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Research Article

Research on Material Selection Method and Brittle Fracture Mechanism of High-Pressure Pipeline

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Aiming at the problem of the brittle fracture of pressure pipeline, the elastic constraint structure is described by using members and engineering building structures, and the concept of elastic constraint is proposed. Through the stress field analysis of the pressure pipeline under internal pressure, it is found that the pressure pipeline under internal pressure is an elastic constraint structure. The elastic constraint effect is applied to the pressure pipeline to explore the influence of elastic constraint effect on the brittle fracture of pressure pipeline. The critical wall thickness and limit load of different materials are calculated by the limit bearing formula. Through simulation analysis of materials with different yield ratios and pipelines with different wall thicknesses of the same material (yield ratio is the ratio of yield strength to tensile strength), it was found that pressure pipelines made of the same material have an increased load-bearing capacity as the wall thickness increases, but their own elastic constraint effects are becoming more obvious, and the probability of the brittle fracture of the pipeline is higher. When the wall thickness of pressure pipelines made of materials with different yield ratios is certain, the lower the yield ratio is, the more likely the pipeline is to generate plastic deformation and the larger the deformation capacity is; the higher the yield ratio, the poorer the plastic deformation capacity of the pipeline and the smaller the deformation capacity. Pipelines with large yield ratio are more sensitive to the brittle fracture than those with small yield ratio.

1. Introduction

Long-distance high-pressure pipeline transportation is the main way of resource distribution. When pipelines are subjected to impact or vibrate during service, fracture accidents are highly likely to occur. Once a pipeline leak occurs, it will cause environmental pollution and serious casualties. In 2010, an explosion occurred in the PetroChina oil pipeline near Dalian Xingang and caused extensive pollution in the sea area [1]. In 2013, a pipeline broke near Qinhuangdao Road in Huangdao District. The leakage part of Huangdao was permanently suspended [2]. In 2012, a natural gas pipeline in British Columbia broke and caused a large amount of natural gas leakage [3]. In 2012, an interstate buried natural gas pipeline in West Virginia ruptured and caused losses of nearly ten million [4]. The investigation results indicate that the sudden increase of internal pressure in the pipeline leads to high local stress concentration in the pipeline and the fracture of the pipeline. In addition, during the construction process, mechanical equipment is prone to hitting the pipeline and generating impact internal pressure, the fracture of the pipeline was caused. In the field of transportation, pipeline engineering often requires crossing traffic facilities such as roads and bridges. Vehicles generate vibration during driving. When the pipeline is subjected to external vibration loads, it is easy to cause an increase in internal pressure, the fracture of the pipeline was caused. This fracture occurs without visible deformation of the pipeline and is also one of the brittle fracture types of the structure.

Academician Li Helin emphasized that the brittle fracture is a problem, and it is difficult to avoid in long-distance high-pressure gas pipelines. Under the action of internal pressure, the fracture length of the pipeline can instantly extend up to hundreds of meters. According to traditional elastic-plastic theory, brittle fracture of pipelines cannot be avoided by increasing the wall thickness of the pipeline or improving the steel grade, and it can also make the pipeline more prone to the brittle fracture in the application process [5]. In the DWTT (Drop-Weight Tear Test) and the research of the thickness effect of the pipeline, Zhang et al. found that the percentage of the shear area of the sample showed a Z-shaped curve with the increase of the wall thickness, indicating that the toughness of the pipeline gradually decreased [6, 7]. In the application of thick walled pipelines and DWTT technology, Ji Lingkang found that, while the steel grade remains unchanged, increasing the wall thickness will lead to an increasing proportion of plane strain in the triaxial stress state of the sample, and it is difficult to maintain a high shear area. If a high DWTT value is blindly pursued, the plastic deformation capacity of the pipeline will decrease, which made the brittle fracture easily generated in high-pressure pipelines [8, 9]. At the same time, relevant researchers conducted impact tests on pipelines and combined them with DWTT tests in an attempt to reflect the true characteristics of materials under special conditions. Researchers found that improving the steel grade can enhance the material's ability of resist crack initiation and propagation, while the brittle fracture of pipeline cannot still be solved [10–12]. In foreign countries, DWTT tests had been carried out for the pipelines to explore the fracture toughness indicators and the shear fracture appearance of the sample corresponding to the wall thickness and pipeline material. The corresponding wall thickness is selected according to the service requirements. This wall thickness selection method can provide a certain theoretical basis, but the brittle fracture of pipelines cannot be avoided [13–15]. From the above analysis, it can be seen that maintaining a high DWTT value of the pipeline will lead to a decrease in the plastic deformation capacity of the pipeline. Increasing the wall thickness will make the pipeline tend to be the plane strain state, which further limits the toughness of the pipeline. However, improving the steel grade can enhance the pipeline's ability of resisting crack initiation and propagation, but the space for improving is seriously limited. The brittle fracture of pipelines cannot be effectively avoided by increasing wall thickness, improving steel grade, and maintaining high DWTT values. Therefore, researchers attempt to identify relevant laws through a large number of experiments and develop design standards that meet the requirements of domestic pipelines.

At present, ASME and ISO are two major international pipeline standard systems. For the ISO, it is only applicable to steel grades below X80. For high steel grades above X80, ISO continues to use the ASME. ASME and ISO use yield strength for calculation [16]. As is well known, the service conditions of pipelines in Russia are relatively harsh. Therefore, Russia does not use ASME and ISO systems but uses its own standards. For safety reasons, according to Russian standards, pipeline wall thickness is calculated based on material tensile strength, and the calculated wall thickness takes into account the safety margin of material deformation. Therefore, the calculated value of wall thickness is relatively large [17, 18]. Although Australia [19] and Canada [20] do not adopt ASME standards, their standard formulas indicate that they are based on the American ASME B31.4-2012 and ASME B31.8-2012 standards. The Chinese pipeline standard is derived from the American standard, so the requirements for pipelines are basically the same. It is calculated based on the yield strength of the material using the third strength theory [21]. It is obvious that the only difference among the Chinese, Australian, and Canadian standards is the value of the coefficient. For European countries, the ISO system, abbreviated as the "European standard," is used. According to the European standard formula, the calculated wall thickness is the minimum wall thickness, and the coefficients taken by the European standard and the American standard are different. Therefore, the wall thickness calculated according to the European standard is often larger than the wall thickness calculated according to the standards of China, Australia, and Canada [22]. Thus, it is clear that the wall thickness calculated by the Russian standard is the largest, while the wall thickness calculated by the Chinese, Australian, and Canadian standards is the minimal. Moreover, the wall thickness calculated by the European standard is between them.

For pipeline engineering, there are relevant design standards in various countries, and wall thickness can be calculated and selected based on these standards. Pipelines may have complex and variable loads that are not recognized by researchers during service. When the pipeline is subjected to external impact, a very large impact internal pressure will be generated inside the pipeline. When the impact internal pressure exceeds the bearing limit of the pipeline, the fracture of the pipeline was caused. When the pipeline is subjected to unexpected loads mentioned above, according to the literature [23, 24], whether increasing or reducing the wall thickness, the brittle fracture cannot be effectively avoided. Therefore, the background of pipeline application engineering in this article is high-pressure gas pipelines. A large number of survey results indicate that most accidents in high-pressure gas pipelines are caused by brittle fracture. Aiming at this issue, we explored the idea of avoiding brittle fracture in pipelines from the perspective of elastic constraints to reduce the probability of brittle fracture in pipelines. This provides relevant theoretical references for the resistance of brittle fracture design of high-pressure pipelines in the future.

2. Elastic Constraint Effect

From the perspective of materials science, dislocation slip is the main physical mechanism of plastic deformation in metal materials. For plastic materials, plastic deformation generates when the stress state meets the yield condition. In theory, whether the plastic deformation generates in the ductile materials is determined by the shear stress, but in practical engineering structures, whether plastic deformation generates in materials is also constrained by elastic constraints in the structure.

$$\begin{cases} \sigma_{AC} = \dfrac{y}{(x+y)}F, \\ \sigma_{CB} = \dfrac{x}{(x+y)}F. \end{cases} \quad (1)$$

The concept of elastic constraint is further explained through the fixed straight bar *AB* at both ends shown in Figure 1.

The stress of the bar in the elastic stage is as follows.

From Figure 1 and formula (1), it is evident that the *AC* part is in tension, and the *CB* part is in compression. The normal stress in the *AC* part is larger than that in the *CB* part because the length of the *AC* part is smaller than that of the *CB* part. As the load *F* gradually increases, the stress in the *AC* part will reach the yield strength of the material at first. However, as the *AC* part and the *CB* part belong to an overall structure, the plastic deformation of *AC* part is affected by the elastic deformation of *CB* part that is the low stress zone. When the stress in the *AC* part reaches the material's own the yield strength, plastic deformation cannot be generated in freely in the material, and thereby the deformation of the entire structure is still at the elastic level. As the load continues to increase, the stress in the low stress elastic zone of the *CB* part also reaches the yield strength of the material. At this time, the high stress zone of the *AC* part is no longer constrained by the low stress elastic zone of the *CB* part, so that the plastic deformation can be generated in the straight bar *AB*. In constrained deformation structures, when the stress intensity in a certain area is higher than the material yield strength, the plastic deformation in this area is constrained by low stress elastic deformation, which is called elastic constraint.

For the structure shown in Figure 1, if the stress in the *CB* part reaches the material's own yield strength before the stress in the *AC* part reaches the material's own fracture strength, the brittle fracture without the plastic deformation will occur in the overall structure. Thus, it is clear that when elastic constraints exist in the structure, the brittle fracture will occur in metal ductile materials under the influence of elastic constraints.

Taking the static indeterminate truss shown in Figure 2 as an example, it is the super constrained brittle fracture analysis of elastic constrained structures. The entire truss is subjected to a vertical force *F*. Assuming that the tensile and compressive stiffness of the three bars is the same, while maintaining the elastic state of each bar, all of the three bars are in tension during the elastic stage. Therefore, the axial force of the *CD* bar, *AC* bar, and *BC* bar is as follows:

$$\begin{cases} N_1 = \dfrac{F}{2\sin^3\theta + 1}, \\ N_2 = N_3 = \dfrac{F\sin^2\theta}{2\sin^3\theta + 1}. \end{cases} \quad (2)$$

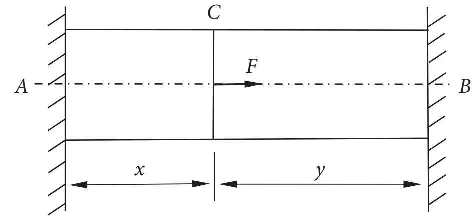


Figure 1: Fixed straight bar with both ends subjected to axial load.

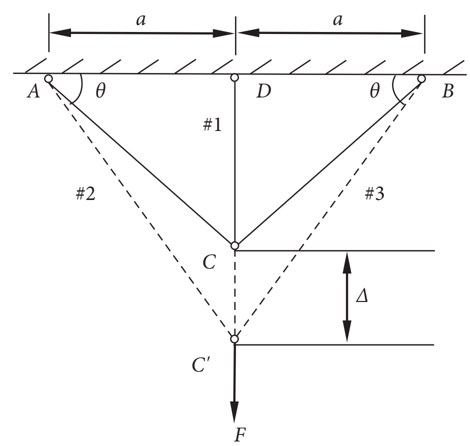


Figure 2: Three-bar symmetric statically indeterminate truss subjected to vertical force *F*.

According to formula (2), N_1 (i.e., the axial force of the *CD* bar) is always larger than that of N_2 (i.e., the axial force of the *AC* bar) and N_3 (i.e., the axial force of the *BC* bar). As the load *F* gradually increases, the stress in the *CD* bar reaches or exceeds the yield strength of the material at first; meanwhile, the *AC* bar and *BC* bar are still in the elastic deformation stage. As the *CD* bar, *AC* bar, and *BC* bar belong to an overall structure, the plastic deformation that freely generates in the *CD* bar will be restricted by the elastic deformation of the *AC* bar and *BC* bar. The entire truss does not fully enter the stage of free plastic deformation until the stress of the *AC* and *BC* bars reaches the yield strength of the material itself. During the process of increasing load continuously, if the stress in both *AC* bar and *BC* bar does not reach the yield strength of the material itself and the stress in *CD* bar reaches the fracture strength of the material, the brittle fracture without the plastic deformation will occur in the *CD* bar at this time.

There is also the elastic constraint phenomenon in civil engineering, such as the over-constraint brittle fracture of steel bars. Statically indeterminate structures are often used in the elastic design theory of civil engineering in order to improve the strength and stiffness of the beam. Initially, a higher reinforcement ratio was often used in order to make the structure safer. In current specifications, it is believed that the higher the reinforcement ratio of the over-reinforced beam is, the safer the beam will be. However, in practical applications, engineering technicians have found that the brittle fracture is more prone to occur in the over-reinforced beam [25]. Moreover, it is difficult to provide a reasonable explanation for the phenomenon of the brittle fracture in the over-constraint beams based on traditional elastic-plastic theory. The over-constraint brittle fracture phenomenon mentioned above is discovered and proposed by engineering technician through a large number of practical engineering and embodied in the current design specifications of civil engineering [26].

Pressure pipelines are almost designed based on elastic theory. Under the design load, the elastic deformation only generates in the pipeline. The stress on the inner wall of the pipeline is larger than the stress on the outer wall. Under the internal pressure of the pipeline, the elastic deformation generates in the inner wall at first. The stress at the inner wall firstly reaches the yield strength when the internal pressure gradually increases. The plastic deformation generates in the inner wall, and the plastic zone extends from inside to outside. As the stress on the outer wall is much smaller than the stress on the inner wall, the outer wall is still in the elastic stage, and the elastic deformation of the outer wall has a restraining effect on the plastic deformation of the inner wall, which indicates that the pressure pipeline is an elastic constraint structure. A large number of pressure pipeline accidents show that pipelines are subjected to impact external loads, which can cause the brittle fracture of pipelines. The length of crack in the pipeline may instantly extend up to hundreds of meters. In practical engineering, the fracture in the pipeline cannot be avoided. It is hoped that the ductile fracture with certain early warning will occur in the pipeline without the brittle fracture.

From analysis mentioned above, it is clear that whether it is the stressed bar, engineering building structure, or pressure pipeline, provided the elastic constraint effect is involved in the structure, the influence of elastic constraint on the brittle fracture should be attached importance in the design process. It can also be seen that when the material is subjected to external forces, even if external factors meet conditions of the plastic deformation, plastic deformation may not necessarily generate in the material. Therefore, whether the plastic deformation can generate in the material is not determined by a single factor of shear stress but determined by the combined effect of shear stress and elastic constraints. In the process of pipeline fracture, once the visible plastic deformation generates in the pipeline, the fracture in the pipeline will transform from the brittle fracture caused by elastic constraints to ductile fracture, and the speed of fracture in the pipeline will significantly reduce, so the safety of the pipeline is improved.

3. Material Selection Method and Wall Thickness Design for High-Pressure Pipelines

According to plastic theory, a long-distance thick walled cylinder can be simplified as a plane strain problem. As shown in Figure 3, a thick walled cylinder under internal pressure has an inner radius of a, an outer radius of b, and an inner pressure of p. When the internal pressure is small, the entire thick walled cylinder is in elastic state. According to the von Mises yield condition, when the stress on the inner wall of a thick walled cylinder reaches the yield strength, the

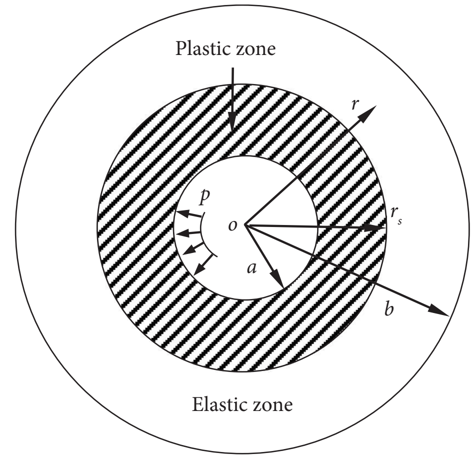


FIGURE 3: Thick walled cylinder under internal pressure.

inner wall of the cylinder reaches the yield state, and plastic deformation begins to generate on the inner wall of the thick walled cylinder. As the internal pressure continues to increase, the plastic deformation will generate in the thick walled cylinder; at the same time, the plastic zone will extend from the inside out. At this point, the thick walled cylinder enters an elastic-plastic state; the thick walled cylinder is divided into elastic and plastic zones by the interface between elastic zones and plastic zones with a radius of r_s. When the interface between elastic zones and plastic zones coincides with the outer wall of the pipeline ($r_s = b$), the thick walled cylinder reaches the plastic limit state and loses its load-bearing capacity.

From the analysis mentioned above, it is clear that even if the maximum shear stress at a certain point that is in the pipeline under elastic constraints reaches the yield strength of the material itself, the plastic deformation cannot generate in the material, so the brittle fracture will occur in the pipeline. If the stress on the inner wall of the pipeline does not meet the fracture condition of the material itself and the stress on the outer wall of the pipeline reaches the yield condition of the material at first, the overall plastic deformation of the pipeline can generate under internal pressure, which can effectively avoid the occurrence of the brittle fracture. Applying first strength theory that is a simple fracture condition to the inner wall and the Tresca yield condition to the outer wall can deduce the conditions to avoid the brittle fracture of the thick walled cylinder. In formula (3), σ_s is the yield strength of the pipeline, σ_b is the tensile strength of the pipeline, a is the inner radius of the pipeline, b is the outer radius of the pipeline, and p_u is the limit bearing internal pressure of the pipeline. The limit bearing internal pressure of the pipeline p_u can be calculated by formula (3), and the minimum value of p_u is selected [27].

$$\begin{cases} p_u = \sigma_s \dfrac{b^2 - a^2}{2a^2}, \\ \\ p_u = \sigma_b \dfrac{b^2 - a^2}{a^2 + b^2}. \end{cases} \tag{3}$$

From Table 1, it is apparent that the yield ratio of Q235 material is smaller than that of X80 material (X80 and Q235 are two kinds of steel); meanwhile, selectable range of the wall thickness of Q235 pipeline is wider than that of X80 pipeline. Therefore, the range of wall thickness dimensions that do not cause brittle fracture is larger for Q235 pipeline, and the limit bearing capacity of Q235 pipeline is greater within the critical wall thickness range. According to formula (3), the limit bearing internal pressure p_u of pipelines is related to wall thickness, yield strength, and tensile strength. Therefore, the probability of the brittle fracture of pipelines can be reduced by selecting appropriate wall thickness of pipelines and reasonable yield ratio of the material. However, in engineering, further verification is needed to determine whether the above two methods can reduce the probability of brittle fracture occurrence. Taking pipelines made of two kinds of materials with significantly different yield ratios (Q235 and X80) as the research objects, a certain wall thickness between the critical wall thickness of Q235 and X80 pipelines is selected for simulation to explore the sensitivity of the two kinds of materials to brittle fracture. The elastic and plastic limit loads for the selected wall thickness are calculated based on the elastic-plastic limit load formula of the thick walled cylinder. Elastic limit load formula (4) and plastic limit load formula (5) are as follows [28].

$$q_e = \left(1 - \frac{a^2}{b^2}\right)\frac{\sigma_s}{\sqrt{3}}, \quad (4)$$

$$q_p = \frac{2\sigma_s}{\sqrt{3}}\ln\frac{b}{a}, \quad (5)$$

where q_e is the elastic limit internal pressure and q_p is the plastic limit internal pressure.

In formulas (4) and (5), the elastic limit internal pressure q_e and the plastic limit internal pressure q_p of pipelines are directly related to wall thickness and yield strength, and calculation principle of formulas (4) and (5) is the same as formula (3). Therefore, according to the limit bearing internal pressure p_u the elastic limit internal pressure q_e and the plastic limit internal pressure q_p, select simulated internal pressure and conduct simulation analysis for the pipeline. Table 2 indicates that when the wall thickness of the pipeline is 120 mm, the limit bearing internal pressure p_u of X80 is smaller than its own plastic limit internal pressure q_p ($p_u < q_p$), while the limit bearing internal pressure p_u of Q235 is larger than its own plastic limit internal pressure q_p ($p_u > q_p$). Therefore, for X80 pipeline, when the internal pressure of the pipeline p_i reaches the plastic limit internal pressure q_p, the internal pressure p_i has already exceeded the limit bearing internal pressure p_u before overall plastic deformation generates in the pipeline ($p_i > p_u$), so only the elastic deformation is allowed to generate in the pipeline. For Q235 pipeline, when the internal pressure of the pipeline p_i is in the range of the limit bearing internal pressure p_u ($p_i < p_u$), even if the internal pressure of the pipeline p_i is larger than the plastic limit internal pressure q_p ($p_i > q_p$), the brittle fracture may not occur in the pipeline, and the plastic deformation can freely generate in the pipeline. The analysis above indicates that the brittle fracture is not easy to occur in Q235 pipeline compared to X80 pipeline. Under the condition of 120 mm wall thickness, simulation analysis was conducted for X80 and Q235 pipelines. The simulated internal pressure is between the limit bearing internal pressure p_u and the plastic limit internal pressure q_p. The sensitivity of pipelines to the brittle fracture is explored in the limit state, as shown in Figures 4 and 5.

Figure 4 shows that the equivalent stress on the inner wall of the pipeline has reached the yield strength. According to traditional plastic theory, the plastic deformation will generate in the pipeline. From Figure 5, it can be seen that the equivalent plastic strain value of the outer wall of the pipeline that is made of X80 material is close to 0 (shown in Figure 5(a)), and the plastic strain value of the outer wall of the Q235 pipeline is approximately 0.01 (shown in Figure 5(b)), which indicates that the plastic deformation cannot generate in the pipeline made of X80 material. Obviously, traditional plastic theory cannot explain the phenomenon that the plastic deformation cannot generate in the pipeline under elastic constraints. From the perspective of the elastic constraint, as the internal pressure increases, when the equivalent stress on the inner wall of the pipeline reaches the yield strength, the plastic deformation will generate on the inner wall; meanwhile, the outer wall is still in the elastic stage, so the plastic deformation on the inner wall will be constrained by the elastic deformation on the outer wall. In all, under the elastic constraint, the plastic deformation cannot generate in the pipeline made of X80 material even if the inner wall reaches the yield strength.

During the service process of pipelines, when the pipeline is subjected to unexpected impact load, the pressure in the pipeline will suddenly increase. When a certain point in the pipeline meets the brittle fracture condition of the material itself, the plastic deformation cannot generate in the pipeline timely, so that the brittle fracture will occur in the pipeline. Figure 6 shows that the maximum value of the first principal stress of X80 pipeline is approximately 576 MPa that is close to its own tensile strength (shown in Figure 6(a)). Moreover, the plastic deformation cannot freely generate in the pipeline under elastic constraints, so the brittle fracture is more prone to occur in the pipeline. However, the first principal stress of Q235 pipeline is close to 282 MPa that is much smaller than its own tensile strength (shown in Figure 6(b)), and the pipeline is less affected by elastic constraints. Moreover, the plastic deformation can freely generate in the pipeline with increasing internal pressure, and the brittle fracture is not easy to occur in the pipeline. Thus, it is evident that when the yield ratio of the pipeline is certain, the brittle fracture is prone to occur in X80 pipeline compared to Q235 pipeline due to the existence of elastic constraints.

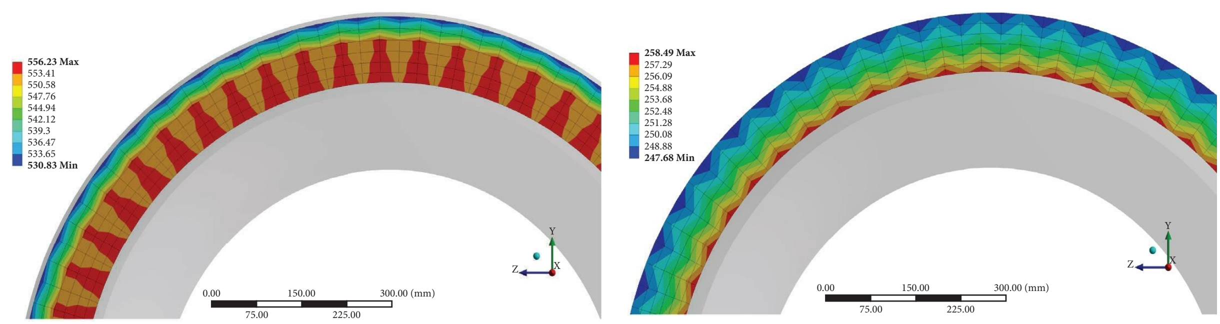
The yield ratio reflects the deformation capacity of materials from yield to fracture. The lower the yield ratio, the larger the deformation capacity of materials from the initial plastic deformation to the final fracture after yield. The higher the yield ratio, the smaller the deformation capacity of materials. The yield ratio also reflects the ability of materials to

Table 1: Critical wall thickness and limit bearing internal pressure of different kinds of steel (outer radius $b = 500$ mm).

Material	Yield ratio	Outer radius (mm)	Inner radius (mm)	Critical wall thickness (mm)	Limit bearing internal pressure (MPa)
X80	0.89	500	448	52	68.15
Q235	0.51	500	293	207	224.67

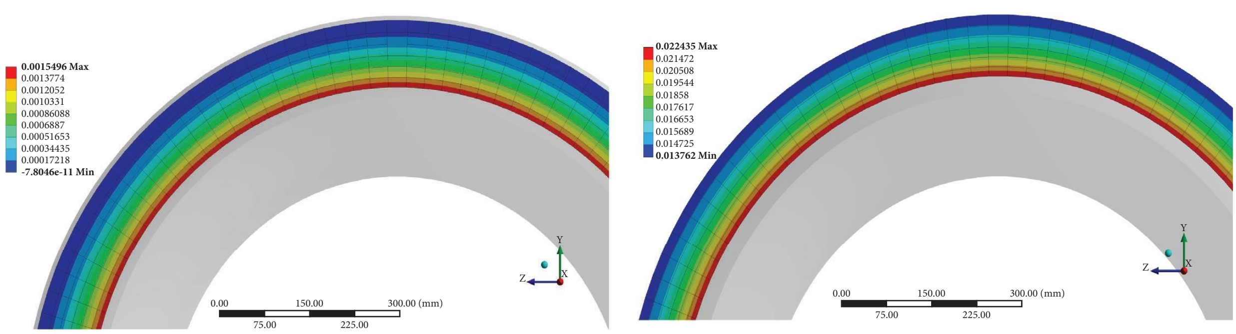
Table 2: Limit bearing internal pressure of pipeline (MPa).

Material	Wall thickness (mm)	P_u	q_e	q_p
X80	120	167.34	135.35	174.27
Q235	120	85.93	57.31	74.47



(a) (b)

Figure 4: Cloud diagrams of equivalent stress of X80 and Q235 pipelines under different pressures. (a) X80 pipeline with 120 mm wall thickness. (b) Q235 pipeline with 120 mm wall thickness.



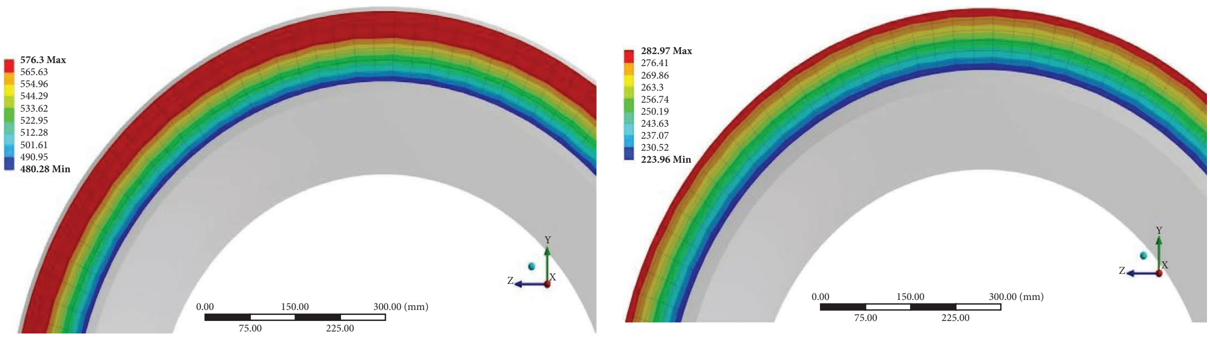
(a) (b)

Figure 5: Cloud diagrams of equivalent plastic strain of X80 and Q235 pipelines under different pressures. (a) X80 pipeline with 120 mm wall thickness. (b) Q235 pipeline with 120 mm wall thickness.

resist accidental damage in engineering. From the analysis above, it is found that the yield ratios of X80 and Q235 materials are different. Under the same wall thickness, X80 pipeline is more prone to brittle fracture than Q235 pipeline. Therefore, it can be considered that the brittle fracture of pipelines is directly related to the yield ratio of the pipeline.

4. Brittle Fracture Failure Analysis of High-Pressure Pipelines

In order to further verify the influence of yield ratio and elastic constraints on the brittle fracture in the pipeline, ANSYS LS-DYNA is used to simulate and analyze the fracture failure of pipelines with different wall thicknesses of the same material and the same wall thickness of different materials. Multiple sets of wall thicknesses are selected within the critical wall thickness range, and the simulation analysis of the pipeline's fracture failure with different wall thicknesses is taken under the same internal pressure to explore the fracture law of pipelines (the applied internal pressure is 30 MPa). In order to avoid errors caused by size of grids, the same size grid for models with different wall thicknesses is used in the simulation analysis process. Because the speed of the brittle fracture is high in the pipeline, the duration of fracture analysis is set to 0.1 seconds. Simulation analysis is shown in Figure 7.



(a)

(b)

Figure 6: Cloud diagrams of the first principal stress of X80 and Q235 pipelines. (a) X80 pipeline with 120 mm wall thickness. (b) Q235 pipeline with 120 mm wall thickness.

4.1. Simulation Analysis of Pipelines with Different Wall Thicknesses of the Same Material. The simulation analysis of the Q235 pipeline with the wall thicknesses of 30 mm, 45 mm, 53 mm, 60 mm, 90 mm, and 120 mm is taken, and the cloud diagram of the simulation analysis is shown in Figure 7.

For the pipeline with the wall thickness of 30 mm (shown in Figure 7(a)) and 45 mm (shown in Figure 7(b)), the obvious plastic deformation can generate on the outer wall of the pipeline. For the pipeline with the wall thickness of 53 mm (shown in Figure 7(c)), the equivalent plastic strain value of the outer wall of the pipeline is close to 0.008, and ability of the plastic deformation is significantly reduced. For the pipeline with the wall thickness of 60 mm (shown in Figure 7(d)), 90 mm (shown in Figure 7(e)), and 120 mm (shown in Figure 7(f)), the plastic strain values of the inner and outer walls of the pipeline are approximately 0, indicating that the plastic deformation cannot generate in the pipeline under elastic constraints. From the analysis above, it is apparent that when Q235 pipeline is under the same internal pressure state, the ability of plastic deformation gradually decreases with the increase of wall thickness.

Thus, for pipelines under high internal pressure, the obvious plastic deformation generates on the inner wall of the pipeline, but only the elastic deformation generates on outer wall of the pipeline. Therefore, the elastic deformation of outer wall of the pipeline limits the plastic deformation on the inner wall, which results in an elastic constraint effect.

For long-distance transportation pipelines, the length of the pipeline is infinite in theory. In the process of simulation, fixed constraints are applied at both ends of the pipeline, so the middle section of the pipeline can reflect the true situation of pipeline fracture. However, there are countless stress-strain points on the middle section of the pipeline; neither the maximum nor minimum values can truly reflect the overall fracture situation of the pipeline, so all points on the middle section of the pipeline are averaged, and the average value is used to represent the true situation of pipeline fracture (the average equivalent stress on the middle section during pipeline fracture is σ_a; the average equivalent plastic strain on the middle section during pipeline fracture is ε_a). As shown in Figure 8, for the pipeline with the wall thickness of 30 mm, σ_a is close to 588.875 MPa, and ε_a is close to 0.497 (shown in Figure 8(a)). For the pipeline with the wall thickness of 45 mm, σ_a is close to 314.038 MPa, and ε_a is close to 0.078 (shown in Figure 8(b)). For the pipeline with the wall thickness of 53 mm, σ_a is close to 252.128 MPa, and ε_a is close to 0.016 (shown in Figure 8(c)). For the pipeline with the wall thickness of 60 mm, σ_a is close to 235.013 MPa, and ε_a is close to 0.004 (shown in Figure 8(d)). For the pipeline with the wall thickness of 90 mm, σ_a is close to 158.841 MPa, and ε_a is close to 0.0003 (shown in Figure 8(e)). For the pipeline with the wall thickness of 120 mm, σ_a is close to 117.152 MPa, and ε_a is close to 0.00001 (shown in Figure 8(f)). From the analysis above, it is clear that the internal pressure of the pipeline is 30 MPa, and σ_a gradually decreases with the increase of wall thickness, indicating that the bearing capacity of the pipeline gradually enhances.

For the pipeline with the wall thickness of 30 mm and 45 mm (shown in Figures 8(a) and 8(b)), the variation trend of σ_a-ε_a curve is smooth, indicating that the fracture form of the pipeline is ductile fracture. When the wall thickness is 53 mm, 60 mm, and 90 mm (shown in Figures 8(c)–8(e)), the variation trend of σ_a-ε_a curve is gradually upward-sloping with the increase of wall thickness, indicating that the fracture form of pipelines gradually transforms from ductile fracture to brittle fracture. When the wall thickness is 120 mm (shown in Figure 8(f)), the variation trend of σ_a-ε_a curve is steep, and ε_a value at fracture is close to 0.00001, indicating that the fracture form of the pipeline is brittle fracture. Thus, it is obvious that the variation trend of σ_a-ε_a curve becomes more upward-sloping with the increase of wall thickness, and ε_a value sharply decreases, indicating that the pressure pipeline becomes more sensitive to brittle fracture with the wall thickness increasing under the action of elastic constraints.

4.2. Simulation Analysis of Pipelines with Different Materials of the Same Wall Thicknesses. The simulation analysis of X80 and Q235 pipelines with the wall thicknesses of 30 mm, 45 mm, 53 mm, 60 mm, 90 mm, and 120 mm is taken, and the cloud diagram of simulation analysis is shown in Figures 9 and 10.

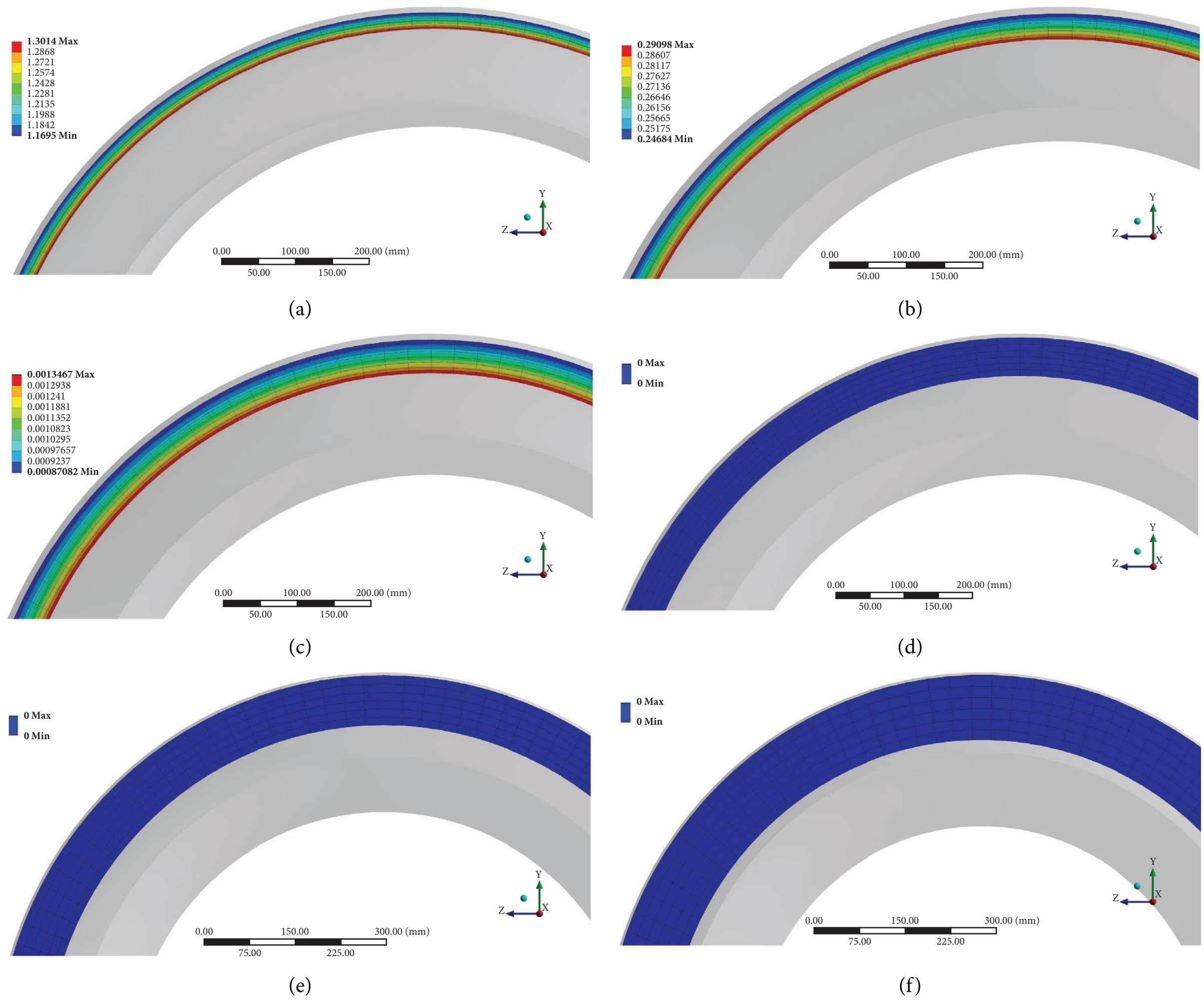


FIGURE 7: Cloud diagrams of equivalent plastic strain ε_a of pipelines with different wall thicknesses. (a) Q235 pipeline with 30 mm wall thickness. (b) Q235 pipeline with 45 mm wall thickness. (c) Q235 pipeline with 53 mm wall thickness. (d) Q235 pipeline with 60 mm wall thickness. (e) Q235 pipeline with 90 mm wall thickness. (f) Q235 pipeline with 120 mm wall thickness.

Under condition of the same grids, the same internal pressure, and the same boundary constraints, X80 pipeline is compared with Q235 pipeline at the same wall thickness to explore the brittle fracture factors of high-pressure pipelines. As shown in Figure 9, for the pipeline with the wall thickness of 30 mm, 45 mm, and 53 mm, the plastic deformation can generate in Q235 pipeline (shown in Figures 9(a)–9(c)), and the plastic deformation cannot generate in X80 pipeline (shown in Figures 10(a)–10(c)). For the pipeline with the wall thickness of 60 mm, 90 mm, and 120 mm, the plastic deformation cannot generate in both X80 (shown in Figures 10(d)–10(f)) and Q235 (shown in Figures 9(d)–9(f)) pipelines. Thus, it can be seen that the elastic constraint effect of X80 pipeline is more serious than that of Q235 pipeline under the same wall thickness conditions. As the wall thickness increases, the elastic constraint effect of both X80 and Q235 pipelines becomes more and more obvious. Moreover, in practical engineering, the brittle fracture is not easy to occur in Q235 pipeline under elastic constraints, but the brittle fracture is likely to occur in X80 pipeline under elastic constraints.

In Figures 11(a) and 12, for the pipeline with the wall thickness of 30 mm, the average equivalent plastic strain ε_a on the middle sections of Q235 (shown in Figure 11(a)) and X80 (shown in Figure 12(a)) pipelines is close to 0.497 and 0.0046, respectively. For the pipeline with the wall thickness of 45 mm, the average equivalent plastic strain ε_a on the middle sections of Q235 (shown in Figure 11(b)) and X80 (shown in Figure 12(b)) pipelines is close to 0.078 and 0.00023, respectively. Thus, it is found that the deformation of Q235 pipeline is much larger than that of X80 pipeline under the same conditions. For the pipeline with the wall thickness of 53 mm, 60 mm, 90 mm, and 120 mm, ε_a of X80 pipeline is close to 0. As shown in Figures 12(c)–12(f), when the value of ε_a is larger than 0, the value of σ_a sharply decreases, indicating that the fracture failure has already occurred in the pipeline at this time. From σ_a-ε_a curves of Q235 (shown in Figures 11(a) and 11(b)) and X80 (shown in Figures 12(a) and 12(b)) pipelines with wall thicknesses of 30 mm and 45 mm, the variation trend of σ_a-ε_a curve of Q235 pipeline is smoother than that of X80 pipeline, indicating that Q235 pipeline has better toughness than X80

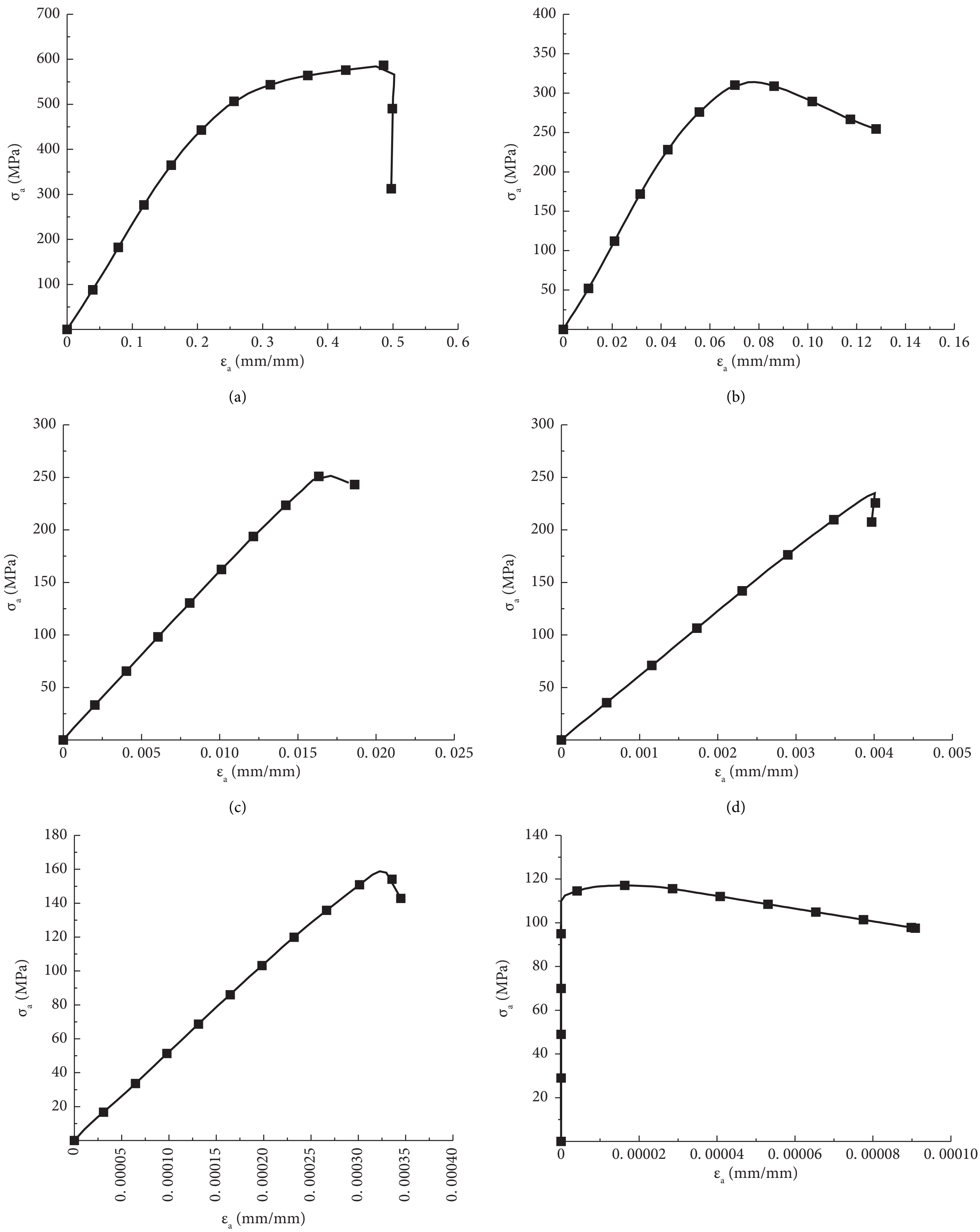


Figure 8: Average equivalent stress σ_a-average equivalent plastic strain ε_a curves of the middle section of Q235 pipeline with different wall thicknesses during fracture. (a) Q235 pipeline with 30 mm wall thickness. (b) Q235 pipeline with 45 mm wall thickness. (c) Q235 pipeline with 53 mm wall thickness. (d) Q235 pipeline with 60 mm wall thickness. (e) Q235 pipeline with 90 mm wall thickness. (f) Q235 pipeline with 120 mm wall thickness.

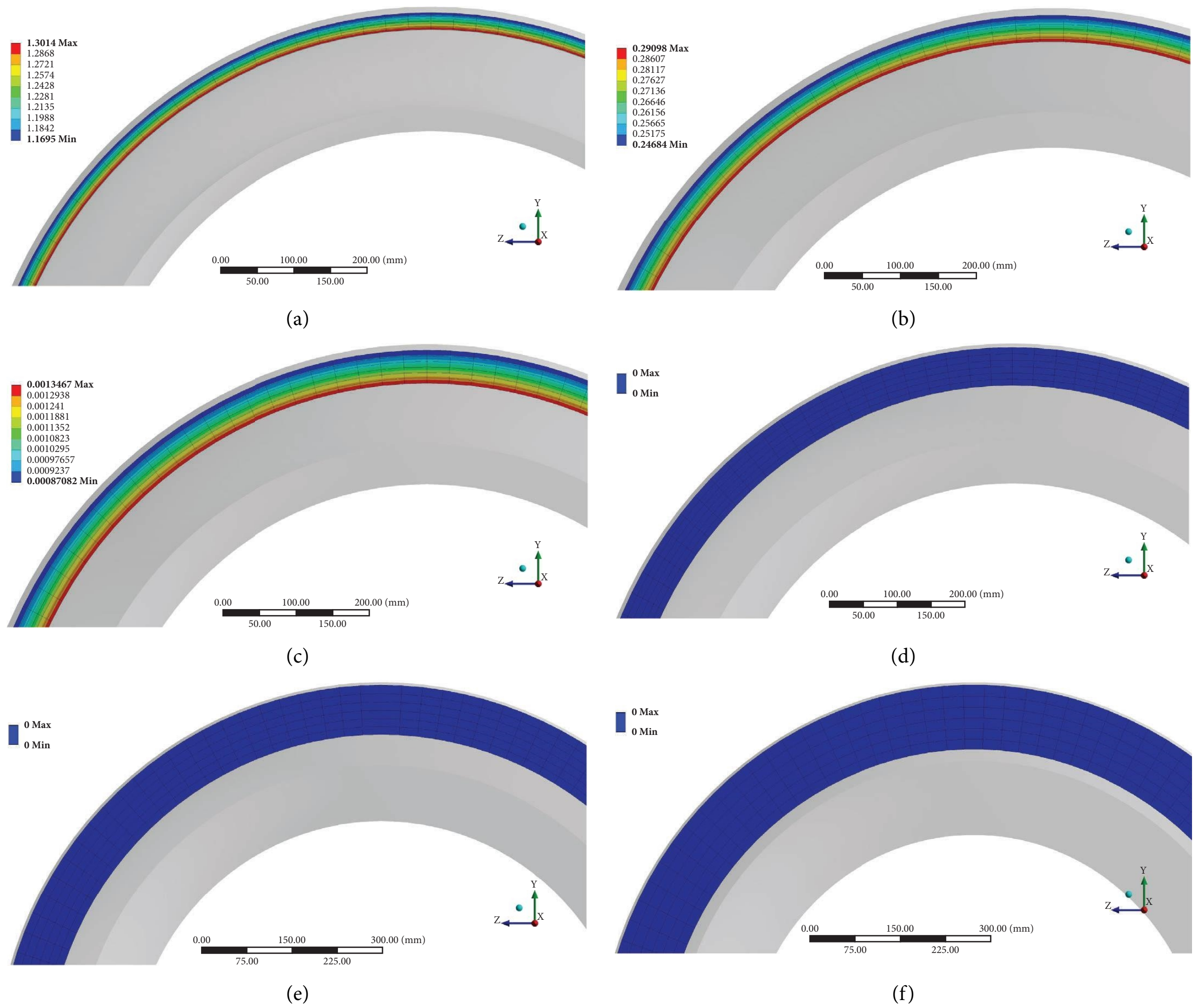


Figure 9: Cloud diagrams of equivalent plastic strain ε_a of Q235 pipeline with different wall thicknesses. (a) Q235 pipeline with 30 mm wall thickness. (b) Q235 pipeline with 45 mm wall thickness. (c) Q235 pipeline with 53 mm wall thickness. (d) Q235 pipeline with 60 mm wall thickness. (e) Q235 pipeline with 90 mm wall thickness. (f) Q235 pipeline with 120 mm wall thickness.

pipeline. For the pipeline with the wall thickness of 53 mm, 60 mm, and 90 mm, the slope of σ_a-ε_a curve of Q235 pipeline is larger than 0 (shown in Figures 11(c)–11(e)), but the slope of σ_a-ε_a curve of X80 pipeline is infinite (shown in Figures 12(c)–12(e)). As shown in the figures, the ductile fracture occurs in Q235 pipeline (shown in Figures 11(c)–11(e)), while the brittle fracture occurs in X80 pipeline (shown in Figures 12(c)–12(e)). For the pipeline with the wall thickness of 120 mm, σ_a-ε_a curves of both X80 (shown in Figure 12(f)) and Q235 (shown in Figure 11(f)) pipelines show the upward-sloping trend, indicating that the fracture of X80 and Q235 pipeline is the brittle fracture. From the analysis above, as the wall thickness increases, the trend of σ_a-ε_a curve of X80 and Q235 pipelines becomes increasingly upward-sloping. For the same wall thickness, σ_a-ε_a curve of X80 pipeline is more upward-sloping than that of Q235 pipeline, indicating that X80 pipeline is more sensitive to the brittle fracture than Q235 pipeline.

According to the fracture simulation analysis of X80 and Q235, the yield ratio is one of the important factors that lead to the brittle fracture in the pipeline. Under the condition of a certain yield ratio, when the size of wall thickness is larger than its critical wall thickness, the larger the wall thickness of the pipeline is, the more prone it is to the brittle fracture. The lower the yield ratio of the material, the larger the range of wall thickness dimensions that do not cause brittle fracture and the better the limit bearing capacity of the pipeline within the range of the critical wall thickness size. Under the same wall thickness, the higher the yield ratio is, the more prone the pipeline is to the brittle fracture.

5. Discussion

The brittle fracture of pipelines under impact internal pressure is discussed in this article. In this paper, through simulation analysis, it is proved that the pipeline under internal pressure is an elastic constraint structure, and it is verified that the elastic constraint limits the ability of the plastic deformation ability of the pipeline. Therefore, the brittle fracture is easy to occur in the pipeline under the action of internal pressure. Many researchers think that the

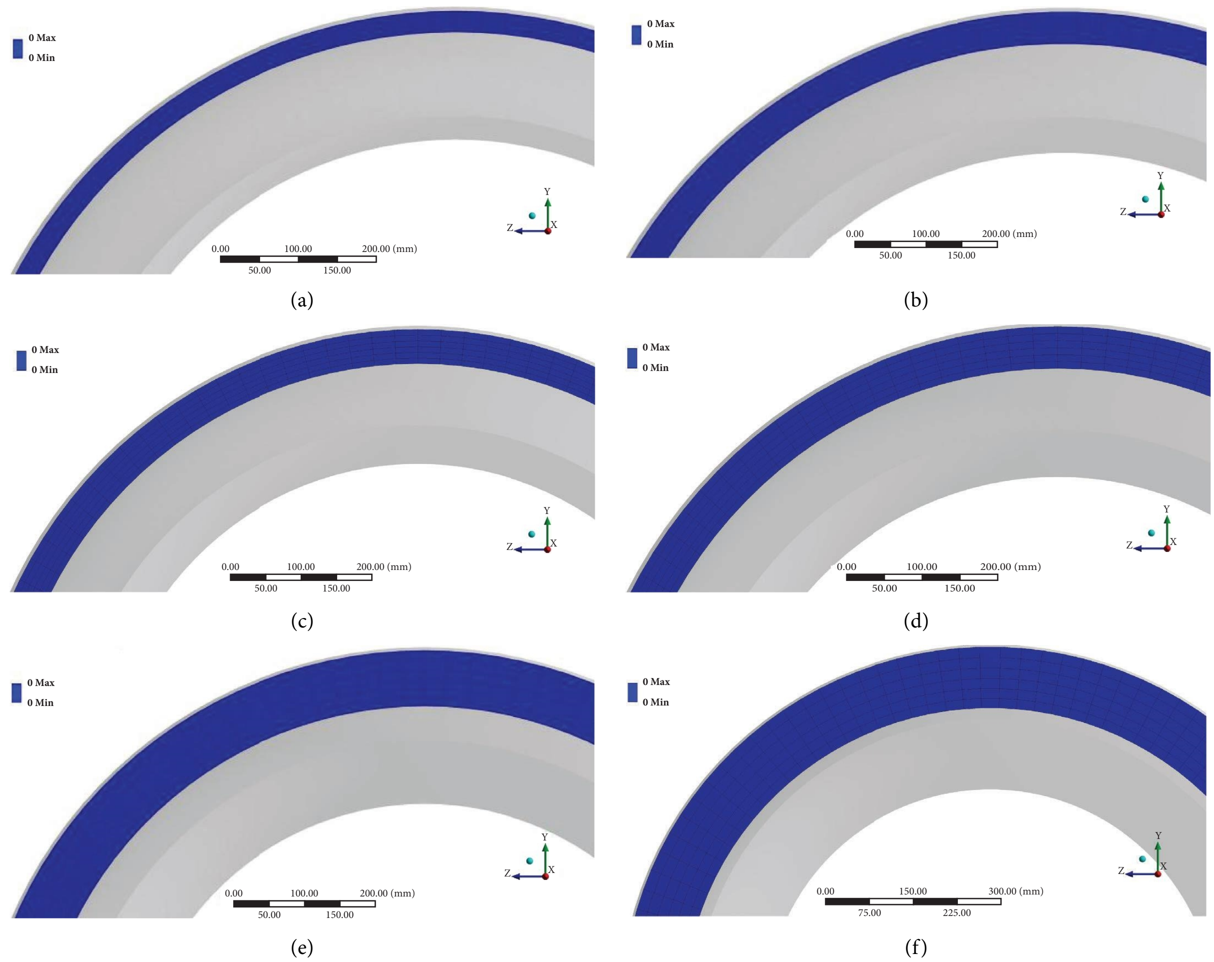


FIGURE 10: Cloud diagrams of equivalent plastic strain ε_a of X80 pipeline with different wall thicknesses. (a) X80 pipeline with 30 mm wall thickness. (b) X80 pipeline with 45 mm wall thickness. (c) X80 pipeline with 53 mm wall thickness. (d) X80 pipeline with 60 mm wall thickness. (e) X80 pipeline with 90 mm wall thickness. (f) X80 pipeline with 120 mm wall thickness.

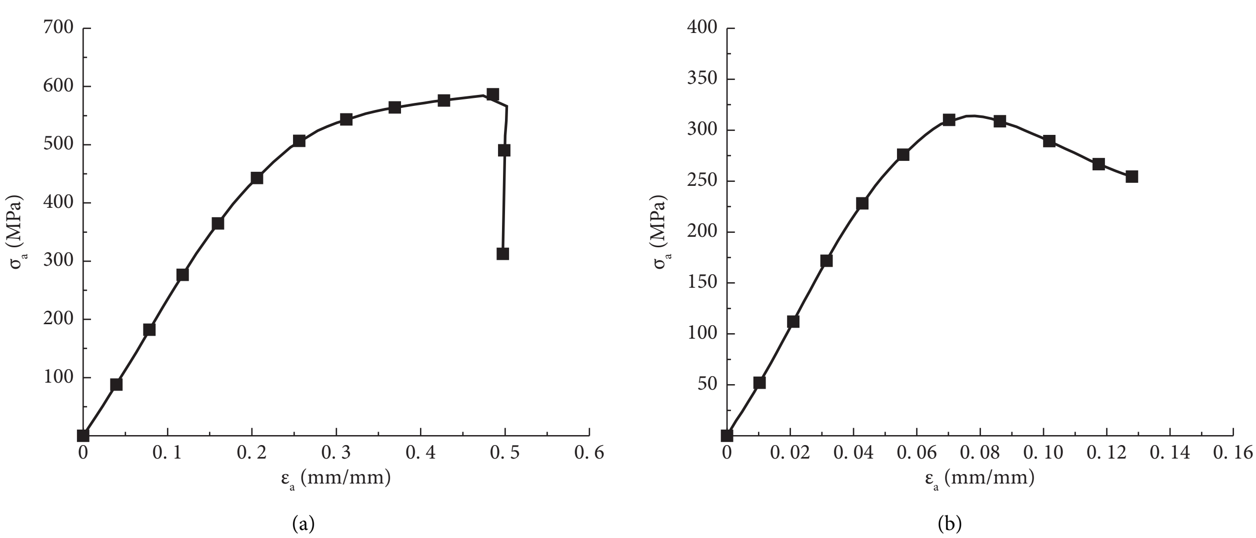


FIGURE 11: Continued.

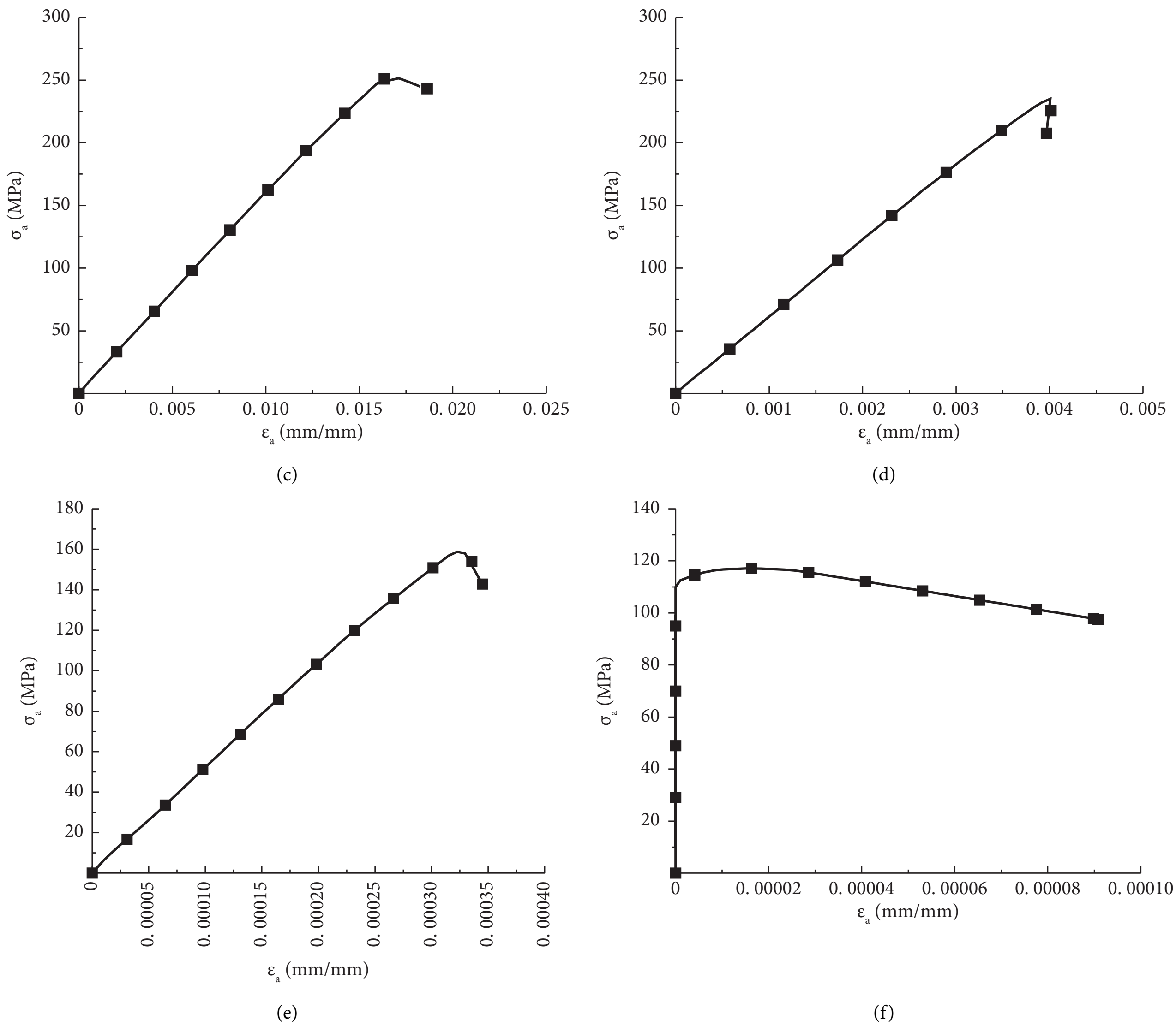


Figure 11: Average equivalent stress σ_a-average equivalent plastic strain ε_a curves of the middle section of Q235 pipeline with different wall thicknesses during fracture. (a) Q235 pipeline with 30 mm wall thickness. (b) Q235 pipeline with 45 mm wall thickness. (c) Q235 pipeline with 53 mm wall thickness. (d) Q235 pipeline with 60 mm wall thickness. (e) Q235 pipeline with 90 mm wall thickness. (f) Q235 pipeline with 120 mm wall thickness.

brittle fracture of pipeline under internal pressure is caused by cracks inside the pipeline [29], but they have not recognized the plastic deformation conditions of pipeline that bears internal pressure under the elastic constraint. Stress at crack tip is highly concentrated, so the stress state at crack tip is mostly in the triaxial stress state. Even if the ability of plastic deformation of ductile metal material is so great, the brittle fracture is prone to occur in ductile metal materials. In fact, even if the stress on the inner wall of the pipeline without cracks reaches the yield strength and the plastic deformation cannot generate in the pipeline under elastic constraints, the brittle fracture can occur in the pipeline. If there are microcracks in the pipeline, the stress at the crack will be more concentrated under elastic constraints, so that the brittle fracture is more prone to occur in the pipeline. From the analysis above, it is obvious that the brittle fracture will eventually occur in the pipeline, but the principle of the brittle fracture is fundamentally different. Therefore, the brittle fracture of high-pressure pipelines is not determined by a single factor but determined by multiple factors.

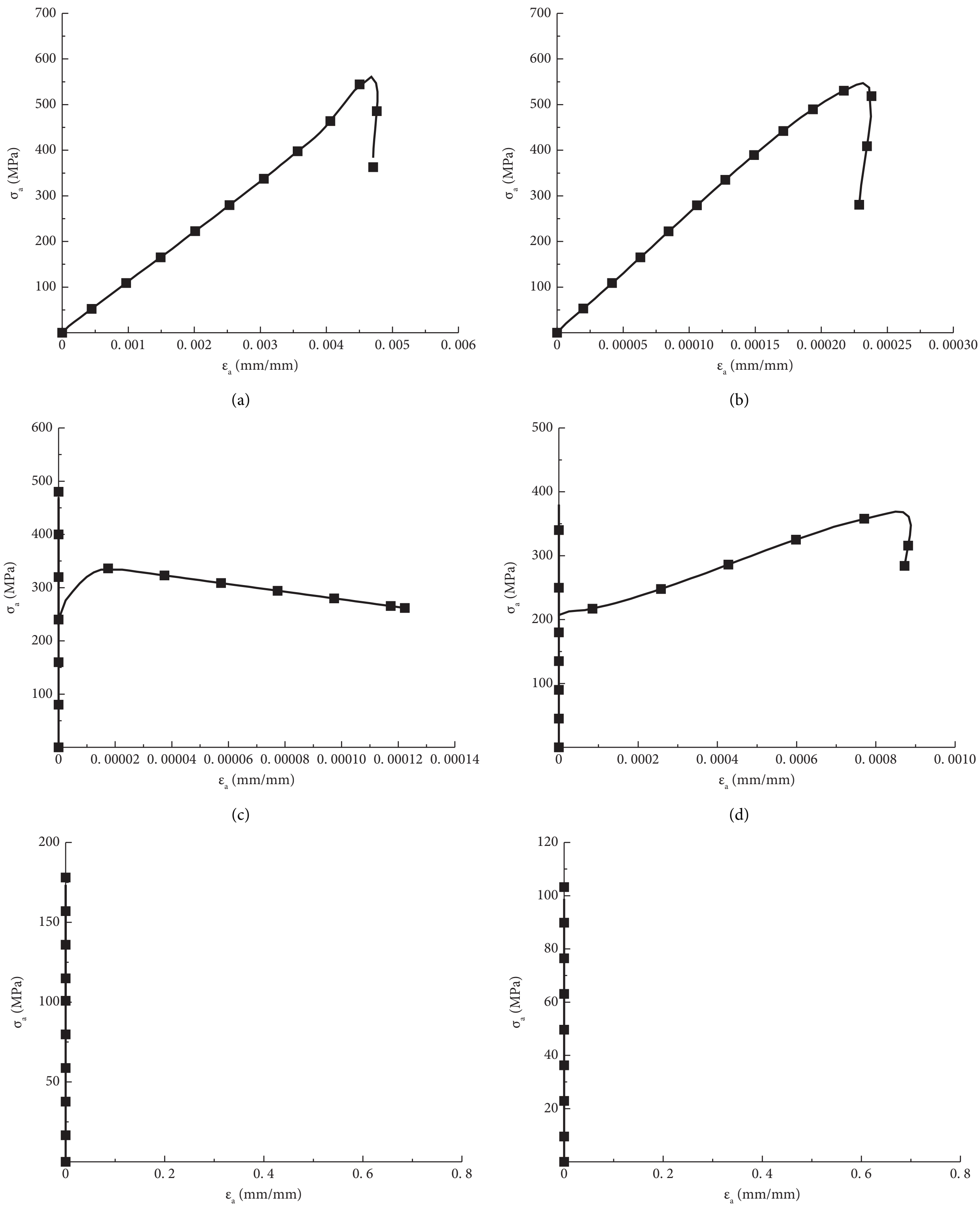


Figure 12: Average equivalent stress σ_a-average equivalent plastic strain ε_a curves of the middle section of X80 pipeline with different wall thicknesses during fracture. (a) X80 pipeline with 30 mm wall thickness. (b) X80 pipeline with 45 mm wall thickness. (c) X80 pipeline with 53 mm wall thickness. (d) X80 pipeline with 60 mm wall thickness. (e) X80 pipeline with 90 mm wall thickness. (f) X80 pipeline with 120 mm wall thickness.

6. Conclusions

This article focused on the brittle fracture problem when the pressure pipeline is subjected to impact internal pressure. Comparing domestic and foreign pipeline design standards, the main differences in design standards between countries were identified. The limit load of the pressure pipeline was calculated by the formula, including plastic limit load, elastic limit load, and critical limit load. We analyzed the plastic deformation of the pressure pipeline under various limit loads and proposed that the elastic constraint effect is the main factor leading to the brittle fracture of the pressure pipeline. Based on the main factors of the brittle fracture, simulation analysis was conducted on pressure pipelines to obtain material selection methods and wall thickness design concepts, in order to avoid the brittle fracture in pressure pipelines. Through fracture failure simulation analysis, it was verified that the material selection method and wall thickness design concept of pressure pipelines were reasonable. The following conclusions were obtained:

(1) It was proposed that the elastic constraint effect was the main factor leading to the brittle fracture of elastic constrained structures. In practical engineering, whether it was an engineering building structure or a pressure pipeline, provided it was an elastic constrained structure, the impact of elastic constraints on the brittle fracture should be considered.

(2) When the yield ratio of the material was same, as the wall thickness increases, the load-bearing capacity of pressure pipelines was gradually enhanced, but their elastic constraint effect becomes more and more obvious. When the wall thickness of the pipeline was less than the critical wall thickness, the elastic constraint effect had a small limit on the plastic deformation ability of the pipeline, and there will be no brittle fracture caused by the elastic constraint effect in the pipeline. When the wall thickness of the pipeline was larger than the critical wall thickness, the elastic constraint effect had a significant limitation on the plastic deformation ability of the pipeline and even cannot generate plastic deformation. The pipeline was prone to the brittle fracture under the elastic constraint effect.

(3) When the wall thickness was certain and pressure pipelines were made of materials with different yield ratios, the lower the yield ratio was, the more likely the plastic deformation was generated in the pipeline and the larger the deformation capacity was; the higher the yield ratio, the poorer the plastic deformation capacity of the pipeline. The lower the yield ratio, the larger the design range of wall thickness for pipelines to prevent the brittle fracture. Therefore, in engineering, yield ratio was an important factor to consider when selecting materials for elastic constrained structures.

(4) When the yield ratio of material was same, as the wall thickness increases, the trend of σ_a-ε_a curve of the pipeline gradually changed from smooth to upward-sloping, and pipelines (X80 and Q235) gradually change from ductile fracture to the brittle fracture. When the wall thickness of pressure pipelines made of different materials was certain, the σ_a-ε_a curve of X80 material pipelines was steeper than Q235 material pipelines, and X80 material pipelines were more sensitive to the brittle fracture than Q235 material pipelines.

Data Availability

All relevant data supporting the results of this study are included in the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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