Study and analysis of the influence of stresses arising in a damaged thin-walled cylindrical container during compression

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Abstract. The subject of the article is important today; it is concerned with study of the effect of stresses, which occur in thin-walled cylindrical containers, such as tanks of fuel-servicing trucks, tankers, railroad tankers, and other containers operated under pressure, which are utilized in various sectors of the national economy. The goal of the undertaken researches is study and analysis of the effect of stresses, which occur in a thin-walled cylindrical container as a result of an inclined dent. Test results showed that during study of the effect of stresses, which occur in the damaged area of a thin-walled cylindrical container, it was discovered that their values depend on the angle of the dent’s edge with respect to the container. Moreover, stresses in the damaged area decrease with an increase of the angle and maximum values occur when axes of a dent’s edge and container are parallel with each other. Timely maintenance by applying metal bands to the damaged area greatly decrease stresses, especially if rhomboid bands are used.

1. Introduction

Containers and plants are the key elements of process equipment operated in chemical and oil refining industries.

The most commonly used form of containers is a cylindrical capsule with two closing elliptical heads.

Many of such constructions may have various defects, such as dents, lumps that are the most prevailing defects and account for more than 25% of the total defects [1,4].

Following the conducted analysis of dimensions and forms of dents, the conclusion was made: basically, dents are of round and elliptical form. The depth of a dent is between K1 = 1÷2 thicknesses (let alone huge uncommon containers having radius to thickness ratio γ = 1072,9) and, on average, may be taken as γ = 100. As a rule, dents occur during transportation and/or operation when a container interacts with various objects with a higher degree of hardness.

Small containers are commonly exposed to impact of stresses due to their large surface and easy deformation of their thin walls; that is why it is important to consider the risk of wall deformation of such containers and to study their damages by calculating and analyzing maximum stresses in the deforming area [5-7].

Containers are classified depending on their wall thickness: Thick-walled and thin-walled. A container may be classified as thin-walled, if the following ratio is observed between its thickness (t) and diameter (D):

\[ t \leq 0,1D \]
Correct construction of a solid computer model of a cylindrical container and metal bands of various geometric forms, of a bond between a container and a corresponding bend, and of load application are essential to conduct researches.

Workability of such model depends on different factors, such as: container surface thickness; the material, of which a containers is made, and its properties; load appliance to internal surface of a container; imposing required constraints on a rod model only at one end of a container with an option to expand sides and perimeter; breaking up a program solid model into end superficial elements, and making direct calculations [8-12].

According to prime engineering dependences, strength assessment of damaged containers is possible only within certain limits of allowable deviations from a canonical form of a dent’s geometry (a circle, an ellipse, a rectangle).

In case of significant difference of a dent’s form from a canonical one, a detailed analysis including complete account of its topology, geometrical and physical nonlinearity of problem is required. Such analysis is possible only by applying numerical methods such as the finite element analysis, which is currently the most developed method realized in ANSYS software package [1,6].

2. Goal of research
To consider changes of maximum stress in the area of a dented thin wall of a cylindrical container, compressed at the angle of a normal crease edge with a container axis (figure 1), as well as an opportunity to reduce stress values in this area by closing the damaged area with bands of various geometry and dimensions, which ensure maximum decrease in stress values. In the course of this study, stresses, which occur under compression of thin walls of a cylindrical container, are considered using the finite element analysis as well [1]

![Figure 1. Inclination of a dent’s crease.](image)

Theoretical mathematical laws were applied to consider and calculate stresses in a thin-walled cylindrical container under compression without deformation. Comparative study of the received values and values resulted from the finite element analysis was conducted using a container’s program model and ANSYS program [6].

3. Applying of the finite element analysis
Peripheral, axial and diagonal stresses, which occur in thin walls of containers having the diameter of D and the wall thickness of t, are affected by inner pressure as follows:

- axial stress - \( \sigma_a \) occurs when a container is closed 2a) peripheral\( \sigma_t \) and diagonal stresses\( \sigma_r \) are considered to be insufficient 2-b):

\[
\sigma_a = \frac{pD}{4t}; \quad \sigma_t = \frac{pD}{2t}; \quad \sigma_r = 0
\]
Parameters of a container used during the test:

- Diameter $D = 500$ mm, length $L = 500$ mm, thickness $t = 1$ mm, internal pressure $p=0.1$ MPa, elastic coefficient $E = 200000$ MPa, Poison's ratio $\mu = 0.3$.

According to the performed theoretical calculations, the following values of $\sigma_t$ and $\sigma_a$ are received:

- peripheral stress is caused by pressure of the following value:
  \[ \sigma_t = \frac{pD}{2t} = \frac{0.1 \times 500}{2 \times 1} = 25 \text{ MPa} \]
- axial stress, caused by internal pressure, has the following value:
  \[ \sigma_a = \frac{pD}{4t} = \frac{0.1 \times 500}{4 \times 1} = 12.5 \text{ MPa} \]

Calculation with the use of the finite element analysis requires creation of a container model, which is constructed by applying ANSYS program and represented in figure 3-a.

Then this program was used to finish the process of the analysis in according with the following procedure:

- to define the type and action of the operation;
- to define the thickness of a container's surface;
- to define the material, of which the container is made, and its properties;
- to apply the load of 0.1 MPa to the internal surface of the container;
- to impose required constraints on a rod model only at one end of a container with an option to expand sides and perimeter;
- to break up a program solid model into end superficial elements, and making direct calculations, as illustrated in figure 3-b;
- to conduct calculations and to obtain results.

Calculation results made with the use of the finite element analysis for peripheral and axial stresses are illustrated in figures 3-c and 3-d.
In Table 1, we can see results of calculations that are received for a wall of the central area of a container with the use of the finite element analysis and those performed according to theoretical ratio.

| Diagonal stresses, MPa | Axial stresses, MPa | Peripheral stresses, MPa |
|------------------------|---------------------|--------------------------|
| Exterior surface       | Internal surface    | Exterior surface         | Internal surface |
| 0                      | 0                   | 12.5                     | 12.5             |
| 12.52                  | 12.52               | 24.906                   | 25.06            |

Results in Table 1 show the convergence of theoretically calculated values and values received applying the finite element analysis. It confirms the validity of this method for stress analysis of thin-walled containers.

3.1. Stress analysis in a damaged thin wall of a cylindrical container compressed before maintenance

At this stage of the research agenda the finite element analysis (4) will be applied to receive values of von Mises equivalent stress and values of maximum shear and deformation stresses in the damaged area at five different values of its inclination angle between axes of a dent’s edge and container.

3.1.1 Where the angle between the dent’s edge axis and the cylindrical container’s axis is \( \theta = 0^\circ \). Figure 4-a illustrates the program model of a cylindrical container with a dent, the edge of which makes the angle \( \theta = 0^\circ \) to the container’s axis. Figure 4-b illustrates the finite element mesh in the dented area. Figure 4-c illustrates the calculation result for distribution of stresses and their values in the dented area.

![Figure 4](image1.png)

**Figure 4.** a) the dented container’s model, where the angle between the dent’s edge axis and the cylindrical container’s axis is \( \theta = 0^\circ \); b) the mesh in the dented area c) the calculation result for distribution of stresses and their values in the dented area.

3.1.2 Where the angle between the dent’s edge axis and the cylindrical container’s axis is \( \theta = 30^\circ \). Figure 5-a illustrates the program model of a cylindrical container with a dent, the edge of which makes the angle \( \theta = 30^\circ \) to the container’s axis; figure 5-b represents the mesh in the band’s area; figure 5-c illustrates distribution of stresses and their values in the dented area.

![Figure 5](image2.png)
3.1.3. Where the angle between the dent's edge axis and the cylindrical container's axis is $\theta = 45^0$. Figure 6-a illustrates the program model of a cylindrical container with a dent, the edge of which makes the angle $\theta = 30^0$ to the container’s axis; figure 5-b represents the mesh in the band’s area; figure 5-c illustrates distribution of stresses and their values in the dented area.

Figure 5. a) the dented container’s model, where the angle between the dent’s edge axis and the cylindrical container’s axis is $\theta = 30^0$; b) the mesh in the dented area c) the calculation result for distribution of stresses and their values in the dented area.

3.1.4 Where the angle between the dent’s edge axis and the cylindrical container’s axis is $\theta = 60^0$. Figure 7 illustrates the program model of a cylindrical container with a dent, the edge of which makes the angle $\theta = 60^0$ to the container’s axis; figure 8 represents the mesh in the band’s area; figure 5-c illustrates distribution of stresses and their values in the dented area.

Figure 6. a) the dented container’s model, where the angle between the dent’s edge axis and the cylindrical container’s axis is $\theta = 45^0$; b) the mesh in the dented area c) the calculation result for distribution of stresses and their values in the dented area.

Figure 7. a) the dented container’s model, where the angle between the dent’s edge axis and the cylindrical container’s axis is $\theta = 60^0$; b) the mesh in the dented area c) the calculation result for distribution of stresses and their values in the dented area.
3.1.5 *Where the angle between the dent’s edge axis and the cylindrical container’s axis is* \( \theta = 90^\circ \). Figure 8-a illustrates the program model of a cylindrical container with a dent, the edge of which makes the angle \( \theta = 90^\circ \) to the container’s axis; figure 8-b represents the mesh in the band’s area; figure 8-c illustrates distribution of stresses and their values in the dented area.

**Figure 8.** a) the dented container’s model, where the angle between the dent’s edge axis and the cylindrical container’s axis is \( \theta = 60^\circ \); b) the mesh in the dented area c) the calculation result for distribution of stresses and their values in the dented area.

Table 2 shows values of maximum equivalent stress, shear and deformation stresses in the damaged area for each case studied.

**Table 2.** Values of maximum equivalent stress, shear and deformation stresses in the damaged area.

| Edge inclination, degrees | \( \theta = 90^\circ \) | \( \theta = 60^\circ \) | \( \theta = 45^\circ \) | \( \theta = 30^\circ \) | \( \theta = 0^\circ \) |
|--------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Maximum equivalent stress, MPa | 81.01 | 122.32 | 159.58 | 206.72 | 258.27 |
| Shear stress, MPa | 45.65 | 68.62 | 88.74 | 117.05 | 147.6 |
| Deformation, mm | 0.18 | 0.192 | 0.208 | 0.231 | 0.257 |

It should be noted that the deformation value is highly approximate and negligible compared with the original model for all studied cases. Note the fact that the stress values considerably decrease with an increase of the angle of a dent’s edge in the dented area with respect to a container. The stress values in a rigid cylindrical wall, which have been studied in points 1 to 3, are shown in table 1.

Figure 9 shows diagrammic reflection of stress change to the damaged area of a container during compression, obtained as the angle between the dent edge axis and the container’s axis.

**Figure 9.** Graphic representation of changes in stresses in the dented area at the different inclination angles between the dent’s edge axis and the container’s axis.
Results represented in table 2 and figure 18 show that the highest risk is a dent located in parallel to the cylindrical container’s axis, and the minimum risk is a dent located normal to its axis.

3.2. Stress analysis in a damaged thin-walled cylindrical container compressed after maintenance services

At this stage most of the focus is on the model of a thin-walled container, calculation of which results in the largest stress and deformation values at the previous stage. Axes of a dent and container are parallel with each other in this model.

There are relatively many ways to reinforce the damaged areas, for example:
- to apply a band inside a container what is difficult to realize;
- to delete the damaged area by cutting off and welding a new band, which conforms the shear area;
- to delete the damaged area by cutting a container and covering a dent with a metal band by means of special paste, adhesive, or solder alloy;
- to repair the damaged area by deposition with strain-hardening metal.

At this stage it is important to consider the fact that the damaged area of a cylindrical container is reinforced with a metal band of the same form as a wall of the container under study, which is applied with metal-based adhesive in a layer of 15 mm.

Parameters of the container under study:

- Diameter $D = 500$ mm, length $L = 500$ mm, thickness $t = 1$ mm, internal pressure $p = 0.1$ MPa, elastic coefficient $E = 200000$ MPa, Poison's ratio $\mu = 0.3$.

In this study, thickness of adhesive layer and its specification are ignored. Stresses in the area of a dent and band are only under consideration.

3.2.1. Applying of a rectangular band. Figure 10-a illustrates the program model of a cylindrical container with a rectangular band; figure 10-b represents the mesh of the rectangular band; figure 10-c represents distribution of equivalent stress in a cylindrical wall in the dented area; figure 10-d illustrates distribution of equivalent stress in a rectangular band.

Figure 10. a) the program model of a cylindrical container with a rectangular band; b) the mesh of a rectangular band; c) distribution of stresses in a wall in the dented area; d) distribution of stresses in a rectangular band.
3.2.2. Applying of a round band. Figure 11-a illustrates the program model of a cylindrical container with a round band; figure 11-b represents the mesh of a round band; figure 11-c represents distribution of equivalent stress in a cylindrical wall in the dented area; figure 11-d illustrates distribution of equivalent stress in a round band.

![Figure 11](image1)

3.2.3. Applying of an ellipsoid band. Figure 12-a illustrates the program model of a cylindrical container with an ellipsoid band; figure 12-b represents the mesh of the ellipsoid band; figure 12-c represents distribution of equivalent stress in a cylindrical wall in the dented area; figure 12-d illustrates distribution of equivalent stress in an ellipsoid band.

![Figure 12](image2)
3.2.4. Applying of a rhomboid band. Figure 13-a illustrates the program model of a cylindrical container with a rhomboid band; figure 13-b represents the mesh of a rhomboid band; figure 13-c represents distribution of equivalent stress in a cylindrical wall in the dented area; figure 13-d illustrates distribution of equivalent stress in a rhomboid band.

Table 3 shows maximum stress and deformation values under these conditions.

Table 3. Maximum stress and deformation values under various conditions.

| Band's geometry               | Diamond | Ellipsis | Circle | Rectangle |
|-------------------------------|---------|----------|--------|-----------|
| Maximum stress in a container’s wall, MPa | 63.59   | 102.1    | 93.62  | 84.04     |
| Maximum stress in the area of a band, MPa | 47.59   | 42.04    | 61.08  | 48.59     |
| Maximum shear stress in a container’s wall, MPa | 34.87   | 56.92    | 53.21  | 47.84     |
| Maximum shear stress in the area of a band, MPa | 26.25   | 24.17    | 32.23  | 24.51     |
| Deformation in a container’s wall, MPa | 0.087   | 0.973    | 0.0663 | 0.0586    |
| Deformation in the area of a band, MPa | 0.091   | 0.109    | 0.0659 | 0.0744    |

Figure 14 shows diagrammic reflection of equivalent stress in a container’s wall and in bands of each above-mentioned form.

Figure 15 shows diagrammic reflection of shear stress in a container’s wall and in bands of each above-mentioned form.
Results and discussion

In case of compression of a cylindrical container, a thin wall of which was damaged, it was defined that theoretical mathematical laws are not applicable for stress calculation in this area. It required the finite element analysis.

4.1. Discussion of results of analysis before maintenance

In studying of influence of stresses, which occur in the damaged area of a thin-walled cylindrical container, it was found that their values depend on the angle of a dent’s edge with respect to the container. Moreover, the wider the inclination angle, the lower stresses in the dented area. The reason was that internal pressure spreads over larger surface of a dent when axes of the dent and container are parallel with each other, as it is shown in figure 16. This is not the case of perpendicular arrangement of axes, when internal pressure is concentrated on lower surface, as it is indicated in figure 17.
4. Discussion of results of analysis after maintenance

Results show similar values of deformation in a wall of a cylindrical container and a band with respect to the original model, which allows neglecting them.

Stress analysis in a wall of a cylindrical container after maintenance showed lower stress values in the damaged area for each form of bands as compared to their values before maintenance. Moreover, it was noted that a rhomboid band provides for maximum decrease of stress:

\[ \lambda_p = \frac{\sigma_{do} - \sigma_{nace}}{\sigma_{do}} = \frac{258,3 - 63,059}{258,3} = 75,6\% \]

Applying of an ellipsoid band resulted in the lowest decrease of equivalent stress values.

\[ \lambda_E = \frac{\sigma_{do} - \sigma_{nace}}{\sigma_{do}} = \frac{258,3 - 102,1}{258,3} = 60,5\% \]

The same is true for other forms of bands.

In all studied case, stresses in bands in the dented areas are lower than in a container’s wall, while maximum shear stresses in a container’s wall appeared to be higher than in bands of any of studied form. It demonstrates that applying of bands provides for sufficient reinforcement of a cylindrical container wall.

5. Conclusions

The study found that a dent in a thin-walled cylindrical container, resulting from an incident, forces a significant increase of stresses in the dented area in respect to stresses in a similar non-damaged wall. Moreover, it was noted that stresses in the dented area changed due to changes in the angle of a dent’s edge with respect to a container. Their maximum values occurred when these axes were parallel with each other.

State-of-the-art maintenance by means of applying metal bands to the damaged area decreases stresses. Applying a rhomboid band provides for maximum decrease of stress in the damaged area.

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