Ultimate Strength Analysis of Local Thinning Tee Pipe Considering Plastic Strengthening Effect

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Abstract. In this paper, the locally thinned three-way structure under internal pressure is analyzed based on the theory of plastic strengthening effect and limit analysis. A finite element model is presented through ANSYS commercial software to simulate the mechanical properties of orthogonal and oblique three-way structures. This paper systematically analyses how the shape and size of the thinning effect the plastic limit load of the pipe and what is the typical failure mode of plastic failure. Some valuable conclusions are drawn, which provide a useful reference for the design and production of the tee pipe.

Keywords: Tee Pipe, Ultimate Strength, Finite Element Analysis, Local thinning.

1. Introduction
The three-way pipe is an indispensable part of the piping system, and it is the most likely part to be damaged and cause various accidents as well [1]-[2]. Due to the stress concentration caused by the discontinuous geometric structure, it may reach or be over the yield state in some areas during operation [3]. Fluid scouring, medium corrosion, and fatigue loading make the tee pipe likely to cause serious damage such as pits and local thinning [4]. This paper presents the study on the ultimate load of the tee pipe with local thinning. It provides an important reference for enhancing the safety and reliability of the three-way pipe operation, reducing unnecessary equipment loss, repairs, and corresponding shutdown losses [5].

2. Modeling of the three-way pipes
To simplify the problem, we simplified the welded tee into two orthogonal intersecting cylinders. The trapezoid-like thinning with a smooth transition from the periphery to the center is used to describe the local thinning of the tee. It avoids stress concentration caused by sudden changes in the thinning shape. The model is a symmetrical structure, so to reduce calculations, The author selects half of the model for finite element analysis. The internal pressure is uniformly applied to the inner surface of the model.
The mechanical model and meshing are shown in Figure 1 and Figure 2. In the figure, \( L \) is partial thinning of the axial half-length, \( A \) is partial thinning of annular half-angle, and \( B \) is thinnest part after partial thinning. For the convenience of calculation and analysis, this paper define dimensionless parameters of local thinning as: axial length of local thinning \( l=2L/D \), thickness of the thinnest part \( b=B/T \), circumferential length \( a=A/90 \) [7].

![Figure 1. Local thinning model of orthogonal tee pipe](image1)

![Figure 2. Meshing model of tee pipe](image2)

3. Simulation results of the three-way pipe

The twofold elastic slope method is used to get the ultimate load of orthogonal equal-diameter three-way pipes with different degrees of thinning. The resulting analysis of the tee with thinnest thickness \( b=0.875 \) is shown in Figure 3 and Figure 4.
The next step is to use the theoretical solution of the limit load of the straight pipe with the same diameter as the tee main pipe, and normalize the limit load of the tee. The formula is the theoretical solution for the ultimate load of straight pipes. The ultimate pressure ratio $P_{L0}$ in Figure 5-7 is the ratio of the ultimate load $P$ to $P_{L0}$.

$$P_{L0} = 2\sigma_t T/D$$
Figure 5. Influence of axial length on the ultimate load

Figure 6. Influence of annular length on ultimate load

Figure 7. The influence of the thickness at the thinnest point on the ultimate load
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. At present, the research work on the ultimate pressure load of the oblique thinning tee pipe has not yet started. This article discusses the oblique tee pipe with the angle between the main and branch pipes of 75°. The applied load is still internal pressure, and the form of thinning is still a local large-area thinning. The meshing model of the oblique tee pipe with an angle of 75° is shown in Figure 8. The resulting analysis of the tee with the thinnest thickness $b = 0.875$ is shown in Figure 9 and Figure 10.
Figure 10. Structural strain under maximum load substep

The ultimate load $P$ is normalized.

Figure 11. Influence of annular length on ultimate load (oblique intersection)

Figure 12. Influence of axial length on ultimate load (oblique intersection)
4. Conclusion

(1) The limit load of the local thinning tee decreases with the increase of the axial length and annular length, and it increases with the increase of the thickness of the thinnest part. Among them, the thickness at the thinnest point has the greatest influence on the rate of change of the ultimate load, while the axial length and annular length have relatively little influence. At a certain degree of thinning, increasing the axial length and the annular length have little effect on the ultimate load. When the thickness of the thinnest part reaches a certain value, the load-bearing capacity of the structure is significantly weakened.

(2) When the degree of thinning of the orthogonal tee pipe is small, the corners in the longitudinal plane of the intersecting zone yield first. As the pressure increases, the yield zone expands toward the shoulders, and then slowly develops in the thinning zone. In this case, the failure of the tee first occurs in the intersecting area, and the effect of the thinning on the ultimate load can be ignored. When the degree of thinning is large, the central part of the thinning zone almost simultaneously yields, and then the plastic zone will expand to the surroundings. At this time, the thinned part of the tee leak locally, and its failure mode is a partial failure instead of overall failure.

(3) The oblique tee is an asymmetrical structure. The stress concentration in the intersecting area is more severe than that of the orthogonal three-way, and the ultimate pressure of the three-way is smaller. The side of the angle (<90°) between the main and branch pipes yield first. When considering plastic strengthening, the smaller-thinned tee yields first on the side of the corner in the longitudinal plane of the intersecting zone. In this case, the failure of the tee first occurs on the side of the angle of the intersecting zone, and the effect of the thinning on the ultimate load can be ignored. When the thinning is large, the central part of the thinning zone almost simultaneously yields. Then the plastic zone expands around. At this time, it will also cause local leakage at the thinned part of the tee.

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