Ultimate Strength Analysis of Three-Way Pipe Considering Plastic Reinforcement Effect

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Abstract. Considering the plastic reinforcement effect in materials, the plastic limit load of the three-way structure is analyzed. ANSYS commercial finite element software is used for numerical simulation. According to the results, the paper discusses the influence of the plastic reinforcement effect on the pipe's plastic ultimate load and failure mode. And the structure is further analyzed to verify the theory and design ideas in actual engineering. For improving the design and safety assessment of the three-way structure, the results provide a theoretical basis and a numerical reference, and the finite element method is economical than the experimental method. At last, it satisfies the accuracy requirements of engineering.

Keywords: Three-Way Pipe, Ultimate Strength, Plasticity, Finite Element Analysis.

1. Introduction
Three-way pipes are used in important industrial fields such as nuclear power, petrochemical, and metallurgy [1]. The failure of the three-way pipe often causes the entire system to be paralyzed, causing significant economic losses and even casualties [2]. Large openings, three-dimensional intersection, complex loads, and other factors lead to greater stress concentration. Under normal working pressure, the relevant area yields [3]. Tee structure is one of the weakest links of pressure-bearing devices and piping systems, and many serious accidents are caused by this. Thus, the strength design and safety assessment of the three-way pipe are of great significance in actual engineering. [4]-[5].

2. Modeling of the three-way pipes
Considering that the model is symmetrical in terms of structure, external load, and constraints, the author simplifies the three-way pipe into two ideal orthogonal cylinders. To reduce the computation, half of the model is selected for finite element analysis [6]. The internal pressure is applied to the inner surface of the model.
3. Simulation results of the three-way pipe

First, the equal diameter three-way pipe under internal pressure is analyzed. The mesh is divided as shown in Figure 1. The method by setting the unit type as a 20-node isoparametric unit (Solid95) and dividing it into 6000 ~ 8000 hexahedral units is established which reduce the calculation time and improve the calculation accuracy.

![Finite element model](image1)

**Figure 1.** Finite element model

The analysis results of the unreinforced orthogonal equal diameter three-way pipe are shown in Figure 2 and Figure 3.

![Structural stress under the maximum load substep](image2)

**Figure 2.** Structural stress under the maximum load substep
Figure 3. Structural strain under maximum load substep

The analysis results of the reinforced orthogonal equal diameter three-way pipe are shown in Figure 4 and Figure 5.

Figure 4. Structural stress under the maximum load substep
Figure 5. Structural strain under maximum load substep

Using the double elastic slope method to obtain the corresponding strengthened and unstrengthened ultimate loads are shown in Table 1.

Table 1. Comparison of finite element numerical solution and experimental solution

| d/D | D/T | t/T | D (mm) | P₀ | P₁ (MPa) | P₂ (MPa) |
|-----|-----|-----|--------|----|-----------|-----------|
| 1.0 | 29.57 | 1.0 | 207.0 | 11.26 | 9.17 | 11.60 |

Among them, $P₀$ is the experimental solution obtained by hydraulic blasting, $P₁$ is the finite element solution of the three-way pipe under ideal elastoplastic conditions, $P₂$ is finite element solution of the three-way pipe considering strengthening, $D$ and $d$ are main and branch pipe diameters respectively, $t$ and $T$ are thickness of the main and branch pipes respectively. Considering different pipe diameter ratios, the corresponding calculation results are shown in Table 2. ($D/T = 29.57, D = 207\text{mm}$)

Table 2. The finite element calculation results of the orthogonal three-way pipe

| d/D | t/T | $P₁$ (MPa) | $P₂$ (MPa) | $(P₂ - P₁)/P₁$ |
|-----|-----|------------|------------|----------------|
| 1.0 | 1.0 | 9.17       | 11.60      | 26.50%         |
| 0.8 | 1.0 | 9.34       | 11.73      | 25.59%         |
| 0.7 | 1.0 | 9.92       | 12.52      | 26.21%         |
| 0.6 | 1.0 | 10.63      | 13.71      | 28.97%         |
| 0.9 | 0.9 | 7.32       | 10.43      | 15.57%         |
| 0.8 | 0.8 | 7.85       | 9.97       | 14.78%         |
| 0.7 | 0.7 | 8.32       | 9.01       | 16.11%         |
| 0.6 | 0.6 | 8.83       | 8.46       | 18.12%         |

Some three-way pipes (oblique three-way pipes) with a certain angle between the main pipe and the branch pipe are sometimes used in engineering. The result of the unstrengthened three-way pipe with an angle of $75°$ are shown in Figure 6 and Figure 7. The processing method is the same as above.
The results of the strengthened three-way pipe with an angle of 75° are shown in Figure 8 and Figure 9.
When considering different angles between the main and branch pipes, the corresponding calculation results are shown in Table 3.

| $\alpha$ | $d/D$ | $D/T$ | $t/T$ | $D$(mm) | $P_1$(MPa) | $P_2$(MPa) | $(P_2 - P_1)/P_1$ |
|---|---|---|---|---|---|---|---|
| 75° | 1.0 | 29.57 | 1.0 | 207.0 | 6.32 | 8.16 | 29.11% |
| 60° | 1.0 | 29.57 | 1.0 | 207.0 | 3.58 | 4.39 | 22.63% |
| 45° | 1.0 | 29.57 | 1.0 | 207.0 | 2.01 | 2.55 | 26.87% |

4. Conclusion

(1) When $D/T=29.57$ and the thickness ratio ($t/T$) is constant, as the diameter ratio ($d/D$) increases, the ultimate load of the tee pipe has a decreasing trend. This is consistent with the conclusion that the plastic ultimate pressure of three-way pipes decreases with the increase of pipe diameter ratio in
engineering. When other conditions are certain, the ultimate bearing capacity of the tee pipe can be increased by increasing the branch thickness. This is consistent with the design idea that three-way pipes with thicker branch pipes are prior.

(2) As the angle between the main and branch pipes decreases, the stress concentration in the intersecting area of the oblique three-way pipe is more severe than that of the orthogonal three-way pipe. The ultimate pressure load of the tee pipe decreases, and the change is more severe than the above two cases. The yield zone appeared on the side of the angle (<90°). Then a plastic zone is formed along the intersecting line and expands to the outer wall of the abdomen. The plastic zone of the strengthened oblique tee pipe extends slowly.

(3) The value of \(\frac{P_2 - P_1}{P_1}\) is between 15% and 30%. This result shows that the plastic ultimate pressure load considering plastic strengthening is higher than that under the ideal elastoplasticity. This provides a theoretical basis and numerical reference for improving the use of materials, enhancing the design of the three-way structure and safety assessment.

Acknowledgments
This work was financially supported by the MOE Key lab of Disaster Forecast and Control in Engineering (20180930008), Jinan University.

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