation capacity of material has reached the ultimate state.

3.3. The Critical Index Recommendation of σ_y/σ_u *and* δ

The yield to tensile ratio is not the unique index, which can determine plastic deformation capacity of material. From the above analysis, we can see that: the percentage uniform elongation is another key index, which can reflect plastic deformation capacity of material. The analysis of the relationship between σ_y/σ_u and δ (showed in Fig.8) is significant in researching the influence of plastic deformation capacity to pipeline bearing capability.

As shown in Fig.8, we can see that:

1) The percentage uniform elongation is reduced, with the increase of yield to tensile ratio, that is to say, the resistance capacity to deformation is reduced in the plastic stage;

2) When σ_y/σ_u reaches 0.85, the value of δ is about 10%, and in this point, the falling speed of δ begins to accelerate;

3) When σ_y/σ_u reaches 0.93, the value of δ is about 8%, the plastic deformation capacity of material has reaches the limit state.

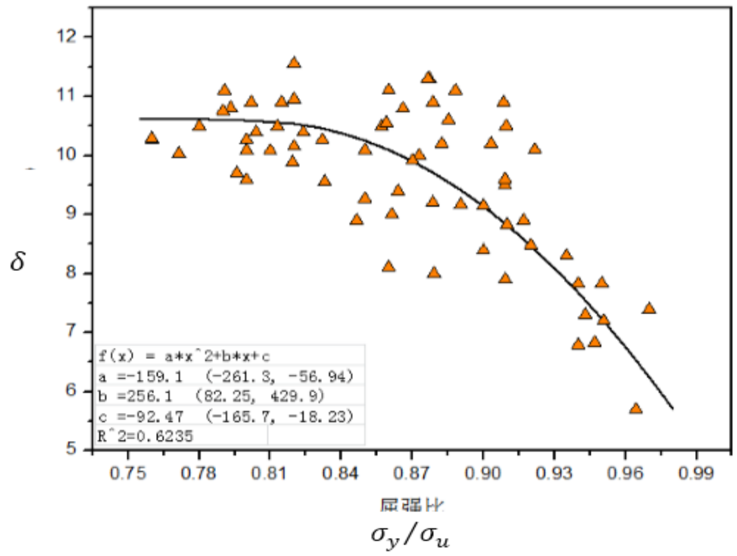

Figure 8. The relationship between σ_y/σ_u and δ

Based on the above analysis result, we recommend the critical plastic deformation capacity index of pipeline steel:

For the pipeline steel that is below X65, the index is $\sigma_y/\sigma_u \leq 0.85$ and $\delta \geq 10\%$;

For the pipeline steel that is X70-X80, the index is $\sigma_y/\sigma_u \leq 0.93$ and $\delta \geq 8\%$.

4. The Influence of Plastic Deformation Capacity on Limit Bearing Capacity of Pipelines

20 groups of finite element examples are designed to analyze the influence of yield to tensile ratio and uniform elongation on the limit pressure of pipeline. In order to avoid the influence of geometric parameters on the limit pressure pipeline, we unify pipeline geometry size to D=1016m, t=14.6mm and without defects.

4.1. The Influence of σ_y/σ_u on Limit Pressure

In this section, the influence of σ_y/σ_u (vary with σ_y or σ_u) with the same δ is investigated. It is well known that, σ_y/σ_u is not an independent physical quantity, and is composed of σ_y and σ_u, and the variation of σ_y or σ_u causes the variation of σ_y/σ_u. Therefore, the research on σ_y/σ_u itself is unreasonable. Firstly, we designed 6 groups of finite element examples (described in Table 2) to research the influence of σ_y/σ_u on limit pressure when σ_y/σ_u varies with σ_u.the increase of σ_y/σ_u (which varies with the decrease of σ_u) will led to the decrease of limit pressure, which shows a linear decline.

Then, we designed another 6 groups of finite element examples (described in Table 3) to research the influence of σ_y/σ_u on limit pressure when σ_y/σ_u varies with σ_y.

Table 2. The influence of σ_y/σ_u (varying with σ_u) to P_{Limit}

σ_y/σ_u	δ(%)	σ_y(MPa)	σ_u(MPa)	P_{Limit}(MPa)
0.76	10	524	689	20.051
0.8	10	524	655	19.335
0.85	10	524	624	18.691
0.88	10	524	595	17.963
0.93	10	524	563	16.890
0.96	10	524	546	16.320

Table 3. The influence of σ_y/σ_u (varing with σ_y) to P_{Limit}

σ_y/σ_u	δ(%)	σ_y(MPa)	σ_u(MPa)	P_{Limit}(MPa)
0.76	10	524	689	20.051
0.8	10	552	689	21.927
0.85	10	579	689	22.769
0.88	10	607	689	22.676
0.93	10	641	689	22.577
0.96	10	662	689	22.551

σ_y/σ_u increases when σ_y decreases. When $\sigma_y/\sigma_u \le 0.85$, limit pressure increases; when $0.85 < \sigma_y/\sigma_u \le 0.93$, limit pressure will decreases slightly; and when $\sigma_y/\sigma_u > 0.93$, the limit pressure will no longer changes, and tends to be gentle.

By analyzing the influence of σ_y/σ_u (varying with the above reasons) on limit pressure, we can learn that: the limit pressure of high strength grade pipeline is mainly influenced by σ_u. When $\sigma_y/\sigma_u = 0.93$, the change of σ_y almost has no effect on the limit pressure. It also proves that for high strength steel, the critical index of σ_y/σ_u is 0.93.

4.2. The Influence of δ on Limit Pressure

In this section, the influence of δ with the same σ_y/σ_u is investigated. We designed 8 groups of finite element examples (described in Table 4) to research the influence of δ (vary with four level 6%-12%) on limit pressure, when σ_y/σ_u is equal to 0.76 and 0.88 respectively. we can learn that: when σ_y/σ_u is constant, the increase of δ causes the gentle rise of limit pressure.

Table 4. The influence of δ to P_{Limit}

σ_y/σ_u	δ(%)	σ_y(MPa)	σ_u(MPa)	P_{Limit}(MPa)
0.76	6	524	689	19.72
0.76	8	524	689	20.05
0.76	10	524	689	20.47
0.76	12	524	689	21.00
0.88	6	524	595	17.67
0.88	8	524	595	17.96
0.88	10	524	595	18.24
0.88	12	524	595	18.46

5. Conclusions

This paper investigates the influence of plastic deformation capacity parameters to limit bearing capacity of pipelines. Firstly, we analyzed the relationship of plastic deformation capacity parameters, and then, recommend the critical plastic deformation capacity index of pipeline steel, finally, analyzed the influence of two key indexes (σ_y/σ_u and δ) on limit pressure, using theoretical derivation, mathematical statistics, mathematical fitting and finite element analysis methods. Based on the current analysis, the results can be summarized as follows:

(1)The relational expression of the plastic deformation capacity parameters is theoretically deduced, which is based on the stress-strain relation of material meets Swift hardening model.

(2)Based on 95 groups of material tensile test data, we analyze the variation tendency of the plastic deformation capacity parameters, and the empirical formula of the key parameters has been fitted numerically. We can learn that: ① n and δ decrease as the strength grade (yield stress) increases. That is to say: the deformation capacity of material in the plastic stage is reduced with the increase of steel strength grade. ② The resistance capacity to deformation is reduced, with the increase of σ_y/σ_u, in the plastic stage of material.

(3)We recommend the following critical plastic deformation capacity index of pipeline steel are:

For the pipeline steel that is below X65, the index is $\sigma_y/\sigma_u \leq 0.85$ and $\delta \geq 10\%$;

For the pipeline steel that is X70-X80, the index is $\sigma_y/\sigma_u \leq 0.93$ and $\delta \geq 8\%$.

(4)20 groups of finite element examples are designed to analyze the influence of σ_y/σ_u and δ on limit pressure of pipeline. And we can learn that:① when δ is constant, the limit pressure of high strength grade pipeline is mainly influenced by σ_u . After $\sigma_y/\sigma_u = 0.93$, the change of σ_y almost has no effect on the limit pressure. ② When $\sigma_y/\sigma_u\ is$ constant, increasing δ value will causes the gentle rise of limit pressure.

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