Residual strength analysis of steel pipeline with inner and outer defects

C.J. Han[1], S.S. Tan[1], C. Yu[1], J. Zhang[2]*

1.School of Mechatronic Engineering, Southwest Petroleum University, Chengdu, China

2. State Key Laboratory for Strength and Vibration of Mechanical Structures, Xi'an, China

* 574310594@qq.com

Abstract

Corrosion is the mainly effective factor considered as the most threatening element on the transition pipeline and play integral part in residual strength assessment and corrosion allowance design of transition pipeline. Improved ASME B13G method is most widely used. This paper focuses on the pipeline with corrosion defects inside and outside at the same time using nonlinear finite element method analysis, compares simulation results to the theoretical results. Furthermore, this paper investigates its mechanical behaviors and stress-strain distribution regular through simulation on the basis of corroded pipeline with single corrosion defect, predicts accurate residual strength and increasing tendency under different inner pressure, illustrates the failure pressure of transition pipeline with corrosion defects with different interactional location. Stress concentration appears on the edges close to the center of inner corrosion defect and finally expands to the whole defect area circumferentially. Maximum stress and plastic strain occur at the defect center to cause pipeline's failure. Changing rate of stress will increase rapidly under inner pressure once the overlapping region grows and strain will reach higher value after stress exceeds the yield point.

Keywords: corrosion defect, FEM, failure stress, defect alignment

1 Introduction

With global economy developed, world's demand for energy especially the oil and nature gas becomes more and more urgent. Transition pipeline comes to be an indispensable part in petroleum industry. For the aim of safety, saving money and time, reducing human cost, assurance of transition pipeline is valued seriously. Pipeline's invalid elements include erosion, material failure, earthquake, solid impact and so on, among them corrosion defect is the most involved problem the transition pipeline faces in the actual working situation[1]. Eventhough well measures of erosion-protection are taken on transition pipeline, it will damage in complex occasions with service time and failure of anti-corrosion coat gradually. Corrosion divides into location types inside and outside the pipeline, uniform and local types based on the failure form, single and group types based on the corrosion amount[2].

In the past, in order to avoid disasters caused by the failure issues such as leakage and great deformation, transition pipeline is always investigated in empirical formula to predict the failure stress[3]. In recent years, finite element method and numerical simulation model are gradually implied on pipeline with single defect mostly[4].Both the industry model, i.e., ASME B13G, modified B13G and DNV models, and the FEA model developed in this work predict that the failure pressure of a pipe with corrosion defects [5].Among them, ASME B13G is mostly widely adopted[5-6].This paper studies the pipeline with two interactional corrosion defects inside and outside the pipeline at same time, displays the distribution of Von Mises stress of the pipeline with different defects locations. The failure stress is also compared according to the occasions of the defects.

2 Theoretical method and numerical simulation model

2.1 Assessment method

There are so many methods to describe the mechanical behaviors of transmission pipeline, improved ASME B13G is:

$$P_G = \left(\sigma_y + 69\right)\frac{2t}{D}\left[\frac{1-0.85\frac{d}{t}}{1-0.85\frac{d}{t}M_f^{-1}}\right] \tag{1}$$

$\mathrm{L} \leq \sqrt{50}\mathrm{Dt}$

$$\mathrm{M_f} = [1 + 0.6275\frac{\mathrm{L}^2}{\mathrm{Dt}} - 0.003375\left(\frac{\mathrm{L}^2}{\mathrm{Dt}}\right)^2]^{1/2} \tag{2}$$

$\mathrm{L} > \sqrt{50}Dt$

$$M_f = 3.3 + 0.032\frac{L^2}{Dt} \tag{3}$$

In eq.1,P_G is estimated the limit failure stress of the pipeline;σ_y is thesteel's yield stress; t is pipeline's wall thickness; D is pipeline's outside diameter;L is length of corrosion defect and d is depthof corrosion defect.Limit Failure pressure is calculated as 32 MPa by the empirical formulaimproved ASME B13G, which is close to the result of simulation and it means the finite element method is a fitting way to predict the mechanical behaviors of transition pipeline. But it's too conservativeto predict the transition pipeline's failure pressure with corrosion defects inside and outside the pipeline at the same time[7].It leads to energy and money wasting on the unnecessary repairs and parts change. Elastic-plastic criterion is applied in this paper which is much more suitable.

2.2 Numerical simulation model

The choice of pipeline's material has great influence on the analysis of its mechanical behaviors and failure pressure[8]. The X65 pipeline is so widely used in actual working conditions that it was exampled in the paper. Density is 7850kg/m^3,young's modulus of steels material is 207GPa,Poisson's ratio equals 0.3, yield strength is 448 MPa. Considering the effect hardening properties have on the pipeline's failure stress is essential. Material of transmission pipeline has well property of plastic deformation and distinct yield point so the Ramberg-Osgood(R-O) model is usually used to describe the relationship of stress and strain.The curve tells pipeline's mechanical behavior well when the strain is small,but it will have errors fitting the actual stress-strain curve when the strain is big[9]. So the improved R-O model is applied in the research instead. Details of steel material are showed in Fig 1.

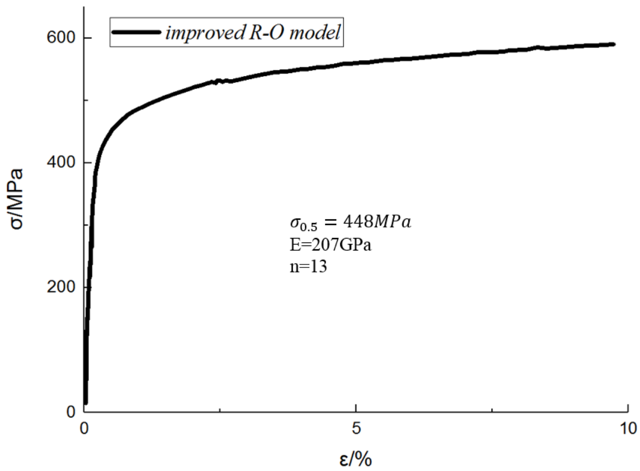


Fig.1 stress-strain curve of X65

Based on the symmetry structure and load of transmission pipeline, a quarter model is built. In order to simplify the calculation process, some assumptions are raised:

a. Only inner pressure applies on the inner face of pipeline.

b. Only pipeline's section with corrosion defects is studied.

c. Other elements such as properties of buried soil and situation outside the pipeline are not considered.

d. The corrosion pit is modeled to transit smoothly to contact area of pipeline through the circular beads.

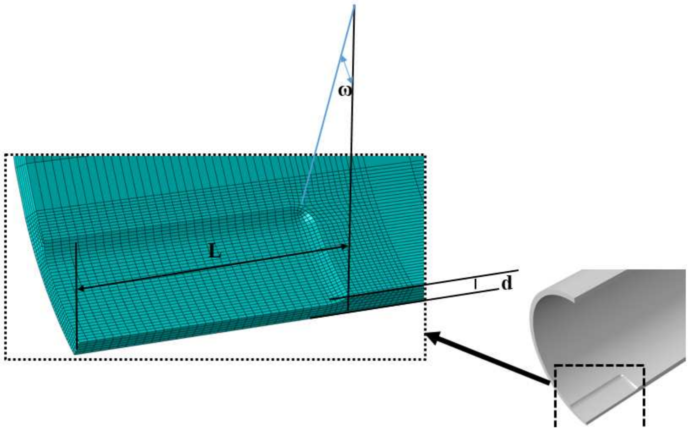


Fig.2 Finite element model

The model is meshed in a finite element method by advanced post-processing software. Grids of the region around the corrosion defect is dividedmore intensively to calculate more accurately. The geometry parameters oftransition pipeline with corrosion defect inside is showed in Table1

Table 1 The geometric parameters of pipeline and corrosion defect

Pipeline			Corrosion defect		
Outside diameter D (mm)	Inside diameter d(mm)	Wall thickness t (mm)	Length L (mm)	Width ω(°)	Depth d (mm)
274	254	10	240	40	3

3 Simulation results and discussion

When the defect's length is 240 mm, width is 40 degrees, depth is 3mm, Von Mises stress of pipeline distribution under different inner pressure is showed in Fig.3. It can be seen that stress appears in the corrosion defects edge region first and extends to the whole defect with the increasing inner pressure. Compared with the circular stress changes, axial changes are more rapid and have wide distribution. The maximum Von Mises stress increases with the inner pressure and its location moves from edge of the corrosion defect to thecenter section. Once the maximum pressure exceeds the limit pressure, the distribution would increase rapidly generating the obvious deformation of pipeline.

3.1 Effects of corrosion defects distributed axially

When inner and outer corrosion defects are aligned axially, the distance between them is describe by letter with values of 0,0.5l, l and1.5l. l is half length of single defectas 0.12m. Observed from distribution and curve in Fig.4, Fig.5, Fig.6, maximum stress happens on the defects' edges, increases then expands to the defects' center areas with increasing inner pressure. Stress on the inner face is always larger than the outer face, close to each other since it reaches the yield point. Different from the close stress when deformation comes to the pipeline, stress impacting region is much wider in outer corrosion defect. The maximum deformation will happen at outer corrosion defect center area approaching inner corrosion defect.

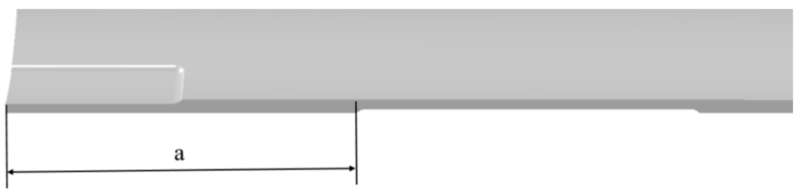
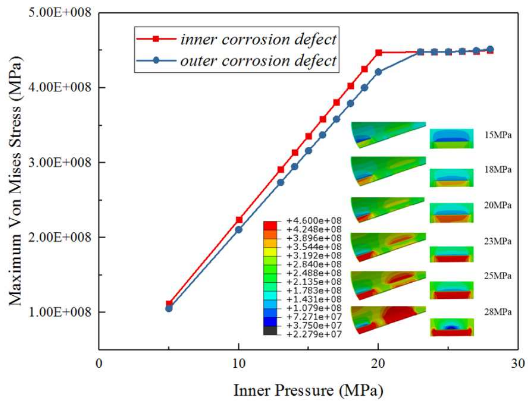


Fig.3 Finite element model of corroded pipeline

Once defects have overlapping area, it will have a big influence on the stress of pipeline. Stress will be affected by the inner pressure more easily and rise rate is higher when the overlapping area is not the whole defect big. With the decreasing distance between the two defects, not only the maximum Von Mises stress is much higher, but also the strain change more rapidly under the same inner pressure. Maximum stress appears on the defect inside initially, then transits to the defect outside with the increasing inner pressure.



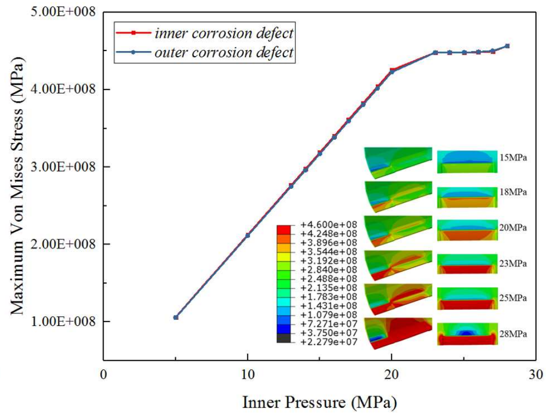
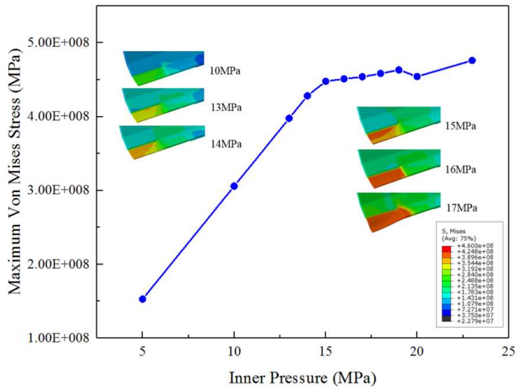


Fig.4 Max Von Mises stress (a=1.5l) **Fig.5** Max Von Mises stress (a=l)



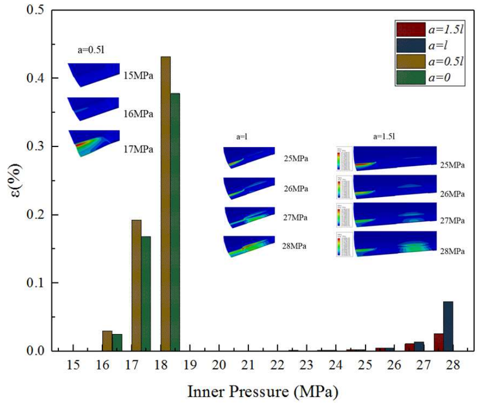


Fig.6 Max Von Mises stress (a=0.5l) **Fig.7** Plastic strain of defects area

Fig.8 shows failure stress grows with increase of defects' axial distance. Stress is little different when a equals 0, 0.5l and l, 1.5l respective. Once the superposition is not zero, inner stress increases rapidly to reach the yield stress point and cause large deformation of corroded pipeline.

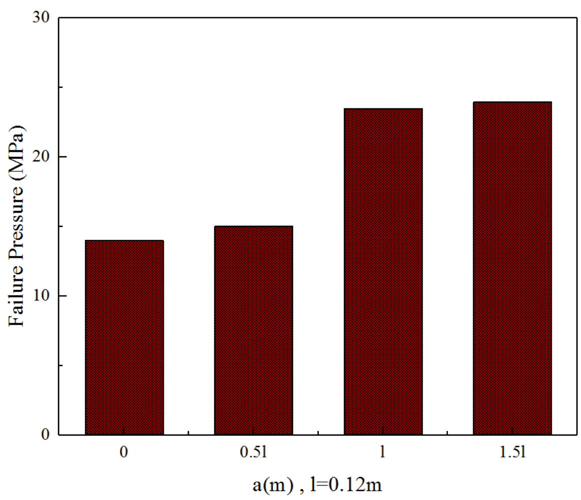


Fig.8 Failure pressure with different corrosion defects' axial distances

3.2 Effects of corrosion defects distributed circumferentially

Circumferentially interactive defects can be researched by the circular angle between inner defect andouter defect. The whole finite element model is showed in Fig.9. The angle between inner and outer defect is 60 degrees.

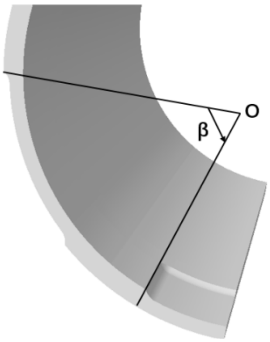
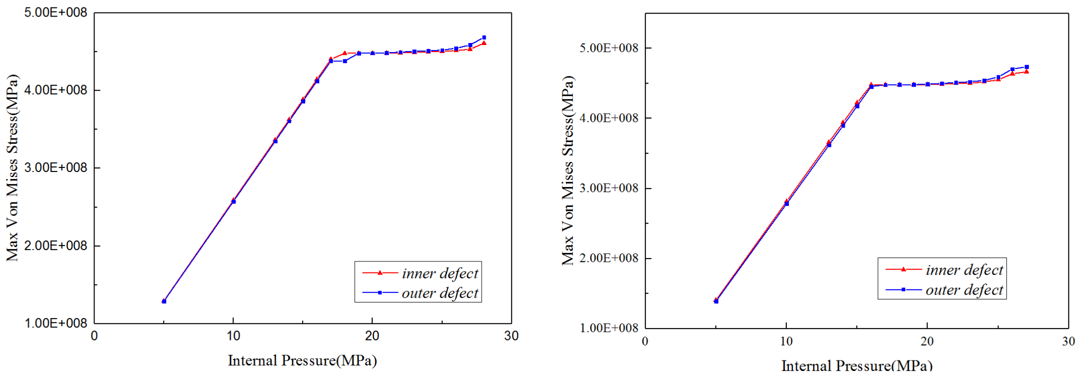


Fig.9 Finite element model of pipeline with corrosion defects

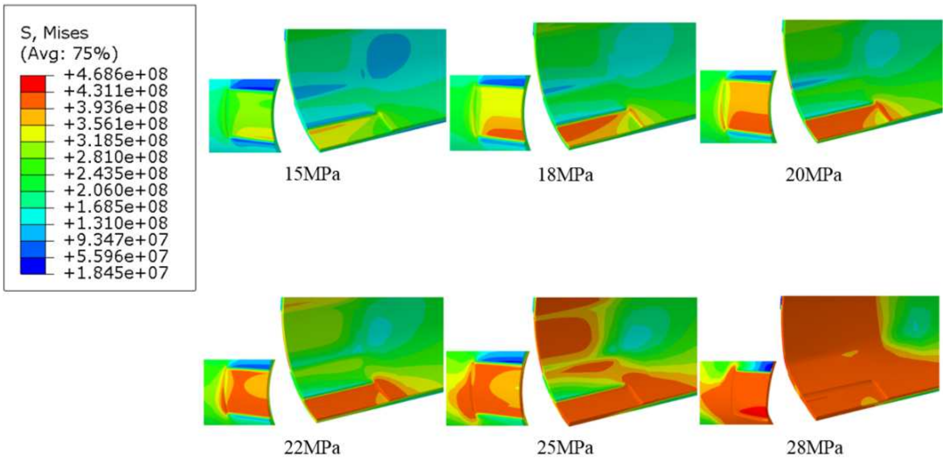
Fig.10 (a) is the curve of maximum Von Mises stress under increasing inner pressure when βequals 60 degrees. Fig.10(b) is the curve of maximum Von Mises stress under increasing inner pressure when β equals 50 degrees.Maximum Von Mises stress changes with inner pressure, inner defect and outer defect's stresses are almost the same until it reached the yield stress. maximum stress of outer defect will be bigger than the inner one with the continually increasing inner pressure.



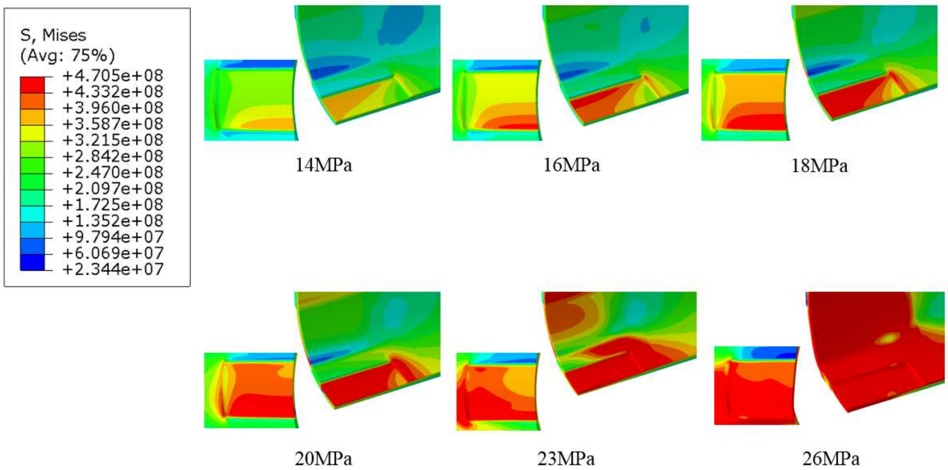
(a) β=60° (b) β=50°

Fig.10 Max Von Mises stress curve of inner and outer corrosion defects

Fig.11 (a) is the Von Mises stress distribution of corrosion defects when β equals 60 degrees while Fig.11 (b) shows it when β equals 50 degrees. As stress displayed inFig.11 (a), maximum Von Mises stress always appears on edge of defect firstly, then spread similar to it is single defect inside the pipeline. Maximum stress of outer defect arises on the edge close to the inner defect. The interaction of inner and outer defects was small before the limit pressure, but functioned heavily when it exceeded the limit pressure and soon caused the sharp submission in location. corresponding to the part outer defect close to the inner defect.



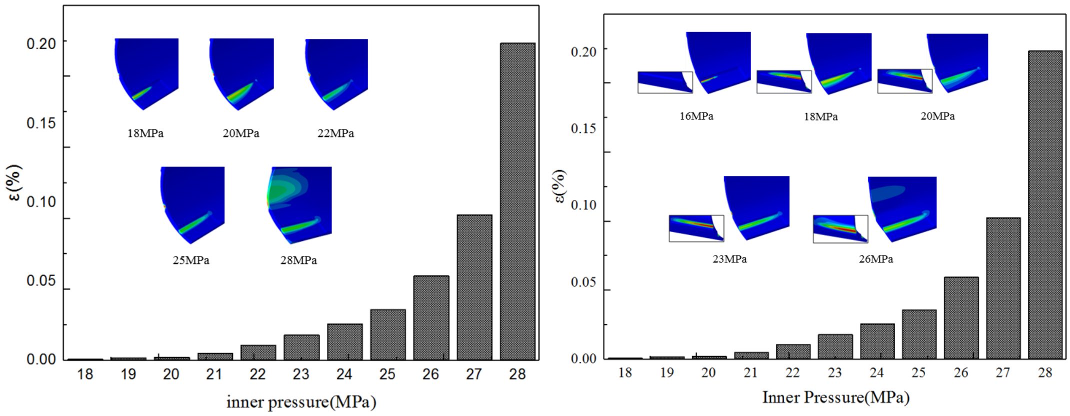
(a) β=60°



(b) β=50°

Fig.11 Stress distribution of defects area under different inner pressures

When β=60°,Plastic strain occurred when the inner pressure increase to 18 MPa, at the adjacent edges of inner and outer defects. It increased with the increasing inner pressure. When the maximum Von Mises stress exceeded the limit inner stress, apparent deformation would take place at the outer defect's defect approaching to the inner defect. When β=50°,Plastic strain occurred when the inner pressure increase to 16 MPa. Fig.12 (b) displays similarly except the large plastic appears strip shaped compared to the oval shaped in Fig.12 (a). deformation happens in the outside corrosion defect of the pipeline.



(a) β=60°　　　　(b) β=50°

Fig. 12 Plastic strain of defects area under different inner pressures

Inner corrosion defect's margin and outer corrosion defect's margin will be tangent when βreduce to 40°, plastic strain distribution changes differently with the overlapping area of inner and outer corrosion defects. Large deformation lies in inner corrosion defect border, expand along the axial direction faster than circular direction. Inside corrosion defect's stress is easier to reach the yield stress point than outside, but they have little differences after the yield point. Once the two defects have overlapping regions, it will have a great influence on the stress under higher inner pressure.

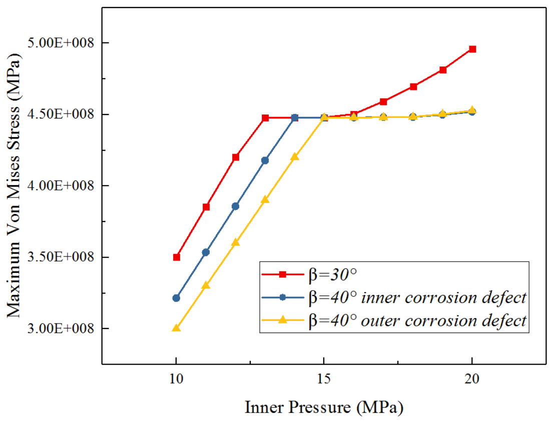
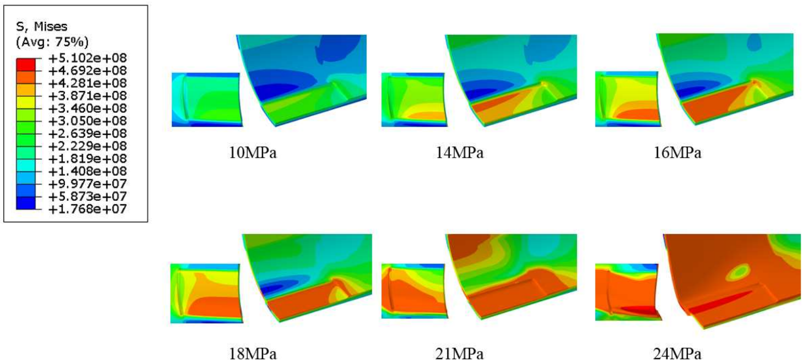
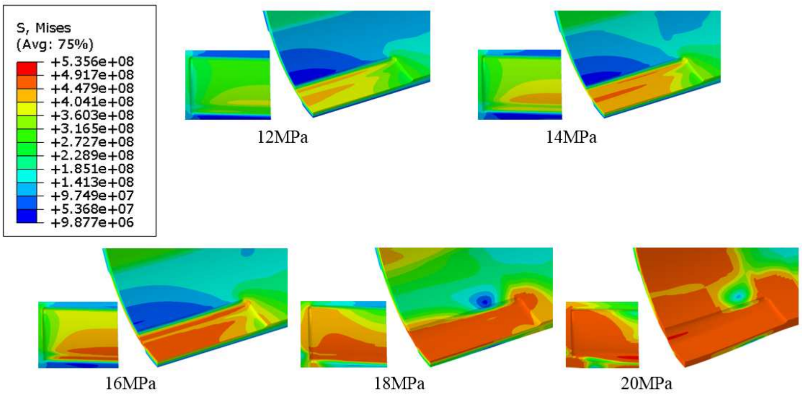


Fig.13 Max Von Mises stress of corroded pipeline under different inner pressures

Plastic strain is much bigger when β=30°, growth rate is much higher and large deformation appears more rapidly with lower inner pressure. Plastic strain appears exactly close to both long sides of inner and outer corrosion defects firstly and distribute along the sides.



(a) β=40°



(b) β=30°

Fig.14 Von Mises stress of defects area under different inner pressures

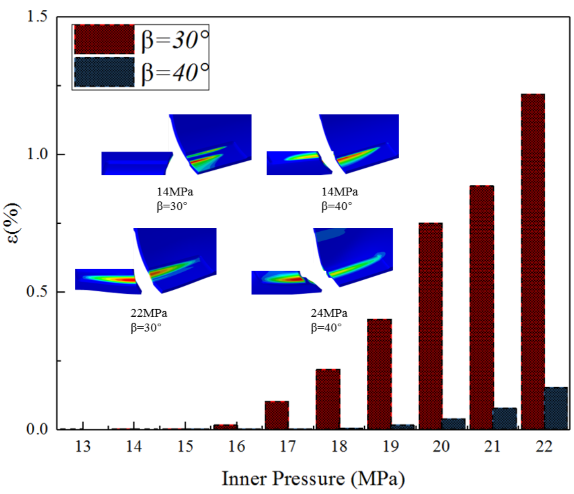


Fig.15 Plastic strain distribution of defects area

Coincident region will be just half corrosion defect since βdecreases from 20°. Maximum Von Mises stress increases with the inner pressure before it reaches yield stress point and after that it will keep stable range. It decreases with decreasing degrees between inner and outer defects and it's contrary to the tendency when β is greater than 20°.

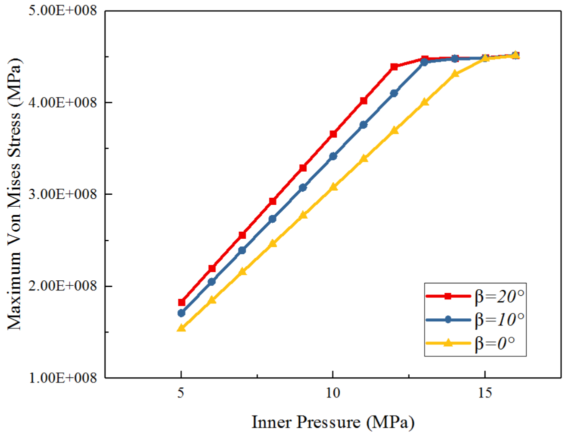
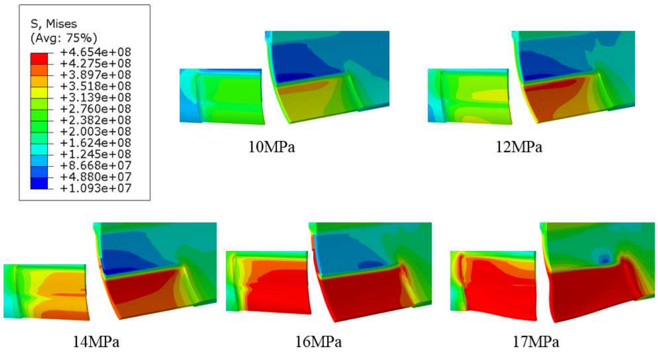
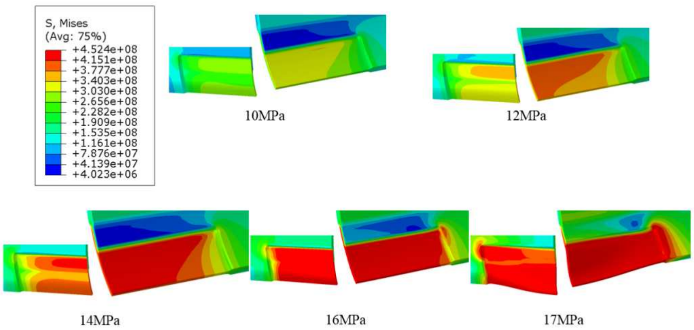


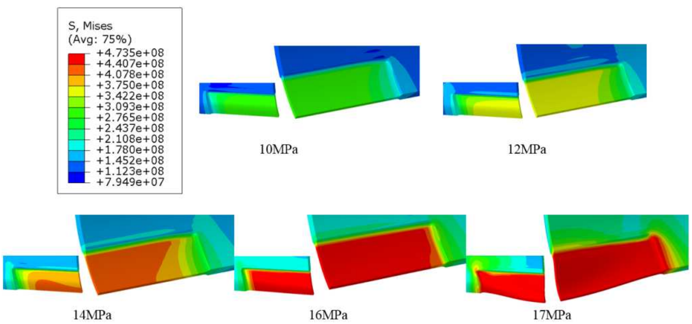
Fig.16 Maximum Von Mises stress curves of corroded pipeline



(a) β=20°



(b) β=10°



(c) β=0°

Fig.17 Von Mises stress distribution of defects area

Maximum plastic strain appears at the edge of inner corrosion defect and on the inner face only. Pipeline deformation spreads to the whole defect area with increasing inner pressure, maximum plastic strain lies the inside corrosion defect's fillet and outside corrosion defect's center. Plastic strain is nearly zero under lower inner pressure when β equals 0° but rises at more rapid rate once it emerges. Variation is similar when β is 20° and 10°.

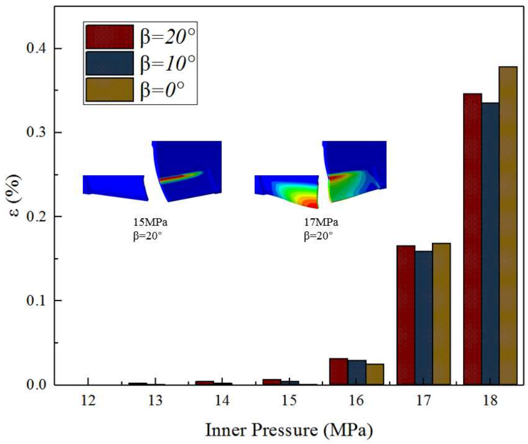


Fig.18 Plastic strain distribution of defects area (β=20°,10°,0°)

Fig.18 shows the failure pressure of corroded pipeline with different corrosion defect types based on the β's value. Failure pressure increases with increasing β generally as the interaction between inside and outside corrosion defects becomes weaker. So do the safety and mechanical properties of corroded pipeline.

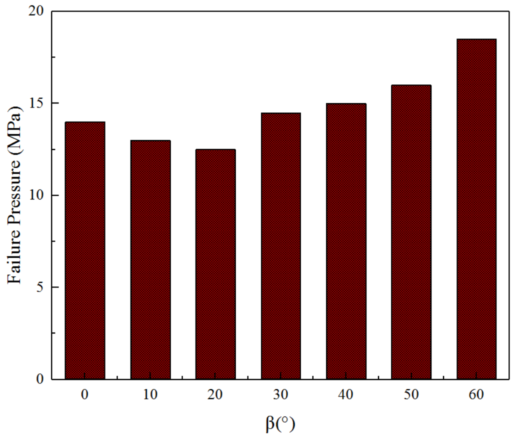


Fig.19 Failure pressure with different corrosion defects' circumferential locations

3.3 Effects of inner and outer layered corrosion defects

Practical situation is complex that corrosion defects is just the same of size. For the defect is always irregular, it can be simplified through the relative size with each other. Define the inner corrosion defect as the default model, distinguish cases by the outer defect's ratio of the inner one and study mechanical behaviors transition pipeline. Outer corrosion defect's size is half of the inner oneWhen ratio is 0.5, same as the inner one as ratio is 1 and twice the inner one as ratio is 2.

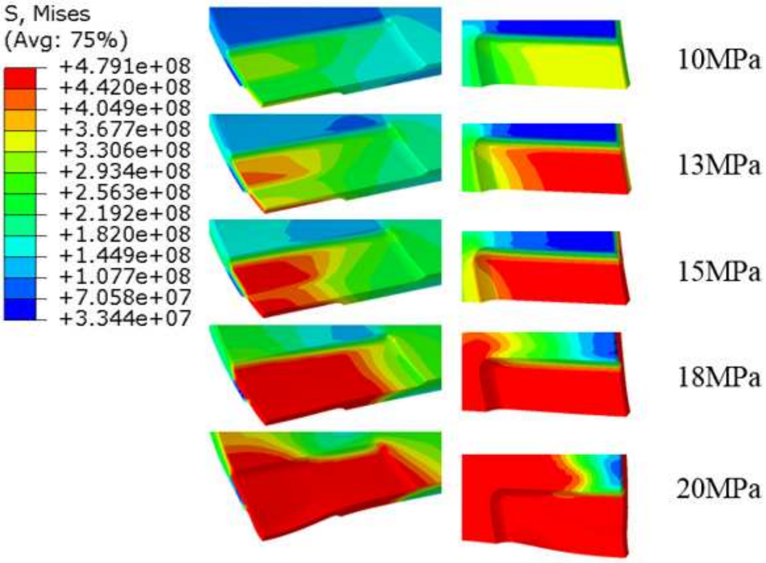


Fig.20 Von Mises stress distribution of corroded pipeline when ratio is 0.5

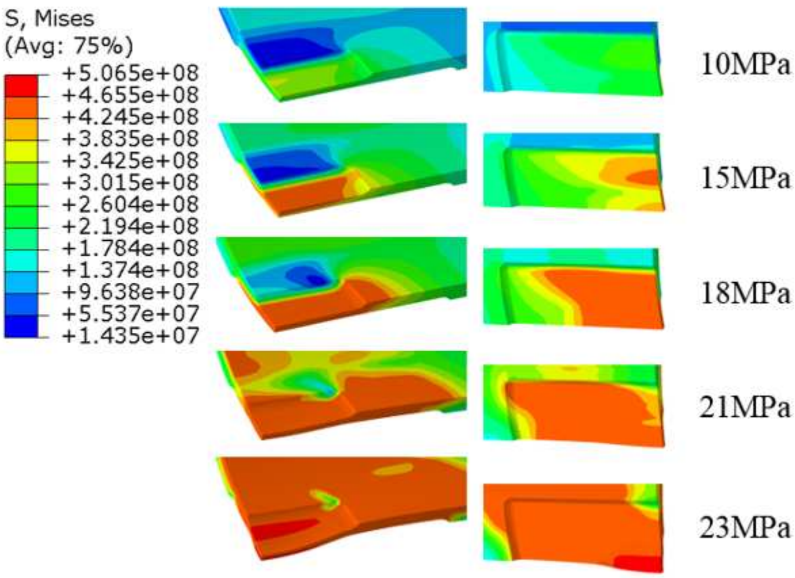
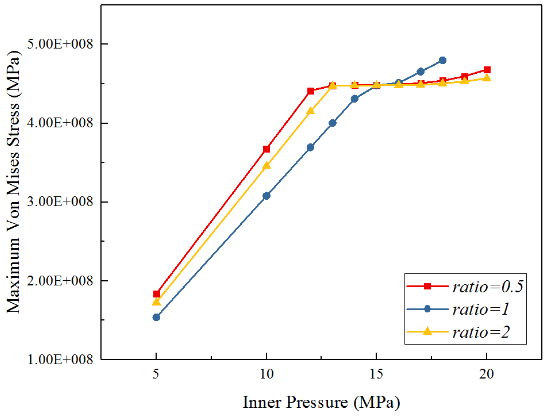


Fig.21 Von Mises stress distribution of corroded pipeline when ratio is 1

When ratio equals 1, the overlapping part is the whole corrosion defect. Corroded section of pipeline can be regarded as thin-wall pipeline approximately. Plastic strain certainly increase rapidly under lower inner pressure and cause deformation easily. But when ratio doesn't equal 1, surface smaller-area corrosion defect lies has influence on the mechanical behaviors of pipeline. Yield point is sooner to get when the outer defect is smaller the inner one and plastic strain values larger than when the deformation appears.



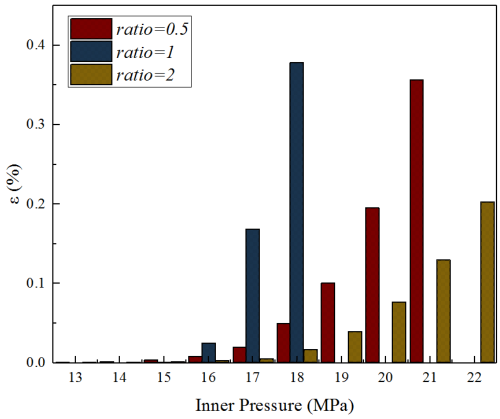


Fig.22 The maximum Von Mises stress curves **Fig.23** Plastic strain histogram

Fig.24 shows when ratio=0.5, maximumplastic strain appears on the edge of outer corrosion defect outside the pipeline firstly, then transforms to the same location inside the pipeline, concentrates the center region of the corrosion defect outside. when ratio is 2, the maximum plastic strain occurs at the circumferential edge of corrosion defect inside and finally transforms to the center region of corrosion defect outside as well.

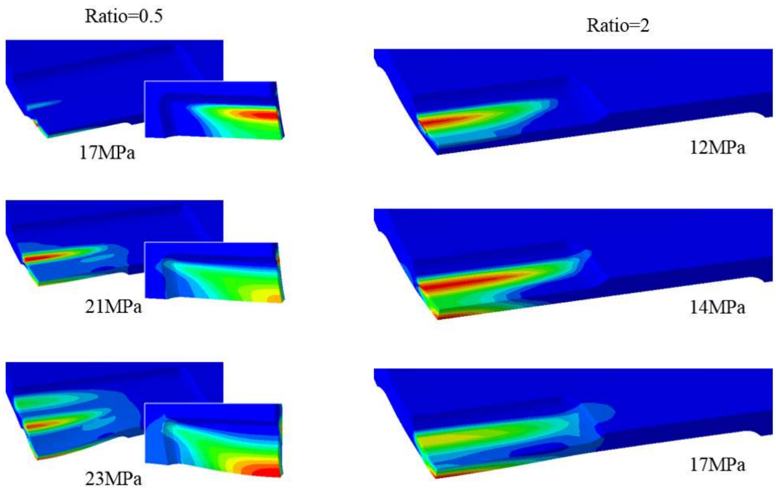


Fig.24 Plastic strain distribution of defects area under different inner pressures

Failure pressure of corroded pipeline is shown in Fig.25. Failure pressure decreases with the ratio of corrosion defects decreases.

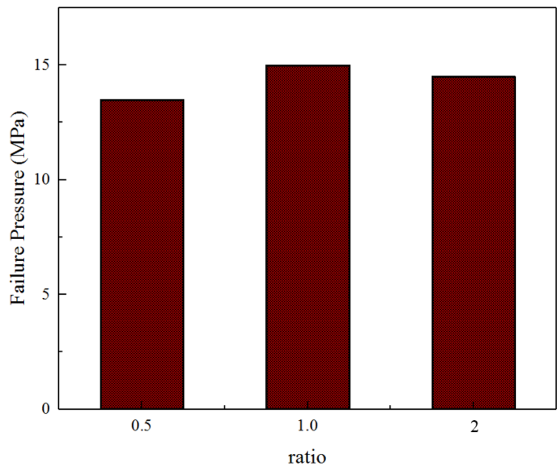


Fig.25 Failure pressure of corroded pipeline with different ratio

4 Conclusions

Both Von Mises stress and plastic strain increase with the increasing inner pressure. Growth rate will be faster after stress exceeds yield point. Stress is easy to increase when axial distance $a$and circular degree βdecrease.

The Maximum Von Mises stress and plastic strain appear on the long side of the defect. Stress functioned area expands along the same direction of pipeline with defects arrangements. The maximum deformation lies the center area of outer corrosion defect close to the inner one and the exact center of inner corrosion defect.

Once the two defects have overlapping area, plastic strain rising rate of pipeline increases faster based on the rising area's proportion, while its mechanical and usage properties decreases.

Acknowledgements

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