IOP Conf. Series: Materials Science and Engineering **398** (2018) 012035 doi:10.1088/1757-899X/398/1/012035

Evaluation of Softening Zone in X80 Pipeline Steels under Tension-bending Load

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Abstract. Softening of heat-affected zone of X80 pipeline steel is common in weld joints. The finite element analysis model was established based on ABAQUS software in this paper, then the numerical simulation of the strain capacity of X80 steel pipe was carried out under tension-bending load. Researches show that the softening zone width has little influence on service performance of the pipelines under tension-bending load. When the softening rates are 5%, 10% and 15%, the peak values of load are similar. However, structural instability of the pipeline with softening rate 15% is worse and more serious. The pipeline with design coefficient of 0 can withstand greater deformation under tension-bending load, and it can keep good performance.

1. Introduction

In recent years, high-strength pipelines with anti large deformation have been widely applicated in long-distance oil and gas transportation, and pipeline welding technology has been rapidly developed [1-3]. The heat-affected zone (HAZ) grains are coarse due to the heat welding input , after the phase transformation and recrystallization appear in some places which lead to the softening of HAZ [4-5]. The welding heat-affected zone is an uneven region where cracks or failure commence, of which the deformation behavior is extremely complex under external load [6-7].

The utilize of numerical simulation method can realize data rich, diverse and accurate. A.BASTOLA et al. [8] presented details of an experiment research method for small-scale and full-scale experiments on X80 line pipe specimen containing girth welds. The tensile tests indicated that the yield stress overmatch of approximately 20% for the weld metal, and that the HAZ region is about 7.5% softer compared with base metal at 1% applied strain, leading to the conclusion that HAZ softening may limit the acceptable critical size in an ECA (Engineering Critical Assessment) for X80 pipes. By using the finite element software, Fengping Yang et al. [9] simulated the crack propagation with fluid-solid coupling method. They found that when the plastic uniform elongation was equal to 0.054 and the damage strain energy per volume was equal to 0.64 J/mm3, the X90 Φ1219 × 16.3 mm gas pipeline with 12 MPa internal pressure produced by lean gas could arrest cracking. Satoshi Igi et al. [10] examined the influence of internal pressure on the tensile strain capacity of pipelines and discovered that the critical tensile strain drastically decreased under a high internal pressure condition. The results demonstrated that the tensile strain capacity of pressurized pipes could be predicted by using the R-curve from SENT tests and the crack driving force curves from FE analyses. However, little researches have been focused on the service performance of pipeline considering more complicated cases such as tension-bending load and the resistance to deformation is not completely understood.

The finite element model was established based on ABAQUS software in this paper, then the numerical simulation of the strain capacity of X80 steel pipe was carried out under tension-bending load considering the influence of internal pressure. By using the above model, the effect of softening zone width on steel pipe's deformation resistance was investigated. Then the softening behaviors with different softening ratios and different design coefficients were evaluated.

2. Materials and methods

2.1. Test materials
X80 pipeline steel was used as research object in the work, and the specimens were taken from the welded joint. The chemical compositions(wt%) of the experimental steel are 0.063 C; 0.28 Si; 1.83 Mn; 0.011 P; 0.0006 S; 0.03 Cr; 0.03 Ni; 0.016 Ti; 0.061 Nb; 0.059 V; 0.22 Mo and remainder Fe.

2.2. Test methods

2.2.1. Tensile test. The stress-strain curve of the experimental steel was obtained by tensile test machine as shown in Figure 1. The mechanical properties of X80 steel pipe shown in Table 1.

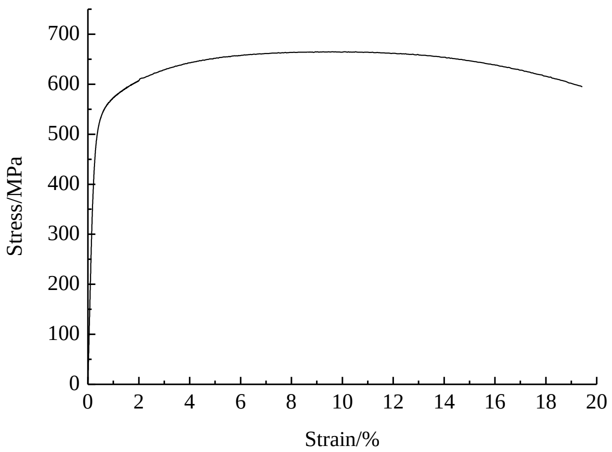

Figure 1. The stress-strain curve

Table 1. Mechanical properties of X80

Material	Yield strength ($R_{t0.5}$ /MPa)	Tensile strength (R_m/MPa)	Elastic modulus (E/MPa)	Poisson ratio
X80	530	670	206000	0.3

2.2.2. Metallographic test. The metallographic sample removed from welded joint was mechanically grinded polished and then examined in optical microscopes. The microstructures were revealed by using 4% Nital etching for 10s. As shown in Figure 2, the geometry of welded joint can be seen clearly.

Figure 2. The geometry of welded joint

2.2.3. Vickers hardness test. According to the geometric contour of welded joint, we took a point at about 1.2mm from the top surface of the cover, and draw another point symmetrically to the center line of the weld, then draw a straight line along these two points. In the specimen thickness direction, another straight line parallelled with the first line was drew 3mm from the first line, so do another 7 parallel lines. Vickers hardness tests are conducted on the 9 lines with spacing of 0.03mm. Hardness values of each point on the center line are in Figure 3. Researches show that the hardness of the weld zone is large, and the hardness suddenly decreases in HAZ either of the weld joint which is the softening zone, while the hardness of the base metal is also large. Form the hardness values of different positions, we can obtain the geometry of weld joint shown in Figure 4.

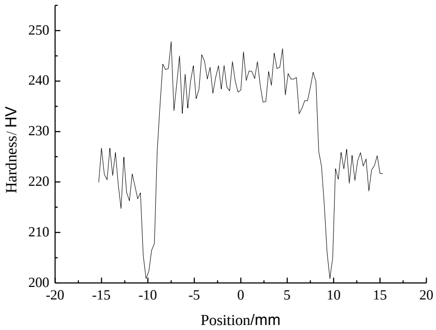

Figure 3. Hardness values of points on the center line

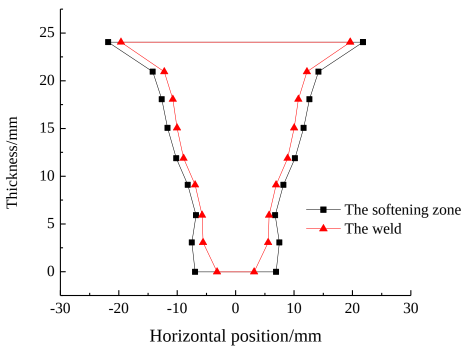

Figure 4. The geometry of welded joint

2.2.4. Bending Test. The bending test conditions are as follows: the demensions of the welded pipe are Φ1219mm × 26.4mm, design coefficient is 0; the length is 10m; the overmatching strength of for weld metal is 10%. The bending test was carried out at the Renqiu branch of Petro China. The degree of ellipticity near the weld was measured with the actual bending angle of 5.5 degrees.

3. Numerical simulation

3.1. Geometric model
The 1/2 two-dimensional model of weld joint is shown in Figure 5, which is built according to the geometry of the etched weld joint.

3.2. Meshing
Actually, it is unnecessary to mesh the model with all fine mesh. To improve calculation efficiency, regions with large deformation or strain concentration should be divided by using fine mesh. Figure 6 shows the finite element mesh of the 2D in weld joint.

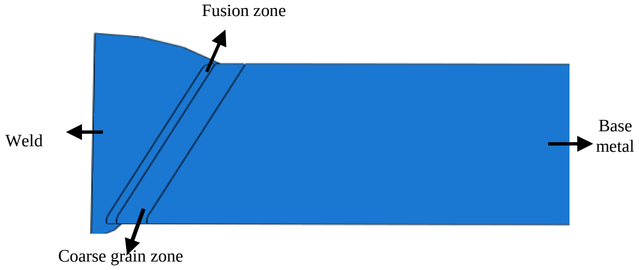

Figure 5. 2D dimension in weld joint

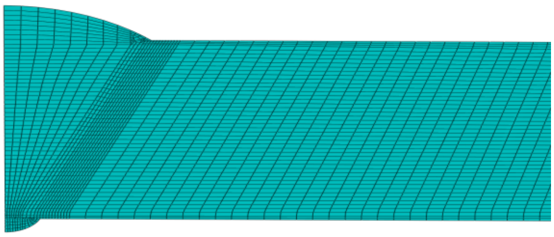

Figure 6. Mesh in weld joint

3.3. Boundary conditions
Two reference points are set on both sides of the steel pipe, which are set up with two surfaces to establish kinematic pairs and constraints. The axial tensile displacement is applied to the reference points on both sides of the model in first stage. Then the bending load of pipe is realized by extrusion with a rigid body, while internal pressure was loaded in the second stage. Figure 7 shows the boundary condition of the whole model.

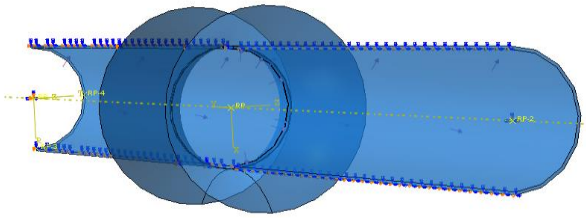

Figure 7. The whole simulation model with boundary condition

3.4. Finite element verification
As shown in Figure 8, the simulation results of bending test show that with the displacement of the reference points increasing, the force occurs rises rapidly until the displacement of 500mm, then slowly.

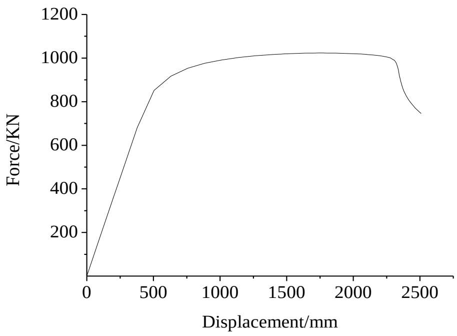

Figure 8. Simulated force-displacement curve of the tension bending test

When the load reaches the peak value, buckling phenomenon occurs, then the applied load decreases quickly. When the displacement reaches about 2276mm, the pipeline buckling occurs shown in the Figure 9.

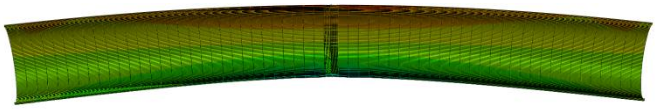

Figure 9. Buckling phenomenon in the pipe

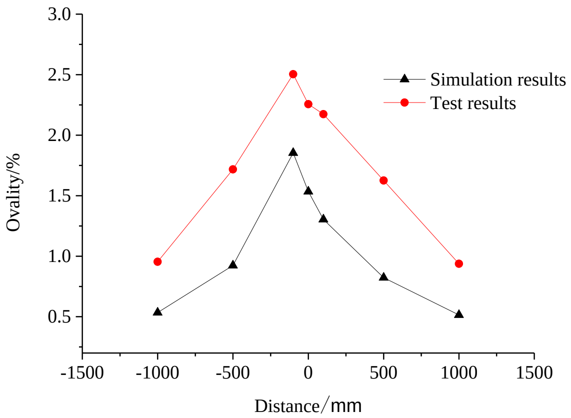

Figure 10. Simulation and measured results of bending test

With the bending angle of 5.5 degrees, the ovality was determined at the same position with the actual bending test. The simulation and test results are shown in Figure 10. The peak values of the ovality exits in the weld zone. The ovality decreases with increasing the distance from the weld zone, which is in coherent with the theory of buckling deformation. On one hand, for the simulation process, the initial ovality of the simulation is 0%. The bending process is carried out according to the ideal process and the simulated results are smaller. On the other hand, many factors affect the change of ellipticity in bending process such as residual stress and residual strain, which leads to large deformation and large ovality.

Taking into account the actual factors, the simulated results compared with the experimental ones are similar, which shows the validity and accuracy of the model.

4. Results and discussion

4.1. Evaluation of softening zone width

The dimensions of the pipeline are Φ1219mm × 16.3 mm, the groove angle is 24°, the align deviation value is 0, the weld overmatching strength of weld metal is 10%, softening rate of the coarse grain zone is 10%, the design coefficient is 0 and the internal pressure is 11.52 MPa. The deformation processes of weld pipe with softening zone width of 1mm, 2mm, 3mm, 4mm and 5mm were simulated. Figure 11 shows strain contour figure of weld pipe with softening zone width of 4mm. Under tension-bending load, the tensile and compressive strain of the five different weld pipes are similar. As shown in Figure 12, with the displacement of the reference points increasing, the force that the pipe bears rises rapidly and then slowly. When the displacement reaches about 180mm, the peak values of load presents and buckling phenomenon occurs, while the applied load decreases quickly. Force-displacement curves of the five weld pipes are almost coincident before buckling phenomenon occurs. In other words, their peak loads are basically the same. After pipeline buckling, the decreasing rates of the loads on the weld pipe with softening zone widths of 1mm, 2mm, 3mm and 4mm are equal to each other, while that of the weld pipe with softening zone width of 5mm is slower than the other pipes.

In conclusion, softening zone width has little influence on actual performance of the pipelines under tensile-bending load due to wide cap welding. The softening zone is covered with higher strength materials through wide cap welding. Therefore, it is better to use wide cap welding considering the premise of economic and technical conditions.

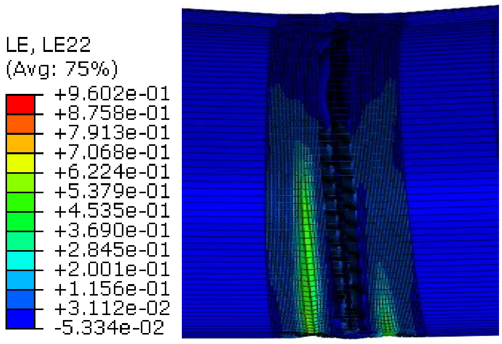

Figure 11. Strain contour figure of weld pipe with softening zone width of 4mm

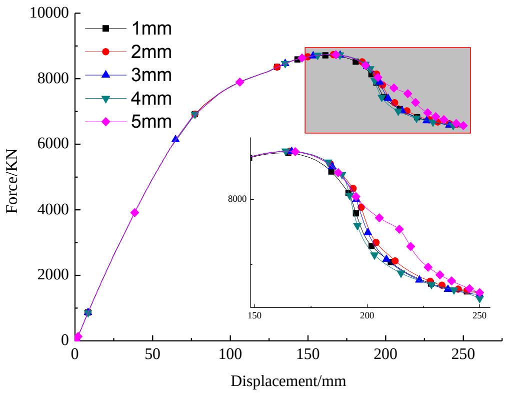

Figure 12. Force-displacement curves of weld pipes with different softening zone widths

4.2. Evaluation of softening rate

The dimensions of the pipeline are Φ1219mm × 16.3 mm, the groove angle is 24°, the align deviation value is 0, the weld overmatching strength of weld metal is 10%, softening zone width is 3mm, the design coefficient is 0 and the internal pressure is 11.52 MPa. The deformation processes of weld pipes whose softening rate are 5%, 10% and 15% were simulated.

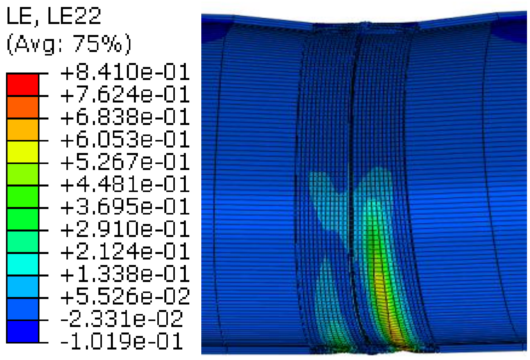

Figure 13. Strain contour figure of weld pipe with 10% softening rate

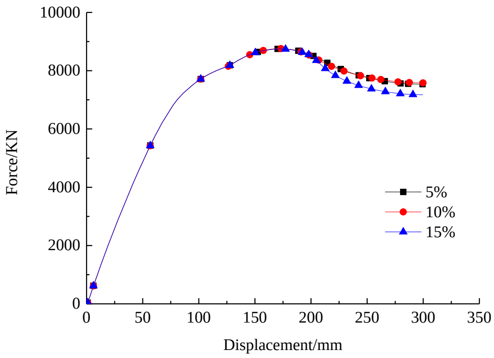

Figure 14. Force-displacement curves of different softening rates

Figure 13 shows strain contour figure of weld pipe with 10% softening rate. Under tension-bending load, the tensile and compressive strain of weld pipes with softening rates 5% and 10% are similar. The weld pipe whose softening rate is 15% has a higher value compared with another two in tensile and compressive strain. As shown in Figure 14, with the displacement of the reference points increasing, the force that the pipe bears rises rapidly and then slowly. When the displacement reaches about 190mm, the peak values of load presents and buckling phenomenon occurs while the applied load decreases quickly. Force-displacement curves of the three weld pipes are almost coincident before buckling phenomenon occurs. In other words, their peak loads are basically the same. The pipeline with softening rate 15% is faster and earlier than the other pipelines in load drop and in loss of performance. The load of the pipelines with softening rate 5% and 10% whose decreasing rates are approximate is higher than another one after buckling phenomenon occurs.

In conclusion, when the softening rates are 5%, 10% and 15%, the peak values of load are approached. However, structural instability of the pipeline with softening rate 15% is worse and more serious, and it has a greater strain value.

4.3. Evaluation of design coefficient

The dimensions of the pipeline are Φ1219mm × 16.3 mm, the groove angle is 24°, the align deviation value is 0, the weld overmatching strength of weld metal is 10%, softening zone width is 3mm. The deformation processes of weld pipe with design coefficients of 0 and 0.5 were simulated. When the design coefficient is 0, the pipeline internal pressure is 0, when the design coefficient is 0.5, the pipeline internal pressure is 11.52 MPa.

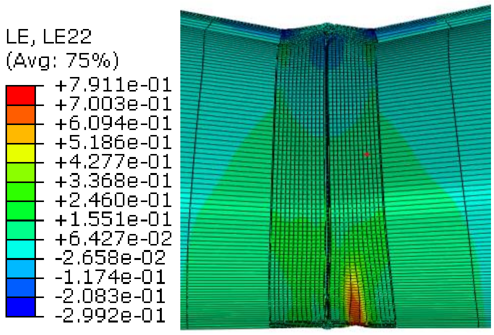

Figure 15. Strain contour figure of weld pipe with the design coefficient 0

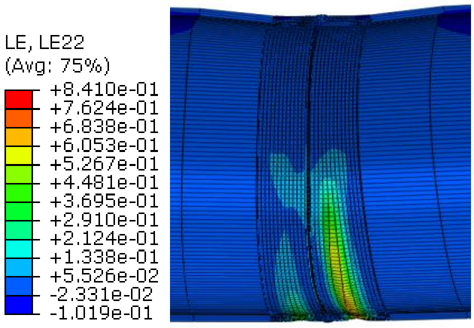

Figure 16. Strain contour figure of weld pipe with the design coefficient 0.5

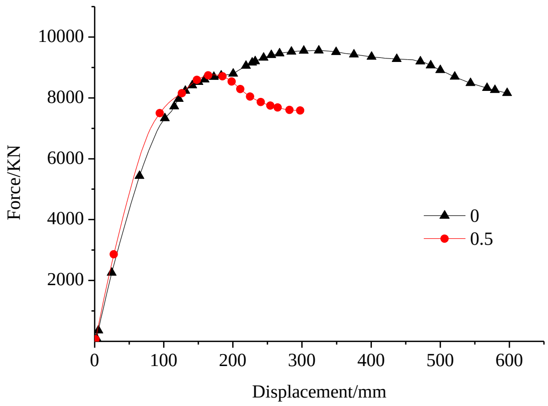

Figure 17. Force-displacement curves of weld pipes with different design coefficients

Figure 15 and Figure 16 are strain contour figures of weld pipes with design coefficient 0 and 0.5. Under tension load combined with bending load, the tensile strain of weld pipe with design coefficient 0.5 is bigger than the pipe of design coefficient 0 while the compressive strain is on the contrary. And large deformation was observed at compression side in Figure 15. As the Figure 17 shows, with the displacement of the reference points increasing, the force that the pipes bear rises rapidly, then slowly. When the displacement reaches about 190mm, the peak load of design coefficient 0.5 pipe's presents and buckling phenomenon happens with structural instability, then the applied load decreases quickly. However, the load of the pipe with design coefficient 0 increases until the displacement reaches about 300mm. Force-displacement curves of the two pipes are almost coincident before buckling phenomenon occurs. The pipeline with design coefficient 0.5 is faster and earlier than the another in load drop and in loss of performance. The load of the pipeline with design coefficient 0 is higher than the other after buckling phenomenon occurs.

In conclusion, the pipeline with design coefficient 0 can withstand greater deformation under tension load combined with bending load, and it can keep good performance.

5. Summary

(1) Taking into account the actual factors, simulated results were compared with experimental ones, which show the validity and accuracy of the model.
(2) The softening zone width has little influence on performance of the pipelines under the effect of tensile-bending load. It is better to use wide cap welding considering the premise of economic and service conditions.
(3) When the softening rates are 5%, 10% and 15%, the peak values of load are approached. However, structural instability of the pipeline with softening rate of 15% is faster and worse while it has a greater strain value.
(4) The pipe with design coefficient of 0 can withstand greater deformation under tension-bending load. So it can keep good service performance.

6. Acknowledgements

The authors are grateful for the financial support from the National Natural Science Foundation of China (No. 51205342 and No. 51275445) and Natural Science Foundation of Hebei Province of China (No. E2016203217).

7. Reference

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