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Failure Pressure Analysis of the Pipe with Inner Corrosion Defects by FEM

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Inner corrosion defects can severely impact the reliability of the corroded pipeline. The mechanical behavior and failure pressure of the pipeline with single inner corrosion defect, multiple interacting inner corrosion defects and multilayer structural inner corrosion defect were investigated by nonlinear finite element method in this paper. Effects of length, width and depth of the corrosion defect and inner pressure were discussed. The results demonstrate that von Mises stress and the plastic strain of the corroded pipeline increase with the increasing of inner pressure. Failure pressure of the corroded pipeline decreases with the increasing of length and depth of the corrosion defect, but width has a small effect on it. The pipelines with multiple and multilayer corrosion defects were also studied. Stress concentration appears on the longitudinal separation of the interacting corrosion defects. Failure pressure of the pipeline with multiple inner defects is lower than it with single inner pressure. Stress concentration and plastic deformation firstly occurs on the lowest layer of the corrosion defects and then expands to other layers with the increasing of the inner pressure.

Keywords: inner corrosion defects, pipeline, FEM, failure pressure, corrosion morphology

1. INTRODUCTION

Massive pipelines have been built to meet with the rapidly ever-growing demand for oil and gas on the worldwide scope. Given the transmission pipeline is wildly used as one of the most effective ways to transport oil and gas, security and reliability of the transmission pipeline, which could even ultimately affect the international energy trade, are extremely significant in engineering practice. Along with the increase of the construction, pipelines often need to through some remote area and extremely difficult environments such as swamp, desert and mountain which might cause corrosions on the outer surface of the pipeline. Besides, due to the corrosivity of transported gas and oil, the appearing of corrosions on the inner face of the pipelines is inevitable. Corrosions are generally perceived as the most dominating failure form of onshore and offshore pipelines which could lead to wall-thinning, stress concentration, reduction of the pipelines' bearing capacity, leakage of oil and gas, etc. Since the rapid development of the pipeline industry, the demand for large-diameter and high stress pipelines is more and more great. Under high pressure, transmission pipelines with randomly distributed corrosions on the wall are very likely to lose efficacy earlier than expected which is very dangerous to safety of the operation of the transportation of oil and gas. [1~5]

In recent years, many earlier researches were related to transmission pipelines with corrosion defects. Xu conducted the reliability assessment of the pipelines with corrosion defects and found out that the geometry of corrosion has a great effect on failure pressure of the pipelines [6]. Gábor investigated the load carrying capacity of the pipelines with outer surface corrosion through finite element method [7]. A finite element model was established by Huang to investigate the effect of pitting corrosion damage on aluminum alloy structures [8]. Mario S.G. Chiodo conducted a verification study to examine a stress-based criterion which is used to predict the failure pressure of pipelines with axial corrosion defects [9]. In order to predict the burst pressure of the corroded pipelines, Shuai built a 3D model through FEA software and presented a new prediction formula [10]. Despite the contributions of these researches are inordinately valuable, most attentions are paid on the effects of small corrosion pits with simple structure on the failure pressure of the transmission pipelines and very few researches refer to large-area corrosion defects with complex structure. Obviously, in the actual situation, corrosive substances in the oil and gas could lead pipe inner surface to be largely corrupted and the structures of corrosion defects are relatively complex. So, it is necessary to do research into the effects of large-area corrosion defects with complex structures on the failure pressure of transmission pipeline. In addition, accurate prediction on failure pressure of the transmission pipelines with corrosion defects can help corroded pipelines be repaired or replaced timely which can not only improve operating stability of the transmission pipelines but also prolong its working life. Therefore, 3D finite element models of the transmission pipelines with complex structural inner corrosion defect were built in this paper. Not merely the effects of geometrical features (length, width, depth) on the failure pressure and mechanical properties of transmission pipeline were discussed, but also the effects of the interaction of corrosion defects. Moreover, the effects of complex structures (multilayer structure) of the inner corrosions were also discussed in this paper.

2. THEORETICAL METHOD AND FINITE ELEMENT MODEL

2.1 Assessment method

In engineering practice, theoretical assessment methods for pipelines with corrosions, which are used to determine the failure pressure of the corroded pipelines, have been studied for years since last century. Based on NG-18, ASME B13G has already become the wildest used method to predict the failure pressure of the corroded pipelines. In order to get even more accurate results of calculations of failure pressure prediction, ASME B13G has been modified many times to reduce conservatism of the method. In this paper, ASME B13G-2009 is selected to calculate the failure pressure of the transmission pipelines. The function can be expressed as follows:

$$P_{failure} = \sigma_{flow} \frac{2t}{D} \left(\frac{1-0.85\frac{d}{t}}{1-0.85\frac{d}{t}\frac{1}{M}} \right) \qquad (1)$$

Where $P_{failure}$ is the failure pressure of the corroded pipeline (MPa); σ_{flow} is the flow stress (MPa); *D* is the outside diameter of the pipeline (mm); *t* is the wall thickness of the pipeline; *d* is the depth of the corrosion on the pipeline wall (mm); *M* is Folias expansion coefficient.

When $\frac{l^2}{Dt} \leq 50$,

$$M = \sqrt{1 + 0.6275\frac{l}{Dt}^2 - 0.00337\frac{l^4}{(Dt)^2}} \qquad (2)$$

And when $\frac{l^2}{Dt} \geq 50$,

$$M = 0.032\frac{l^2}{Dt} + 3.3 \qquad (3)$$

Where *l* is the length of the corrosion (mm).

$$\sigma_{flow} = \sigma_y + 68.95$$

Where σ_y is the yield stress of the material of the pipeline (MPa).

At present, three kinds of failure criteria are widely employed to determine whether the failure phenomenon has occurred at the corroded pipeline.

(1) Elastic failure criterion: If von Mises stress of the corroded area reaches or exceeds the yield strength of the pipeline material, the corroded pipelines is prone to failure.

(2) Failure criterion based on plastic limit state: If circumferential stress of the corroded area reaches or exceeds the tensile strength of the pipeline material, the corroded pipelines is prone to failure.

(3)Plastic failure criterion: When the minimum von Mises stress is greater than the tensile strength of the pipeline material, failure occurs.

It is too conservative to select elastic failure criterion as a failure criteria for the numerical simulation of corroded pipeline. Thereby, plastic failure criterion is employed in this paper which is much more appropriate.

$$\sigma_e = \sqrt{\left\{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]\right\}} < [\sigma] \qquad (4)$$

Where σ_e stands for von Mises stress; $[\sigma]$ stands for allowable stress.

2.2 Material of the transmission pipeline

The frequently-used X65 pipeline was taken an example to analyze its mechanical property and failure pressure. Density is 7800kg/m3, Young's modulus of steel material is 206GPa, Poisson's ratio equals 0.3, yield strength is 448.5MPa and tensile strength is 531MPa. Due to the great effect of material gardening on failure pressure of the transmission pipelines with inner corrosions, taking hardening properties of the pipeline material into consideration makes a lot of sense. Two kinds of strain hardening models are often applied in failure assessment of the corroded transmission pipelines which are the true stress-strain rule and the Ramberg–Osgood stress-strain rule. Since the later rule can satisfactorily reflect the hardening properties after material yield, it is applied in this paper instead of the former one. The function can be expressed as follows:

$$\frac{\varepsilon}{\varepsilon_0} = \frac{\sigma}{\sigma_s} + \alpha \left(\frac{\sigma}{\sigma_s}\right)^n \qquad (5)$$

Where ε is the strain; ε_0 is the initial strain, $\varepsilon_0 = \frac{\sigma_s}{E}$; E is elasticity modulus (MPa); σ is the stress (MPa); σ_s is the yield stress (MPa); α is the hardening coefficient; n is the strain hardening exponent.

2.3 Numerical Simulation Model

Due to the symmetry of geometry and load of the transmission pipeline, a quarter models is established by the advanced finite element software. The corroded pipeline model is meshed by 8 nodes and hexahedron elements. In order to improve the calculating exactness, the areas near the corrosion need to be refined. The whole finite element model is shown in Fig.1. Correlation geometric parameters of the transmission pipeline with corrosion defects on the inner surface are shown in Table.1.

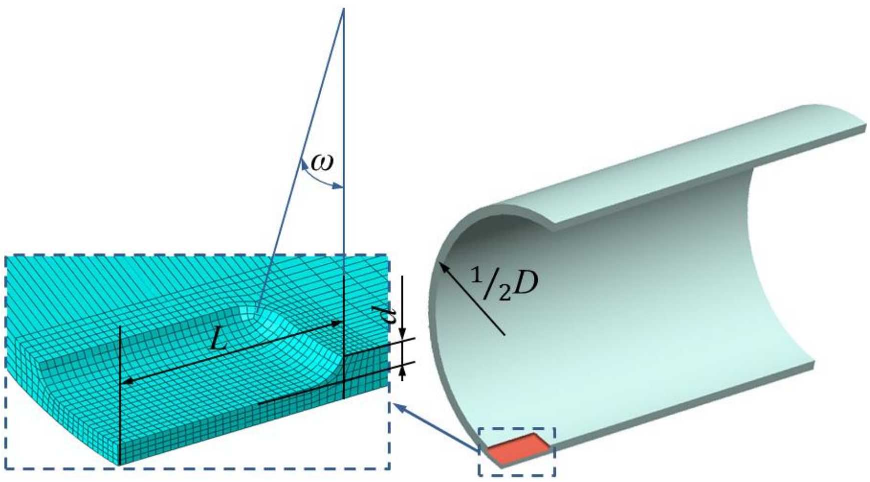


Figure 1. Finite element model

Table 1. Correlation geometric parameters of the corroded pipeline

Pipeline			Corrosion defect		
Diameter (mm)	Length (mm)	Wall thickness (mm)	Length *L* (mm)	Width *ω*	Depth *d* (mm)
273.1	800	10	120	20°	5

Since the structures and working conditions of the corroded pipelines are very complex, it is necessary for mechanical properties and failure pressure research to make the following assumptions:

(1) Only internal pressure works on the corroded pipeline;

(2) Not take the effects of the surrounding soil into consideration;

(3) The corrosion of the transmission pipeline is shape as a rectangle which transits smoothly to the intact pipeline wall.

3. SIMULATION RESULTS AND DISCUSSION

3.1 Effect of single inner corrosion defect

When length of the inner corrosion is 120mm, depth is 5mm and width is 20°, von Mises stress distributions of the corroded pipeline around the corrosion defect under different inner pressure are shown in Fig.2. Under the action of the inner pressure, stress concentration occurs on the corroded area and it appears around the middle of the corrosion defect at the beginning. With the increasing of the inner pressure, concentration areas gradually increase not only from inner surface of the pipeline to outer face around corrosion defect but also along the axis. Besides, axial distribution of the maximum von Mises stress around the corrosion defect is much bigger than circumferential distribution. When inner pressure exceed the limit, von Mises stress of the pipeline around the corrosion defect increases rapidly which might results in a large deformation and invalidation of the transmission pipeline.

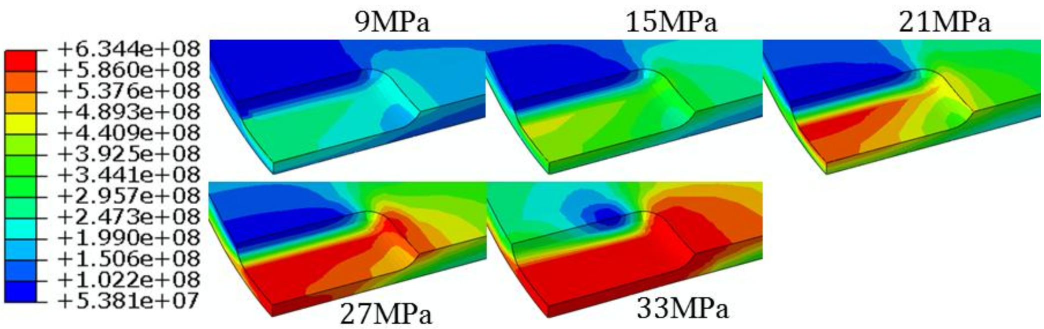


Figure 2. Von Mises stress distribution of the corroded area under different inner pressure

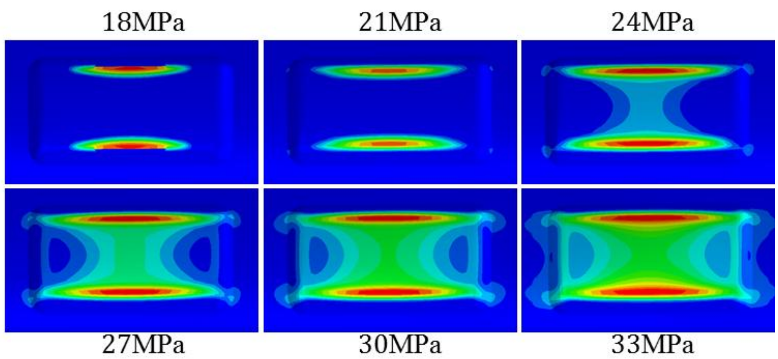


Figure 3. Plastic strain distribution of the corroded area under different inner pressure

Plastic strain distributions of the corroded area under different inner pressure are shown in Fig.3. When inner pressure is larger than 18MPa, plastic strain appears in the corrosion area. The maximum plastic strain distribute near the transition part of the corroded and intact wall of the transmission pipeline. With the increasing of inner pressure, plastic strain distribution expands gradually from the two sides of the corrosion defect to the middle of it. But, the highest plastic strain still distributes on the two sides where near the transition part.

3.2 Length of corrosion defect

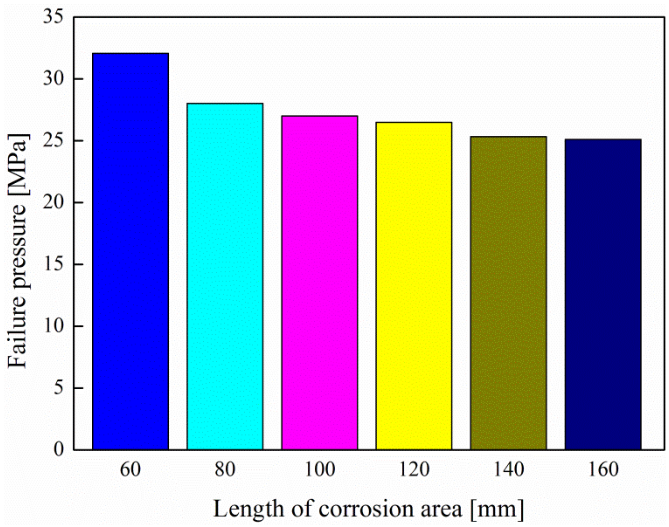


Figure 4. Failure pressure of the corroded pipeline under different corrosion length

Length is an important factor that should be taken into consideration when it comes to the problem about failure pressure of the corroded pipeline. When depth and width of the corrosion defect on the transmission pipeline inner surface are set as the default values (d=5m, ω=20°), failure pressures of the corroded pipelines under different lengths of the corrosion defect are in Fig.4. Failure pressure of the pipeline with single inner corrosion defect decreases with the increasing of the length of the corrosion defect, and so does the decrease rate. Reference [11] studied how $\frac{L}{\sqrt{Dt}}$ affected the failure pressure of corroded pipeline and found that failure pressure decreases slowly with increasing of $\frac{L}{\sqrt{Dt}}$ (*D* is the diameter of the pipeline, *t* is wall thickness of pipeline, *L* is the length of corrosion defect). If $\sqrt{Dt}$ is a fixed value, failure pressure would decrease as *L* increases. So, the research results in this part are very similar with results of reference [11].

3.3 Width of corrosion defect

When depth of the corrosion defect on the transmission pipeline inner surface is 5mm and length is 120mm, failure pressures of the pipelines with single corrosion defect under different corrosion width are shown in Fig.5. Failure pressure of the corroded pipeline changes with the change of width of the corrosion area but relatively little. When width is larger than 20°, average difference of failure pressures among different widths only 0.24MPa.Hence, circumferential width of the corrosion area has a very small effect on failure pressure of the corroded pipelines. In order to studied the effects of width of the corrosion area, reference [12] introduced the width coefficient K_3 ($K_3=\frac{\omega}{\pi D}$). And they found that the effects of width of the corrosion defects can be ignored in the analysis of practical engineering problems. Reference [13] also found that corrosion width had a small effect on failure pressure. Therefore, research results in these two papers are very similar.

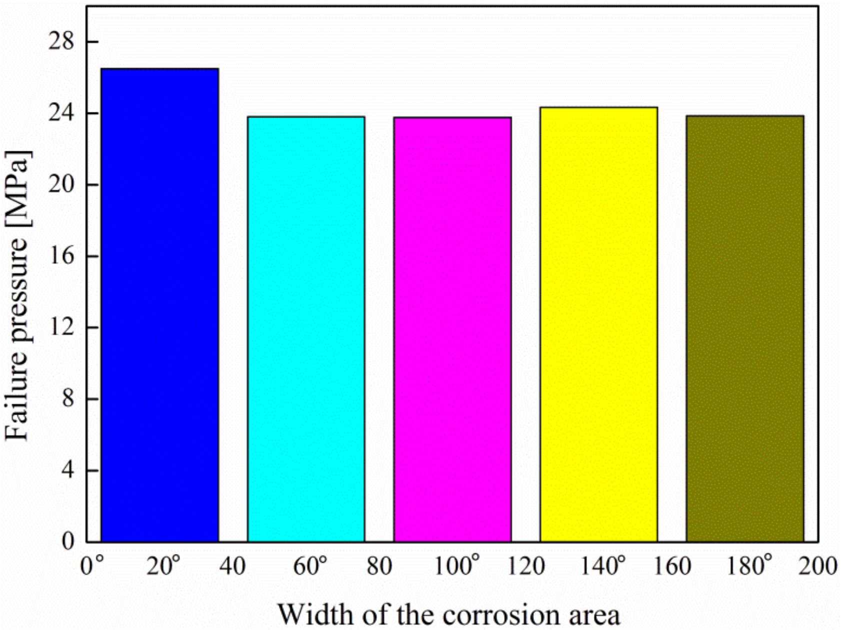


Figure 5. Failure pressure of the corroded pipeline under different corrosion length

3.4 Depth of corrosion defect

The ratio of depth and thickness is defined as r_d =d/t, where d is the depth of the corrosion defect and t is the thickness of the pipeline wall. If the depth of the corrosion defect equals wall thickness, pipeline leakage occurs. In order to ensure a certain working performance, some standards requiring that r_d must not exceed 85%. Fig.6 shows the failure pressures of the corroded pipeline under different depths of the corrosion defect. With the increasing of the r_d, failure pressure of the corroded pipeline decreases rapidly. The deeper the depth of the corrosion defect is, the more material of the pipeline loses and the thinner the residual wall thickness is which could greatly weaken the stability of the transmission pipeline. Therefore, depth of corrosion defect has a significant effect on failure pressure of the transmission pipeline. Reference [6] and [11] studied the effects of the corrosion depth (r_d=20%, 40%, 60%, 80%) on failure pressure and found that failure pressure decreased with the increasing of corrosion depth. Thus it can be seen that research results in this part tallies with reference [6] and [11].

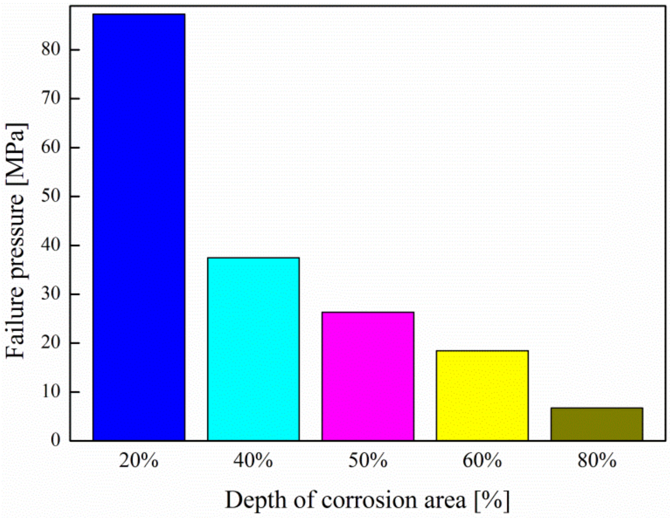
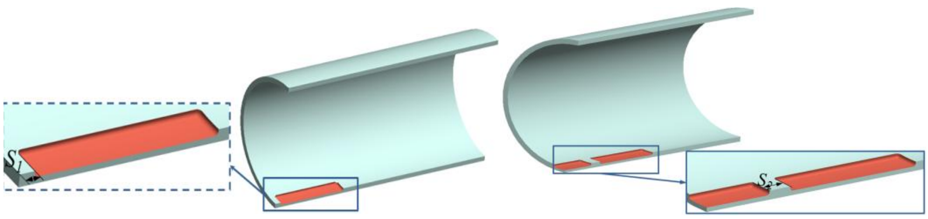


Figure 6. Failure pressure of the corroded pipeline under different corrosion depth

3.5 Simulation of pipeline with interaction corrosion defects



(a) Double corrosion defects (b) Three corrosion defects

Figure 7. Calculation models of the pipeline with interacting corrosion defects

According to the results of detections of corrosion defects, corrosion defect on the inner face of the transmission pipelines usually does not exist on its own. Interaction between corrosion defects should be taken into consideration when plastic failure criterion is used to determine the failure pressure of the transmission pipeline with multiple corrosion defects. Quarter calculation models of the pipelines with interacting corrosion defects are shown in Fig.7. As shown in Fig.7b, there are three corrosions, which of the same size and shape, on the inner face of the pipeline, and the longitudinally separation between corrosion defects is 20mm (S2=20mm). Length of the corrosion defect is 120mm, width is 10° and depth is 5mm.

3.5.1 Effect of double corrosion defects

When double corrosion defects (same shape and size) are longitudinally aligned, which separated at a distance of 20mm (S1=20mm), on the inner face, and length of the corrosion defect is 120mm, width is 10° and depth is 5mm, von Mises stress distributions of the pipeline with double corrosion defects under different inner pressures are shown in Fig.8. First shown on the defect circumferential edge and the longitudinal separation between corrosion defects, stress concentration areas expand to the whole corrosion defect with the inner pressure increases.

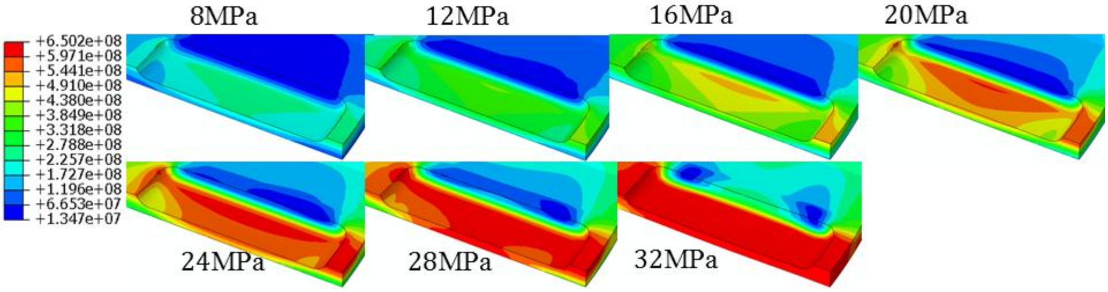


Figure 8. Von Mises stress distribution of the area with double defects

When inner pressure exceeds 20MPa, not only the corrosion area but also the intact area of the pipeline near the corrosion defect where serious stress concentration occurs on. In addition, circumferential stress concentration is less serious than axial stress concentration.

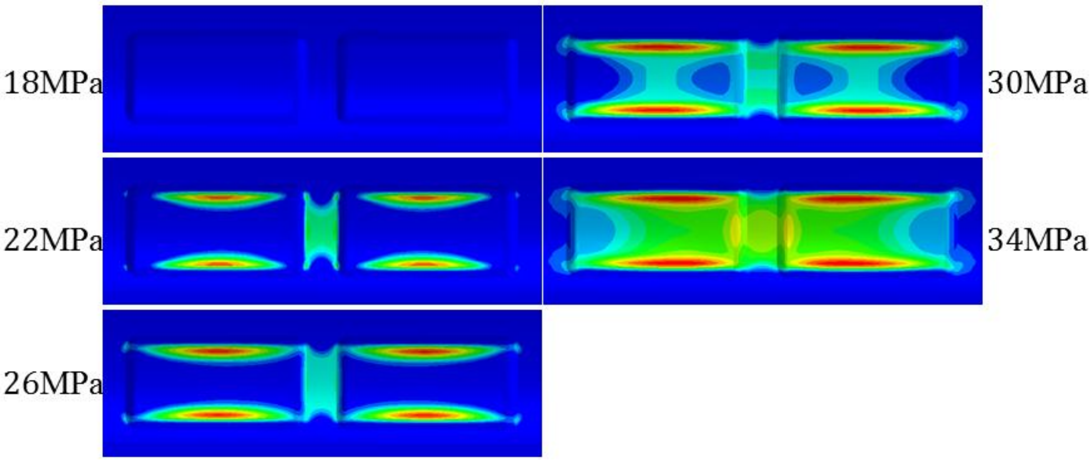


Figure 9. Plastic strain of the area with double corrosion defects under different inner pressure

Fig.9 shows the plastic strain distribution of the area around the double corrosion defects. When inner pressure is smaller than 18MPa, there is no plastic deformation occurred on the corroded pipeline. For interacting double corrosion defects, plastic strain first appears at the circumferential edge of the corrosion defect and the separation between corrosion defects. With the increasing of the inner pressure, distribution of plastic strain covers the whole corrosion defect areas including the separation between corrosion defects. Ultimately, plastic strain occurs on the intact areas of the corroded pipeline near the four corners of the corrosion defect.

3.5.2 Effect of three interacting corrosion defects

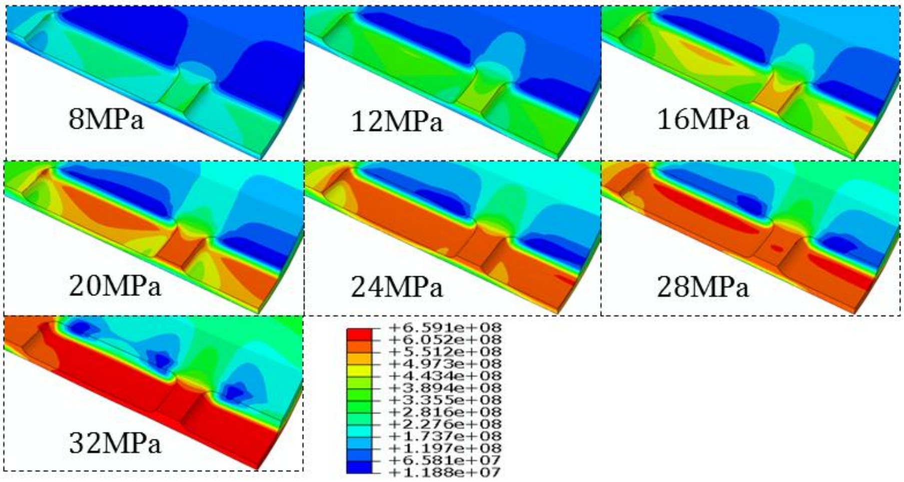


Figure 10. Von Mises stress distribution of the area with three corrosion defects

There are three corrosion defects (same shape and same size) longitudinally aligned on the inner face of the transmission pipeline which separated at a distance of 20mm (S2=20mm). Length of each corrosion defect is 120mm, width is 10° and depth is 5mm. Von Mises stress distributions of the pipeline with three interacting corrosion defects under different inner pressures are shown in Fig.10. Stress concentration start to focus on the defect circumferential edge and the longitudinal separation same as how stress concentration distributes in double corrosion defect area. Stress concentration is getting more and more serious with the increasing of the inner pressure. Due to the geometry of the corrosion defects and the force situation of the corroded pipeline, axial stress concentration is much more serious than circumferential stress concentration.

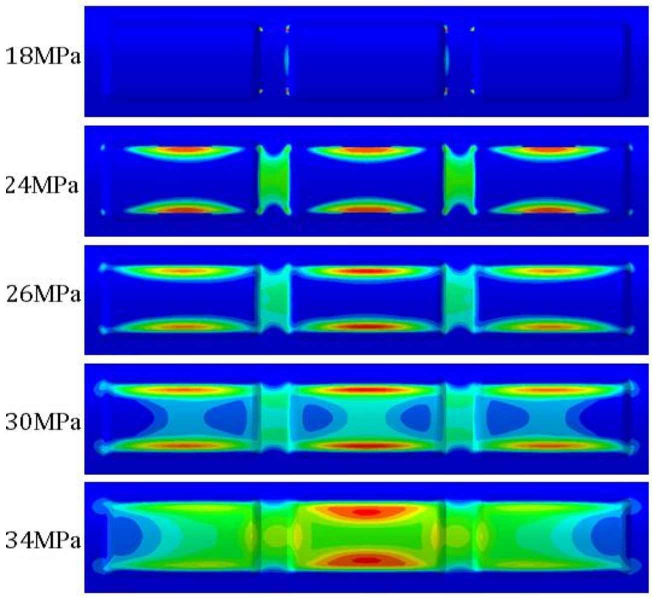


Figure 11. Plastic strain of the area with three corrosion defects under different inner pressure

Fig.11 shows the plastic strain of the areas around the three interacting corrosion defects. When inner pressure is larger than 18MPa, plastic deformation occurs on the corrosion area which starts from the corners of the corrosion defects.

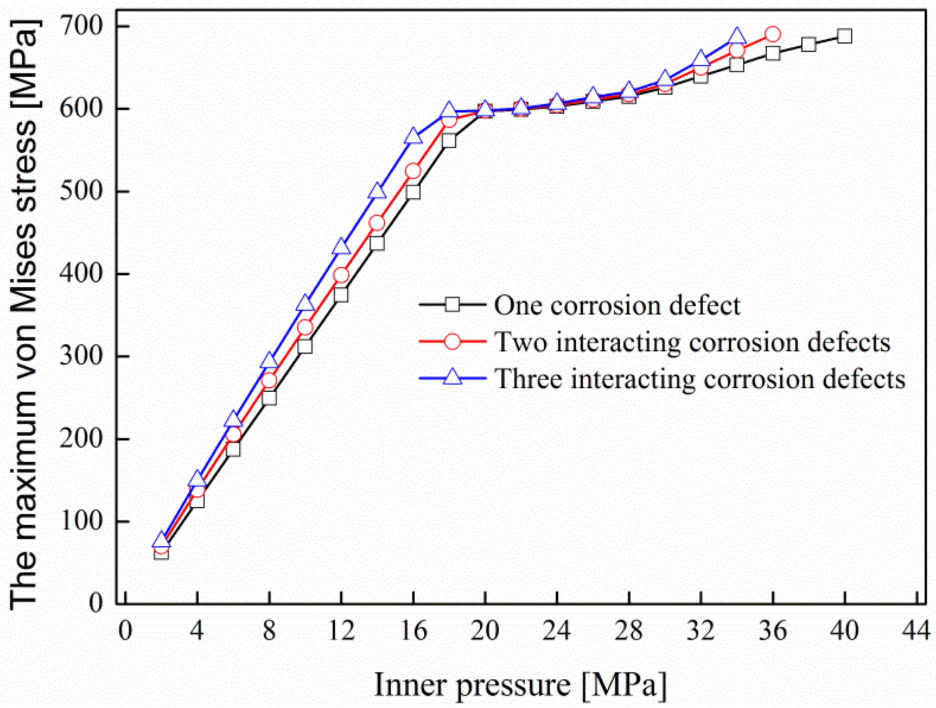


Figure 12. The maximum von Mises stress of the corrosion defect under different inner pressure

With the increasing of the inner pressure, plastic strain of the corroded pipeline increases rapidly. Different from the plastic strain distribution of the pipeline with double interacting corrosion, the maximum plastic strain mainly focused on the middle corrosion defect of the three corrosion defects instead of focusing on each one separately when inner pressure is larger than 26MPa.

The maximum von Mises stresses of the pipeline with multiple corrosion defects under different inner pressures are shown in Fig.12. When inner pressure is smaller than 16MPa, no matter of single corrosion defect, double interacting corrosion defect or three interacting corrosion defect, the maximum von Mises stresses almost linearly increases with the increasing of the inner pressure. In this stage, the number of the corrosion defects could affect the maximum von Mises stress of the corroded pipeline. When inner pressure is set as a certain value, the maximum von Mises stress of the pipeline with tree interacting corrosion defects is larger than the others. In second stage (inner pressure is 16MPa~30MPa), the maximum von Mises stresses of these three kinds of corrosion defects are much the same.

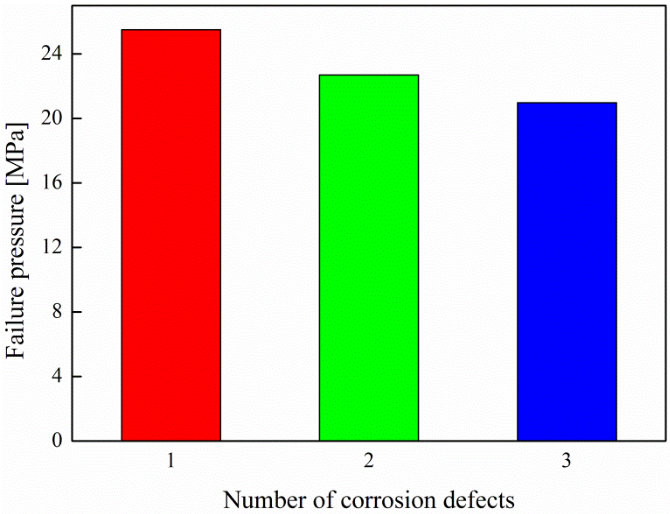


Figure 13. Failure pressure of the pipeline with interacting corrosion defects

When depth and width of each corrosion defect on the inner surface of the transmission pipeline are set as the default values (d=5m, ω=20°), failure pressures of the corroded pipelines are shown in Fig.13. With the increasing of the number of the interacting corrosion defects, failure pressure of the corroded pipeline decreases, so as the safety and usage properties.

Reference [14] studied the effects of longitudinally aligned corrosion defects on pipeline and found that failure pressure of the pipeline with single corrosion defect is smaller than which with multiple corrosion defects. Reference [1] researched how multiple corrosion pits affect mechanical properties and failure pressure of the corroded pipeline and found that failure pressure decreased as the number of corrosion pits increases. Besides, Zhang also found that high stress area occurs on the separation between corrosion defects. Hence, research on effects of multiple corrosion defects in paper is reliable. The references mentioned above can verify the results in this paper are reasonable.

3.5.3 Comparison between simulation and ASME B31G-2009

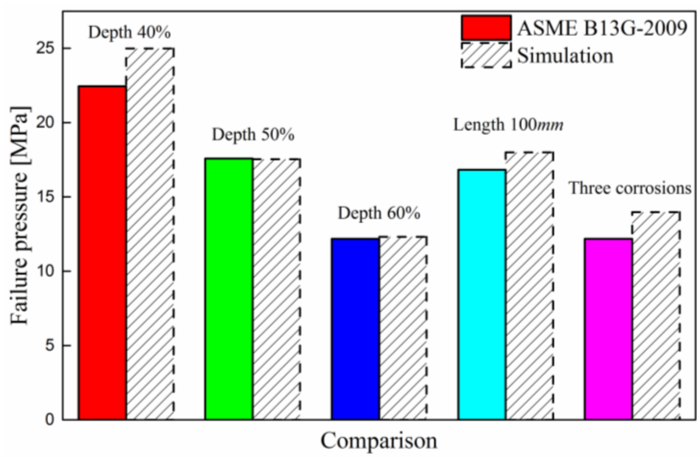
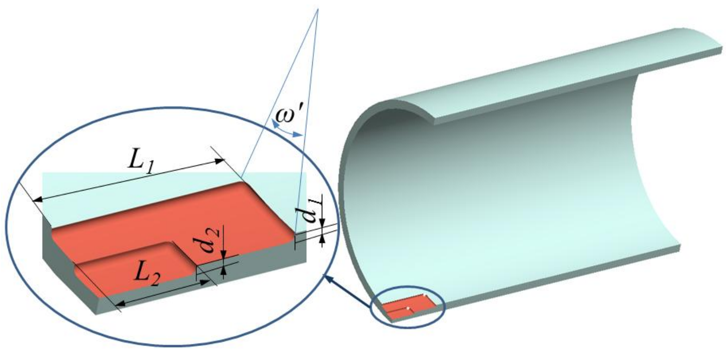


Figure 14. Comparison of failure pressures of pipeline by simulation and ASME B31G-2009

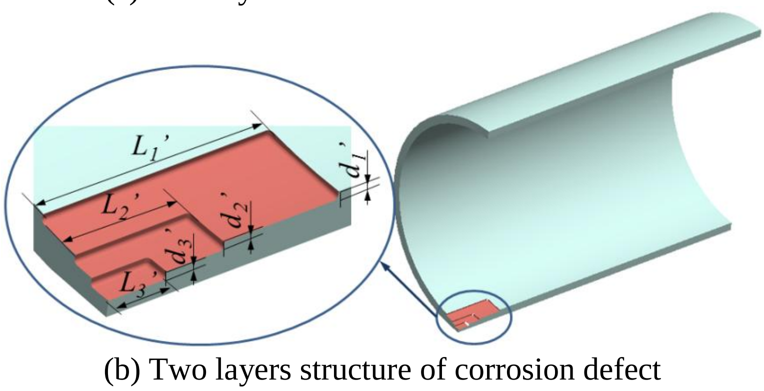
Fig.14 shows the failure pressures of the corroded pipeline with different calculation method (ASME B13G-2009 and Simulation). When depth of corrosion defect is 50% ~60%, failure pressures of the pipeline with single corrosion defect calculated by ASME B13G-2009 and simulation are almost the same and when corrosion defect length equals 100mm the results obtained by these two kinds of methods are still very close which means simulation is a suitable way to predict the failure pressure of the pipeline with single structural corrosion defect of simple construction. Without taking interacting corrosion defects and complex structure as indexes, ASME B13G-2009 cannot predict the failure pressure accurately when it comes to the pipeline with interaction corrosion defects.

3.6 Mechanical behavior of the pipeline with multilayer corrosion defect

In practice engineering, morphology of corrosion defect is very complex and irregular which cannot be regarded simply as a flat dent. Through nondestructive testing technique, morphology of the corrosion defect was found out that it always has not only one layers. In order to approaches closer to the real morphology of corrosion defect, models of the corroded pipeline with single corrosion defect which has multilayer structure in corroded area have been established in this paper. Finite element models of the pipelines with multilayer structure corrosion defect are shown in Fig.15. Define the upper layer as the first layer, the middle layer as the second layer and the lower layer as the third layer. Correlation geometric parameters of the transmission pipeline with corrosion defect which has multilayer structure are shown in Table.2.



(a) Two layers structure of corrosion defect



(b) Two layers structure of corrosion defect

Figure 15. Finite element models of corrosion defects with multilayer structure

Table 2. Correlation geometric parameters of the corrosion defect with multilayer structure

	Two layers			Three layers		
	Length L (mm)	Width ω	Depth d (mm)	Length L (mm)	Width ω	Depth d (mm)
First layer	120	20°	3	120	20°	2
Second layer	60	10°	3	60	10°	2
Third layer				30	5	2

3.6.1 Effect of two layers structure

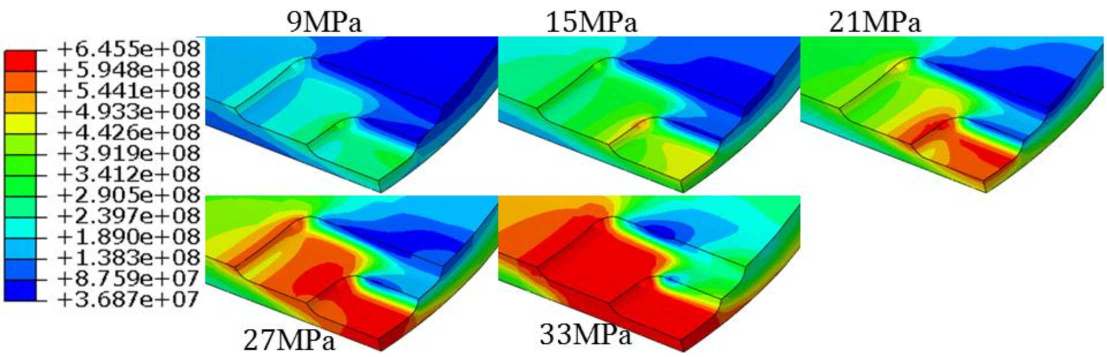


Figure 16. Von Mises stress distribution of the corrosion defect with two layers structure

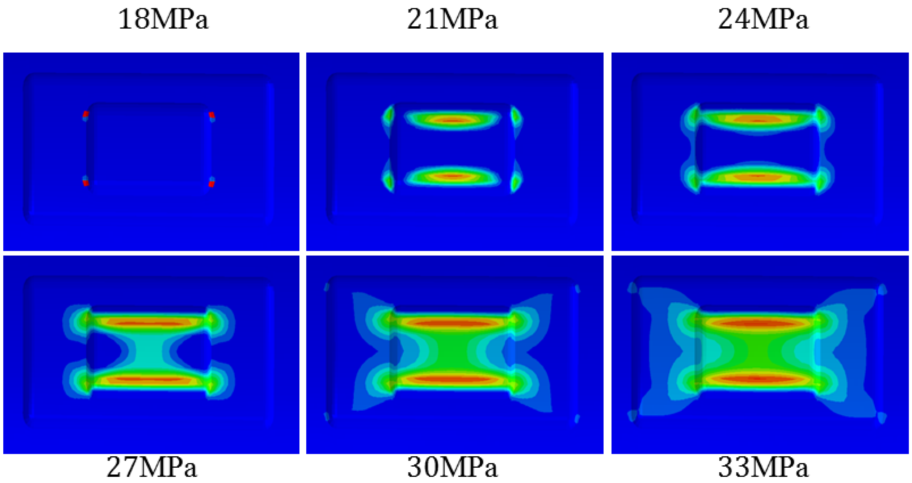


Figure 17. Plastic strain of the area with two layers structure under different inner pressure

Von Mises stress distributions of the corrosion defect with two layers structure under different inner pressures are shown in Fig.16. Instead of the defect circumferential edge, the transition part of the first and the second layer is the place where stress starts to concentrate. With the increasing of the inner pressure, the axial expansion of high stress area is much faster than circumferential expansion of high stress area. Different from von Mises stress distribution of the corrosion defect with one layer structure, high stress area does not cover the whole corrosion defect.

Fig.17 shows the plastic strain of the areas around the corrosion defect with two layer structure. When inner pressure is larger than 18MPa, plastic deformation occurs on the corrosion defect which starts from the corners of the second layer. With the increasing of the inner pressure, plastic strain of the corroded pipeline increases rapidly. Plastic deformation mainly occurs on the circumferential edge of the second layer instead of the first layer. Plastic strain of the first layer expands from the area near the corners of the second layer with the increasing of the inner pressure.

3.6.2 Effect of three layers structure

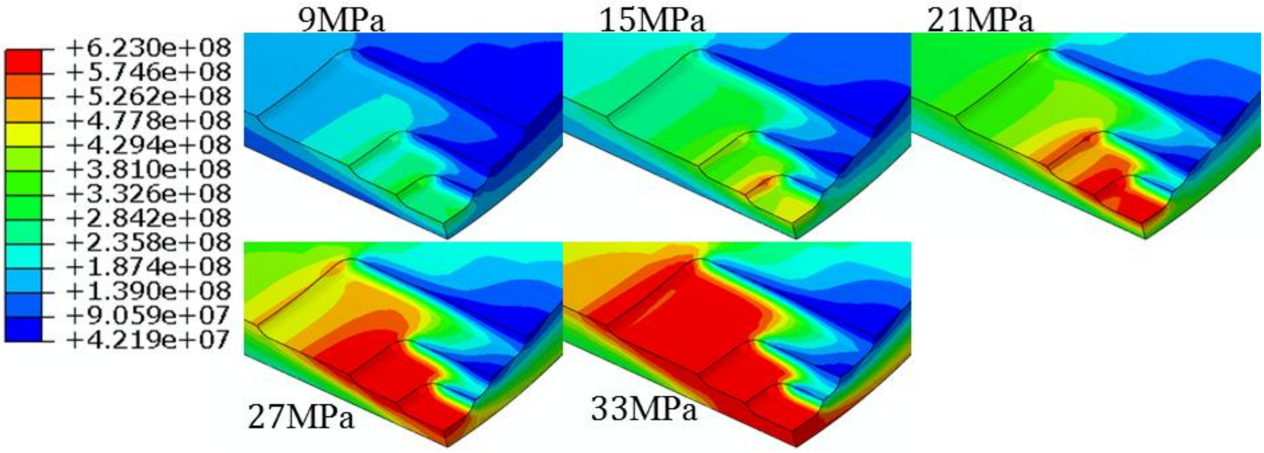


Figure 18. Von Mises stress distribution of the corrosion defect with three layers structure

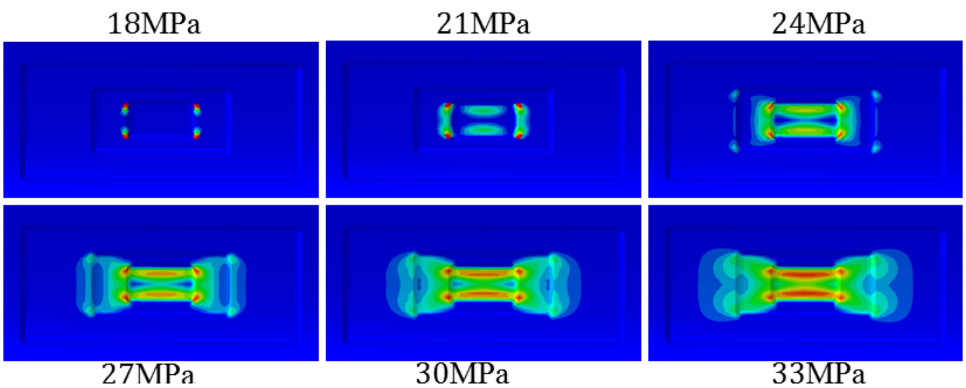


Figure 19. Plastic strain of the area with three layers structure under different inner pressure

Fig. 18 shows the von Mises stress distributions of the pipeline with three layers structural corrosion defect under different inner pressures. Under the action of inner pressure, stress concentration starts first on the transition part of the second and the third layer. With the increasing of the inner pressure, high stress area expands rapidly from the third layer of the corrosion defect to intact area on the wall of the pipeline. Besides, high stress area does not cover the whole corrosion defect due to the structure of the corrosion defect.

Fig.19 shows the plastic strain of the areas around the three layers structural corrosion defect. When inner pressure is larger than 18MPa, plastic deformation occurs on the corrosion defect and starts from the corners of the third layer. Plastic strain increases along the axial direction rapidly with the increasing of the inner pressure. When inner pressure is from 24MPa to 33MPa, plastic mainly occurs on the three layers of the corrosion defect and does not occur on the intact area around the corrosion defect.

4. CONCLUSIONS

1. Von Mises stress and the plastic strain of the pipeline with inner corrosion defect increase as the inner pressure increases. Failure pressure of the corroded pipeline increases with the increasing of length and depth of the corrosion defect. However, width of the corrosion defect has a small effect on failure pressure.

2. With the increasing of the inner pressure, high stress areas and the plastic strain of the pipeline with longitudinally aligned interacting corrosion defects on inner surface (two or three corrosion defects) increase rapidly along the axial direction. Stress concentration appears on the longitudinal separation of the corrosion defects. The maximum plastic strain mainly focused on the middle corrosion defect of the three corrosion defects instead of focusing on each corrosion defect separately. Moreover, failure pressure of the corroded pipeline decreases with the increasing of the number of longitudinally aligned corrosion defects.

3. Multilayer structure of corrosion defect is closer to engineering practice and has an unignorable effect on both von Mises stress distribution and the plastic strain of the corroded pipeline. Stress concentration and plastic deformation firstly occurs on the lowest layer of the corrosion defects and then expands to other layers with the increasing of the inner pressure.

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