A Study on Proper Location of Welding Defect in Three Point Bend Testing with MDPE Pipe

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Abstract

Welding defects affect the performance of welded pipe joints. In this study, a three point bend test of welded steel and medium density polyethylene (MDPE) pipe joints with defects of various defect locations and defect materials was studied using the finite element method. The defect was assumed to be located at 12 o'clock, 3 o'clock or 6 o'clock direction. The results showed that pipes failed more easily on the compression side due to stress or local buckling. The air defect was more dangerous than the steel defect if the defect was located in the compression side; otherwise, the defect material effect on the integrity of pipes was ignorable. It is argued that the integrity of pipes with defects in the compression side is weaker than that in other regions, and the defect should be located in the compression side or the 12 o'clock position in the three point bend test to maximize the effect of defect existence on the pipe structural integrity.

Key words : MDPE, polyethylene, pipe, welding defect, three point bend test, finite element analysis

1. Introduction

Since butt fusion welding is a simple and effective welding method for polyethylene pipes [1, 2], medium density polyethylene (MDPE) pipes for gas distribution are increasingly constructed by butt fusion welding to make a good airproof and structurally sound gas pipeline system. If welding process conditions are judiciously determined, then mechanical properties such as yield strength, elongation at fracture, and fatigue life traversing at the welded joints are not decreased by the welding [3, 4]. Sometimes, the quality of the welded joints is seriously affected by welding defects, such as lack of fusion, shrinkage cavities, and foreign matter inclusions [5]. The defects in the joints can be inspected by the nondestructive technique using the phased array ultrasonic imaging method [6, 7]. Several studies have been conducted to investigate the effect of fusion welding defects on the mechanical performances of the joint, including tension strength [8] and burst strength [9], as well as bending, crushing, and fatigue performances [10]. The applied stress near the welded joint varies at various regions when the welded pipe suffers bend loading. Thus, the effect of welding defects on bending performance is determined by the defect locations. Therefore, in bend testing, the defect location should be carefully and properly determined to maximize the effect of defect existence on the pipe structural integrity. However, in the previous study [8-10], the defect location was chosen at the 12 o’clock position without any firm logic. Therefore, the effect of defect location on bend strength and local stress concentration for three point bend tests should be studied further to determine the proper location of welding defects in
the testing specimen.

In this study, a series of finite element analyses were conducted for various locations of the defect in the fusion weld of the pipes. Since the MDPE pipe suffers large deformations due to small Young’s Modulus, the local behavior near the defect can differ from the case with large Young’s Modulus. Therefore, the elastic deformation steel pipe was simulated first. Then, the large plastic deformation MDPE pipe was simulated. The maximum Mises stress near the defect was determined to study the effect of the defect on the local stress near the defect. In addition, the ratio of the max Mises stress near the defect of the defect specimen to the stress with no defect specimen at the same location (defined as $R$) was also determined.

2. Finite element modeling

Abaqus version 6.11 was used to simulate the three point bend test of welded pipe joint specimens, as shown in Fig. 1 (a). The outside diameter (O.D.) of the pipe was 110 mm and the wall thickness was 10 mm. The welding bead was retained in the specimen modeling to simulate actual application situations. Spherical geometry was modeled as the spherical defect. Air and steel were the two different kinds of defect materials simulated. In this paper, the defects are referred to as “air defect” and “steel defect,” respectively. The Young’s Modulus and Poisson’s ratio of the steel defect were 270 GPa and 0.3, respectively. The material properties of the welded joint were assumed to be the same as those of the pipe material. The defect size was 30, 60, and 90 % of the thickness, as shown in Table 1. The defect was located in the middle of the welded joint. The defect in the welded joint had three different locations, $\Theta = 0^\circ$, $90^\circ$, and $180^\circ$, as shown in Fig. 1 (b). Considering the geometrical symmetry of the specimen, only half of the specimen was modeled. One of the typical specimen models, consisting of 7956 C3D20R (20-node quadratic brick, reduced integration) elements and a spherical air defect at a defect location of $\Theta = 90^\circ$, is shown in Fig. 2. The loading pin and supporting pin were simulated as analytical rigid shells. Symmetry boundary conditions were applied to the symmetry plane. Load application was simulated by increasing the displacement on the loading pin. This increase in displacement was denoted as “applied displacement ($\delta_P$).”

To investigate the elastic deformation of gas steel pipes, the material behavior of the specimen was assumed to be ideal elastic-plastic. The Young’s

![Fig. 1. Schematic diagram for modeling the three point bend test.](image)

**Table 1.** Dimensions and geometries of the defects in fusion welded specimens.

| Planar Defect Width×Length×Height (mm×mm×mm) | Width/Pipe Thickness (%) | Spherical Defect Ball Diameter (mm) | Ball Diameter/Pipe Thickness (%) |
|-----------------------------------------------|--------------------------|-------------------------------------|---------------------------------|
| 0×0×0                                         | 0                        | 0                                   | 0                               |
| 3.0×3.0×1.0                                   | 30                       | 3.0                                 | 30                              |
| 6.0×6.0×1.0                                   | 60                       | 6.0                                 | 60                              |
| 9.0×9.0×1.0                                   | 90                       | 9.0                                 | 90                              |
Modulus, Poisson’s ratio, and yield stress were 206 GPa, 0.3, and 490 MPa, respectively, and they were the material properties of API 5L. Two kinds of defects (air defect and steel defect) were analyzed. The friction coefficient between the surfaces of the steel defect and the pipe specimen was fixed as 0.5.

To investigate the larger plastic deformation of gas pipes, the MDPE specimen was assumed, and the nonlinear elastic-plastic behavior obtained from the tension test was used [8]. The yield stress was 18.8 MPa. The Young’s Modulus and Poisson’s ratio were assumed as 1.1 GPa and 0.3, respectively. Only steel defect cases were analyzed. The friction coefficient between the surfaces of the steel defect and the MDPE specimen was fixed as 0.5.

3. Results and discussion

3.1. Small elastic deformation with API 5L steel specimens

The simulated results of the load-displacement curves of the three point bend test for the steel specimens are shown in Fig. 3. As we can see, the curves of the steel defect with a defect size of 90% of the thickness were almost the same as that of the no defect specimen regardless of the defect location ($\Theta = 90^\circ$). The load increased linearly as the applied displacement ($\delta_P$) increased for $\delta_P < 5$ mm. After that, the load slowly increased to the maximum load at $\delta_P = 13.5$ mm and then almost kept a constant. Other specimens with various defect sizes and defect materials had almost the same curves as that of the no defect specimen; thus, they are not shown in this paper.

The typical Mises stress distribution in the joint is shown in Fig. 4 for the no defect specimen, as are the air defect and steel defect specimens with a defect size of 90% of the thickness. When $\delta_P = 2.1$ mm, the compression side had higher stress than the tension side and the whole specimen was almost under the elastic stage for all specimens, such as shown in Fig. 4 (a) with $\delta_P = 2.1$ mm. Note how $\delta_P = 2.1$ mm in the linear part of the load-displacement curve shown in Fig. 3. The air defect specimen had the smallest stress distribution near the defect shown in Figs. 4 (b) - (d) with $\delta_P = 2.1$ mm. When $\delta_P = 13.5$ mm, the compression side and the tension side reached the yield stage and the local buckling (significant local deformation) appeared at the compression side for all specimens, such as shown in Fig. 4 (a) with $\delta_P = 13.5$ mm. The three specimens had almost the same stress distribution, but the air defect specimen had the largest stress distribution near the defect shown in Figs. 4 (b) - (d) with $\delta_P = 13.5$ mm. The region near the neutral
axis had the smallest stress in the whole bend period for all specimens. Since local bucking appeared in the compression side, failure occurred more easily at this location. This agreed with the experimental results of Østby  E. [11].

The typical effect of defect size on stress distribution near the defect is shown in Fig. 5 for the air defect specimens under the defect location of $\Theta = 180^\circ$ and $\delta_p = 2.1$ mm. We could see that the stress near the defect increased with increasing defect size in the symmetric plane. The max Mises stress near the defect is shown in Fig. 6. For $\delta_p = 2.1$ mm

$$\delta_p = 2.1 \text{ mm} \quad \delta_p = 13.5 \text{ mm}$$

(a) No defect (b) Local stress (no defect, $\Theta = 0^\circ$)

$$\delta_p = 2.1 \text{ mm} \quad \delta_p = 13.5 \text{ mm}$$

(c) Local stress (steel defect, 90%, $\Theta = 0^\circ$) (d) Local stress (air defect, 90%, $\Theta = 0^\circ$)

Fig. 4. Mises stress distribution in the joint of steel specimens.

(a) Air defect, 30% (b) Air defect, 60% (c) Air defect, 90%

Fig. 5. Variation of Mises stress distribution near the defect of steel specimens with air defects against defect size under the defect location of $\Theta = 180^\circ$ and $\delta_p = 2.1$ mm.

Fig. 6. Variation of max Mises stress near the defect against defect location for steel specimens.
2.1 mm, Fig. 6 (a) shows that the defect at the location of $\Theta = 0^\circ$ had the largest max Mises stress and the effects of defect material and defect size on the max Mises stress were ignorable when compared with that of the defect location. The effect of defect location on the max Mises stress was very small for $\delta_p = 13.5$ mm, as shown in Fig. 6 (b). What’s more, the air defect had larger max Mises stress than the steel defect in the defect location of $\Theta = 0^\circ$, as shown in Figs. 6 (a) and (b). Therefore, the defect location of $\Theta = 0^\circ$ is the best location for studying the effect of welding defects on the bend behavior of pipes, and the air defect is more dangerous than the steel defect in the compression side.

To study the seriousness of the defect effect on the local stress near the defect, the ratio $R$ of the max Mises stress near the defect of the defect specimen to the stress of the no defect specimen at the same location was defined. The larger the $R$, the larger the stress concentration induced by the defect. The max Mises stress near the defect and $R$ for all defect specimens are shown in Tables 2 and 3, and also in Fig. 7 under $\delta_p = 2.1$ and 13.5 mm. For $\delta_p = 2.1$ mm, as shown in Fig. 7 (a), the $R$ was almost independent on the defect location, and

| Table 2. Max Mises stress near the defect and $R$ at $\delta_p = 2.1$ mm for steel specimens. |
|---------------------------------------------------------------|
| Defect Location | Defect Size | Defect Size | Defect Size |
|                 | 30% | 60% | 90% | 30% | 60% | 90% | 30% | 60% | 90% |
| Max Mises stress near the steel defect (MPa) | 462.0 | 489.0 | 565.0 | 211.4 | 262.4 | 391.9 | 2.2 | 1.9 | 1.4 |
| Stress at the same location of no defect (MPa) | 489.0 | 565.0 | 489.0 | 262.4 | 391.9 | 391.9 | 2.2 | 1.9 | 1.4 |
| Ratio, $R$ | 2.2 | 1.9 | 1.4 |

| Defect Location | Max Mises stress near the air defect (MPa) | Stress at the same location of no defect (MPa) | Ratio, $R$ |
|-----------------|----------------------------------|----------------------------------|----------|
| 0º              | 531.6 | 567.5 | 527.0 | 225.0 | 221.4 | 319.6 | 2.4 | 2.6 | 1.6 |
| 90º             | 99.0  | 153.0 | 166.6 | 42.8  | 51.5  | 72.9  | 2.3 | 3.0 | 2.3 |
| 180º            | 287.0 | 312.1 | 324.1 | 159.3 | 153.9 | 153.8 | 1.8 | 2.0 | 2.1 |

| Table 3. Max Mises stress near the defect and $R$ at $\delta_p = 13.5$ mm for steel specimens. |
|---------------------------------------------------------------|
| Defect Location | Defect Size | Defect Size | Defect Size |
|                 | 30% | 60% | 90% | 30% | 60% | 90% | 30% | 60% | 90% |
| Max Mises stress near the steel defect (MPa) | 544.0 | 516.2 | 506.6 | 535.5 | 494.0 | 489.8 | 1.0 | 1.0 | 1.0 |
| Stress at the same location of no defect (MPa) | 516.2 | 506.6 | 516.2 | 494.0 | 489.8 | 489.8 | 1.0 | 1.0 | 1.0 |
| Ratio, $R$ | 1.0 | 1.0 | 1.0 |

| Defect Location | Max Mises stress near the air defect (MPa) | Stress at the same location of no defect (MPa) | Ratio, $R$ |
|-----------------|----------------------------------|----------------------------------|----------|
| 0º              | 520.7 | 539.9 | 586.3 | 492.1 | 501.2 | 444.0 | 1.1 | 1.1 | 1.3 |
| 90º             | 547.9 | 542.5 | 498.6 | 304.8 | 365.1 | 387.6 | 1.6 | 1.5 | 1.3 |
| 180º            | 520.7 | 539.9 | 586.3 | 492.1 | 501.2 | 444.0 | 1.1 | 1.1 | 1.3 |

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the $R$ of the air defect specimens seemed a little larger than those of the steel defect specimens. The $R$ decreased with increasing defect size regardless of the defect material when the defect location was $\theta = 0^\circ$ and $90^\circ$. The defect location of $\theta = 90^\circ$ had the largest $R$ under $\delta_p = 13.5$ mm, as shown in Fig. 7 (b). The contrast between Fig. 7 (a) and Fig. 7 (b) indicated that the $R$ decreased with increasing the $\delta_p$. Comparing Fig. 6 and Fig. 7, we found that the larger $R$ did not mean a larger max Mises stress near the defect region.

### 3.2. Large plastic deformation with MDPE specimens

The simulated results of load-displacement curves are shown in Fig. 8 for the no defect specimen and the steel defect specimens with various defect locations and a defect size of 90% of the thickness. As shown in Fig. 8, all the curves changed from non-linear to linear at the onset of the $\delta_p$. The non-linear stage was due to the deformation of the specimen, namely indentation [12]. When the $\delta_p$...
was increased to 155 mm, all curves came to the maximum load. The same phenomenon was found, as the load-displacement curve for the steel specimens was not affected by the defect size and location.

The typical Mises stress distribution in the fusion joint region is shown in Fig. 9 under various $\delta_p$ for the no defect specimen and the defect specimen with a defect size of 90% of the thickness and a defect location of $\Theta = 0^\circ$. All specimens were under the elastic stage when $\delta_p = 30$ mm because the stress was smaller than the yield stress (18.8 MPa), but the specimens were under the yield stage in the compression side for $\delta_p = 90$ and 155 mm, such as shown in Figs. 9 (a) and (b). The inner layer of the pipe wall had smaller stress than the inside wall and the outside wall in the compression side when the compression side was under the yield stage, as shown in Figs. 9 (a) and (b) with $\delta_p = 90$ and 155 mm, respectively. In general, the compression side had larger stress than the tension side regardless of the $\delta_p$. The most important was that the tension side was always under elastic stage because its stress was smaller than the yield stress, even though the compression side had already come to the yield stage and the deformation was very significant. This phenomenon was different from that of the steel specimens shown in Fig. 4. Thus, the specimen failed from the compression side.

The max Mises stress near the defect at various defect locations is shown in Fig. 10 for all specimens. As shown in Fig. 10, the max Mises stress at the defect location of $\Theta = 0^\circ$ was larger than that in other locations. The max Mises stress increased with increasing defect size and $\delta_p$. Therefore, the pipe fails more easily when there is a larger defect size in the compression side.

Max Mises stress near the defect and $R$ for all defect specimens are shown in Table 4 and Fig. 11 under $\delta_p = 30, 90,$ and 155 mm. As shown in Fig. 11, the defect location of $\Theta = 0^\circ$ almost had the smallest $R$ regardless of the $\delta_p$. For the defect location of $\Theta = 180^\circ$, the $R$ increased with increasing defect size. The effect of $\delta_p$ on the $R$ of the MDPE specimen was the same as the steel specimen in which $R$ decreased with increasing $\delta_p$. Therefore, the stress concentration induced by the defect decreased by increasing the applied load.
Based on the above analysis, we found that it was easier for the bend pipe to fail at the compression side because there was larger stress than in other regions or local buckling. Therefore, if the defect was located in the compression side, it was more dangerous than in other regions. In the compression side, the max Mises stress near the defect and the $R$ of the air defect were larger than those of the steel defect. In the tension side, they were almost not affected by the defect material. Thus, the air defect is more dangerous than the steel defect if the defect is located in the compression side. Finally, it is suggested that the defect should be located in the compression side in the three point bend test to maximize the effect of defect existence on the pipe structural integrity, and the effect of defect material on the integrity of pipes may need to be considered if the defect is located in the compression side.

4. Conclusions

The three point bend test of welded steel and MDPE pipe joints with defects of various defect locations and defect materials was studied using the finite element method. The following conclusions were obtained:

(1) Local buckling appeared in the compression side for steel pipes. For MDPE pipes, the tension side was mostly under the elastic stage, even though the compression side had already come to the yield stage, and the deformation was very significant. Therefore, under bend loading, it is easy for pipes to fail at the compression side, and the integrity of pipes with defects in the compression side is weaker than that in other regions.

(2) The max Mises stress near the defect and the stress concentration induced by the defect of the air defect were larger than those of the steel defect in the compression side, but they were almost not affected by the defect material in the tension side. Therefore, the air defect is more influential than the steel defect if the defect is located in the compression side.

(3) Based on the numerical results of this study, it is suggested that the defect should be located in the compression side in the three point bend test to maximize the effect of defect existence on the pipe structural integrity.
structural integrity. The effect of defect material on the integrity of pipes may need to be considered if the defect is located in the compression side.

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