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Effect of the Internal Pressure and External Loads on Nozzles in Cylindrical Vessel

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Abstract. Understanding the potential for supporting the maximum loading conditions in the system is a key feature in the design and analysis of pressure vessel applications. This is especially important for thin-walled pressure vessels, when stresses even reaching the initial material yield point could lead to very dangerous situations. Pressure vessels may be subjected to stresses arising from a variety of loading conditions including internal pressure and multiple external loads from attached piping systems. Once the yield point has been exceeded, the structure can accommodate more loading until the plastic zone becomes excessive leading to plastic collapse. This can be challenging to establish especially when external loads act in tandem with internal pressure. Therefore, this paper develops a finite element method for the limit load analysis of a single-nozzle cylindrical pressure vessel under internal pressure and external loading in a variety of combinations. Thereafter, a parametric study is presented covering various loading conditions, both singly and in combination. Finally, a comparison is made shown the interaction effects of the effects on the limit load for changes in vessel geometry and appropriate conclusions drawn.

1. Introduction

Cylindrical structures with transverse openings are often used in pressure vessel technology. Local stresses occur especially in these intersection regions due to external loads and internal pressure. There are many theoretical solutions in the literature for the determination of local stresses which use shell theory and also finite element approaches. Xue et al [1] argue that despite the various analytical approaches and mathematical solutions to various problems in the literature, development is still needed for branch junction procedures. Xue et al. provide theoretical solutions related to external loading for two intersecting cylindrical structures. The proposed approaches are in agreement with the finite element method and WRC Bulletin 297 [2] which is a thin shell based solution, widely used in industry, but only provides shell-type stresses in the vessel and nozzle.

In pressure vessels with nozzle connection, the nozzle shell connection areas are the areas where the weakest points are due to the presence of stress concentrations arising from the intersection cut. The radius ratios d/D are important and shell theory is reliable for d/D <0.3 but has weaknesses when this rises to 1.0. It is noted that much of the literature is based on establishing the elastic stress solution with little available on limit load calculation for multiple load combinations. Sang et al. [3], attempted to obtain the results of inelastic stress analysis of a pressure vessel and nozzle connection with radius ratios of 0.526 (d/D = 0.526). These results were solved under increasing internal pressures with the help of experimental studies and nonlinear finite element methods (FEM). The analyses were supported by experimental studies to demonstrate limit loads originating from internal pressure and to compare with the results of the FEM. In addition, a burst testing was carried out to understand and validate the limit design method. In addition, the authors stated that this method does not require the elastic analysis stress categorization procedure. They also signified that the applicability of method was much simpler than the elastic design procedure.

In other studies, Mackenzie and Li [4] proposed an alternative solution to find the permissible plastic load in the pressure vessel design with the analysis approach. A three-dimensional finite element analysis was performed for cantilever beam in bending and nozzle combinations to examine the problem. Then internal pressure, torque and combined loads were applied on a cylindrical vessel with a single nozzle. TES (Twice Elastic Slope) Criterion, PW (Plastic Work) Criterion and TI (Tangent Intersection) Criterion were used to compare the proposed approach. As a result of the study, when the material shows strain hardening, higher plastic load values were obtained according to the currently available methods.

The ‘elastic compensation method’ used by Nadarajah et al. [5] was used for internal pressure and moment loading conditions in nozzle cylinder connections. With this method, limit and shakedown intersection diagrams can be obtained. In addition, the mentioned method was used to determine the upper and lower limit of the nozzle cylinder junction. The main objective is to investigate a highly complex vessel problem for the nozzle-cylinder intersection under the internal pressure and the nozzle subjected to torque loading. In conclusion, it is stated that the obtained results were compared with the existing methods and better values were obtained.

Furthermore, Dekkert and Stikvoort [6] conducted research on the stress intensities for the nozzle - cylinder connection. After reviewing the existing standards, some standards such as the PD5500[7], the German AD-Merkblatter [8] and the Dutch Rules for Pressure Vessel have been suggested that it is unreliable for thin-walled and relatively large nozzles. Thereupon the authors determined the purpose of the study as to provide the significant differences between the existing design codes and standards when calculating the stress intensity occurring at the nozzle-cylinder junctions. For this purpose, they compared the results using the existing design codes and finite element method. The proposed analyses have allowed for a more reliable calculation of the external loads on the nozzle.

As such, in this study, a finite element approach is used to develop a suitable model and undertake a parametric limit loads study for cylinder - cylinder intersections subject to internal pressure and combinations of external loads which will lead to an improved design approach.

2. Statement of the Problem

Establishing the maximum loading conditions to be applied in any pressure vessel is of great importance. Traditional design sets a limit on the membrane and membrane plus bending stresses but it is preferable to establish the limit load and thereafter apply a suitable factor of safety. It is desirable to establish the limit load for the system and to thereafter apply a suitable factor of safety. By means of proving the technique, simple closed form limit load calculations for a perfect cylinder are used to verify the FEM approach. In their previous work, Bozkurt et al. [9] proposed a high-fidelity model approach for the cylinder nozzle combination exposed to external loads in the elastic region. As a continuation of this study, a parametric limit load study will be introduced as described in the following steps.

3. Finite Element Model

The finite element program ANSYS [10] was used to simulate the limit load analysis for internal pressure and external loading. An accurate and reliable FEM for nozzle - cylinder interactions has been presented and the details of the FEM approach have also been described in Bozkurt et al [9]. SA-516 Grade 70 Carbon steel pressure vessel plates were selected as the shell material in the analyses to be performed. The material has a Young modulus of 200GPa and a Poisson ratio of 0.29. ASTM A266 Grade 2 Carbon Steel was selected for the nozzle material. Young modulus of the nozzle material was 190GPa and Poisson ratio was 0.29. Yield stress of the shell and nozzle were 260MPa and 290MPa respectively.

In addition, a high fidelity model approach has been introduced with a detailed parametric study on Finite Element Modelling [9]. In the validation study on the model, very close results were obtained

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with studies in the literature (approximately 1% difference). In addition, parametric results obtained with the same model were compared with WRC 537[11] good agreement achieved.

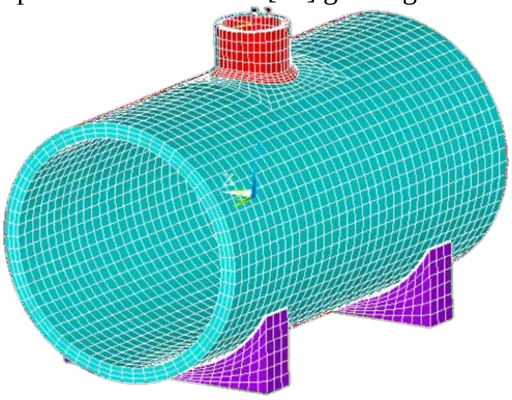

Figure 1. Perspective view of the meshed model

4. Verification of Finite Element Model

While the verification of the model was carried out, the results obtained from the finite element method as well as mathematical methods were used. These results were obtained in 3 stages. Firstly, the maximum internal pressure that the model can carry is examined. Then, the maximum tensile loading status was examined. Finally, the moment effect that will occur as a result of local loads on the nozzle is taken into consideration. The verifications are explained in detail below. For each validation study, the yield stress (σ_y) of the shell was 260MPa, the inner radius of the shell was 250 mm and shell thickness was 33.5mm. Also, the yield stress (σ_y) of the nozzle was 290MPa, the inner radius of the shell was 62.5mm and nozzle thickness was 15mm.

4.1. Verification of limit load for internal pressure and external loading applications

This verification study was carried out only for a single nozzle cylindrical vessel subjected to internal pressure. As can be seen in the Figure 1 an open end model was used and the movement was restricted to the bottom of the saddle. The friction force between the saddle and the nozzle was determined as 0.45. Taking into account the Perfect Plasticity and Tresca criteria, the force and limit required for the initial yield to be realized can be calculated by the following equation (1) and equation (2). Since the yield point of the shell is smaller than the nozzle, the calculations will be made to obtain the limit load in the shell.

$$\text{First yield:} \quad p_y = \frac{\sigma_y}{2}\left(1 - \left(\frac{r_i}{r_0}\right)^2\right). \tag{1}$$

$$\text{Limit load:} \ \ p_l = \sigma_y \ln\left(\frac{r_i}{r_0}\right). \tag{2}$$

Table 1. Comparison the limit load results for internal pressure and external loading

Loading Type	Hand Calculations	FE Results	Difference
Internal Pressure ($P_{int\text{-}max}$)	32.604MPa	30.333MPa	**6.90%**
Moment Effect (Vx_{max})	6773.17kN	6640kN	**1.96%**
Tensile Loading (P_{max})	19132kN	19333kN	**1.04%**

The difference between the results obtained from the finite element model and the mathematical results that can be seen in the table is approximately 2%

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5. Parametric Studies

In the parametric studies, a single-nozzle pressure vessel fitted on the saddles will be used. Nozzle and shell sizes will vary according to the parameters to be applied on the structure. The model is restricted to the movement in each direction with the boundary conditions under the saddle. Internal pressure and external loading conditions are the variables to be used in the studies. A cylindrical pressure vessel with a single nozzle connection was used for parameter studies. Maximum internal pressure or local loads will be analysed for different cases. The local loads to be applied are represented in Figure 2.

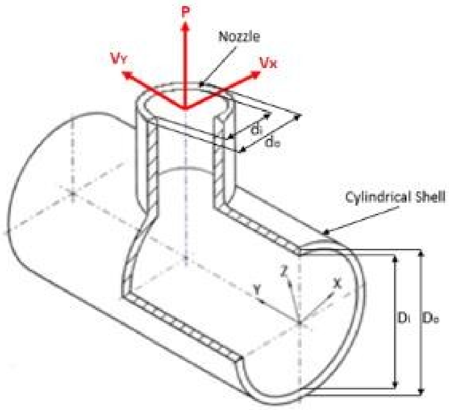

Figure 2. Load conventions for the model

5.1. Loading cases

5.1.1. 1st Case - Changing nozzle thickness. In this study, cylinder sizes for 1 nozzle cylinder combination remained constant for all analyses (D_i= 500mm, D_o = 530mm). Nozzle internal diameter (d_i) is fixed at 125mm. Nozzle thickness (t) is increased by 5 mm in each analysis. In the first case, there is no external load apply to the FEM. In the other case, the external loads affect the system from the nozzle centre. There is a 100kN loading at the same time in X, Y and Z directions. The structure is exposed to combined external loads and it is intended to be found with the limit internal pressure finite element approach. In both cases, an increase in maximum internal pressure values that can be applied in each 10 mm thickness increase was observed in a similar manner.

When the results are examined, the increase in wall thickness caused an increase in the limit pressure values in both cases. If both cases compare within themselves, the limit load is higher only in the case of 'no external load' at 5mm wall thickness, while the limit pressure is higher in the external load application after 15mm. As a result, it can be said that the effect of external loading on the limit load values is less at low thicknesses. In addition, as can be seen in the graphic on the right, the difference for both cases is approximately 4 percent for each thickness.

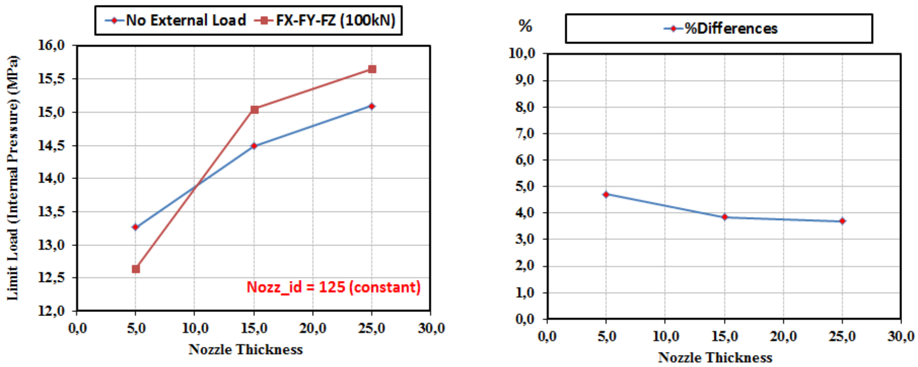

Figure 3. Comparison of the limit loads for changing nozzle thickness

5.1.2. 2nd Case - Changing shell thickness. In this study, the nozzle sizes were kept constant for the same model (d_i = 125mm, d_o = 155mm). Cylinder thickness can be seen from the Figure 4. as well as 5 mm increased in each analysis. Similar to the previous study, the internal pressure was determined by FEA as the maximum resistance of the model which was not exposed to any external load.

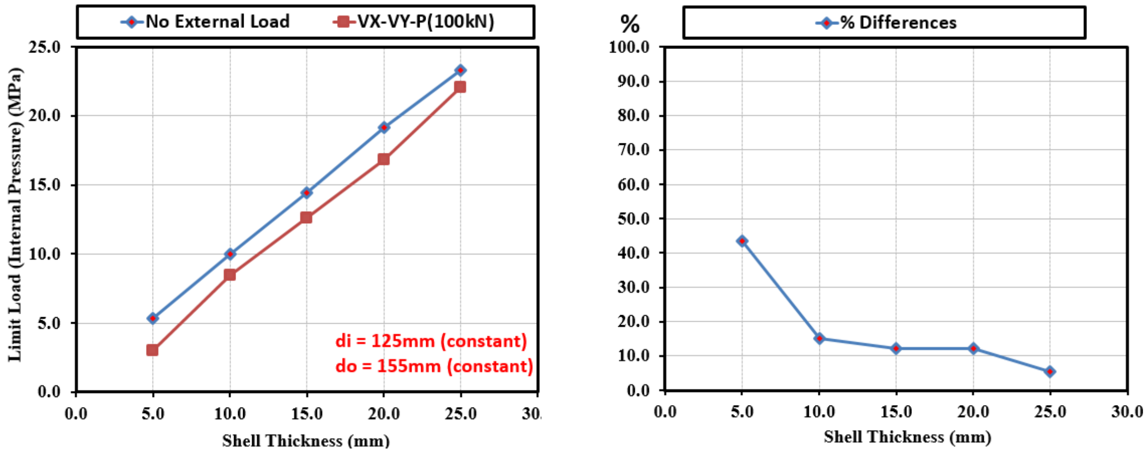

Figure 4. Comparison of the limit loads for changing shell thickness

Subsequently, 100kN loading was performed in 3 directions (Vx, VY, P) at the same time to be nozzle centred. In both cases, as the thickness of the shell increases, the strength of the structure increases and the limit increases linearly. In the case of external loading, the limit will be even less for the internal pressure with the effect of local loads. This difference is approximately 45% for 5mm wall thickness. As the nozzle thickness increases, the limit pressure difference decreases gradually. Values for each case are given in the Figure 4.

5.1.3. 3rd Case - Applying external loading for only 1 direction. For this study, internal pressure values are used as constant values. First of all, a model that was not exposed to internal pressure was used. Then, the internal pressure was increased by 5MPa in each analysis. All analyses were performed with the same dimensions. A single external load is used for each case. Limit external load values are independent of each other for X, Y and Z directions.

In pressure vessels, the internal pressure leads to circumferential and longitudinal stresses on the shell. Likewise, the radial tensile load (P) applied in the Z direction contributes to the longitudinal and circumferential stresses on the shell. Stress calculations due to radial tensile loading are given in detail in WRC537 Bulletin. When these calculations in the Bulletin are taken into consideration, as the internal pressure increases, the radial load will decrease in each step since the limit will be approached further. As can be seen from the Figure 5, the radial load decreased by approximately 30% for the 20MPa internal pressure increased.

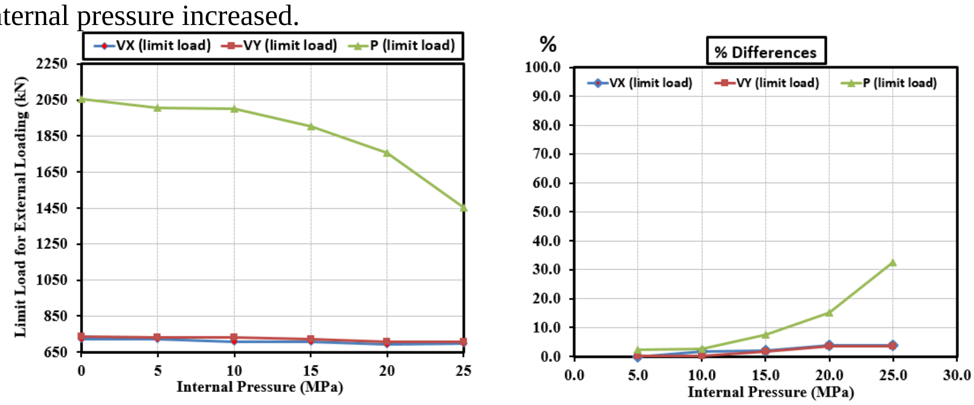

Figure 5. Comparison of limit loads for external load applied separately in 1 direction

5.1.4. 4th Case - Applying combined external loading. This study is very similar to the method described in Case 3, with the only difference is that combined loading from 3 directions are applied to the centre of the nozzle at the same time. The external load is fixed and 100kN for each direction.

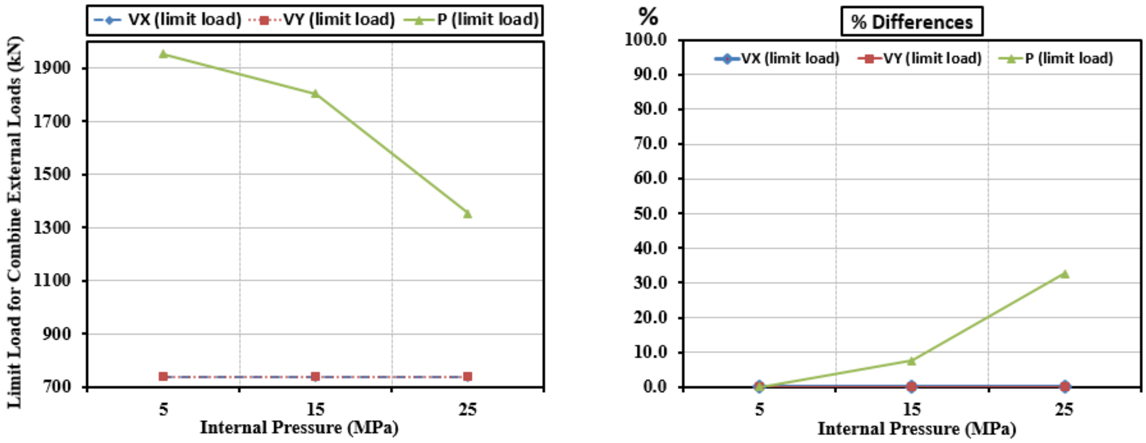

Figure 6. Comparison of limit loads for external load applied together all in 3 directions

The results of the FEA obtained for internal pressure are shown in the Figure 6. The maximum limit pressure differences for VX and VY loadings are approximately 1%, but the difference for tensile limit loads (P) is approximately 32%.

As a result, very similar results were obtained with Case 3. If the 3rd and 4th cases are compared, it can be said that a more minimal difference is observed when the longitudinal and circumferential shear forces are applied together. In other words, changing in the internal pressure are almost unaffected by the combined limit shear forces.

6. Results and Discussions

The parametric study was completed in four main stages. Firstly, the thickness of the nozzle is kept constant and the maximum applied internal pressure value is determined. In addition, the same analyses were repeated with the effect of combined external forces on the nozzle.

In the second case, with a similar approach, dimensional changes were made on the main body by keeping the nozzle dimensions constant. The thickness of the cylinder was increased by 5mm in each analysis. As can be seen in the limit pressure calculations in pressure vessels, the most important variable is the inner and outer diameter ratio. As a result of this approach, when the thickness increases, the limit load increases linearly.

In Case 3, the internal pressure values were increased by 5MPa in each analysis and limit loads were determined for external loading conditions. In the stress calculations of shear force, Bijlaard's [12] calculation approaches were shown in WRC537. According to this approach, the shear forces acting on the nozzle do not cause longitudinal and circumferential stresses in the shell. Therefore, the increase in pressure inside the vessel reduces the shear limit forces to a very small extent (approx. 3%). As a result of this analysis, it was observed that the longitudinal (V_L) and circumferential (V_C) shear forces transfer the material to the plastic region at much lower values. On the Z axis, tensile loading (P) was involved. Tensile loading directly affects the longitudinal and circumferential stresses on the shell [2]. For this reason, to transfer this material into the plastic zone, approximately 3 times more load should be applied. Therefore, tensile limit load values tend to decrease as the internal pressure increases. These results were consistent with the current approach.

Finally, in Case 4, a study similar to Case 3 was conducted. A loading was performed on the nozzle in 3 axes. For each loading state, the loading values were 100kN for 2 axes and the internal pressure value is fixed. Limit load value was tried to be found for the other axis. As a result, the biggest difference was again with tensile loading of about 32 percent. The results were obtained in a manner similar to the case 3 and are quite consistent with the existing approaches.

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7. Conclusions

As a result of this study, a comprehensive parametric study was obtained for a nozzle - cylinder combination which was subjected to internal pressure and external loading conditions. By comparing the existing mathematical calculations with the finite element method, the reliability of the results has been demonstrated. In further studies, additional modifications such as reinforcement plates can be added to the existing model to enhance the results. Limit load analyses can also be performed related to cyclic loads. In the end of all these studies, it is aimed to develop a universal finite element analysis approach leading to a closed form set of equations that can resolve many cylinder-cylinder combinations.

Acknowledgements

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8. References

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