Estimation of pipeline systems flexible connecting pipe strength properties based on numerical study of strain-stress state

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Abstract. Vibration-isolating structures on rubber-cord casings are used in pipeline systems which are of great importance for the transportation of hydrocarbons. Implementation of a compensating pipe eliminates the load transfer from the pressure of the working medium to the structural elements of the pipeline. A three-dimensional model based on a numerical study and reinforced with beam elements is used to estimate the strength properties of a rubber-cord branch. The calculation of the stress-strain state of the rubber-cord casing and the flange connection of the branch pipe has been carried out. The results are to be considered when designing and operating pipe structures based on reinforced casings.

1. Introduction
Compensating connecting branches for pipelines are required when transporting liquid media through them, loading and unloading operations, filling of storage tanks. Vibration isolating pipes of various designs operate as flexible elements to reduce vibration loads and to compensate for the resulting deformations of pipeline systems. At present, vibration isolating structures based on rubber-cord casings are being developed (figure 1). The main role of the compensating branch pipe is to exclude the transfer of forces from the pressure of the working medium in the pipeline cavity to the flanges and attached mechanisms. Theory of the mesh shell was the scientific base for the creation of a non-thrust rubber-cord branch pipe [1].

Figure 1. General view of the vibration isolating branch pipe.

The design of the branch pipe is shown in figure 2, it includes a rubber-cord casing (1) and two metal flanges (2); using them the branch pipe is connected to supply pipelines or mechanisms. The profile of the flanges provides a strong attachment of the branch pipe to the valve, providing the required tightness of the internal cavity.
The design of the rubber-cord casing is shown in figure 3. Its cylindrical part consists of a sealing rubber layer (its thickness is 6 mm), two layers of cords with 1.1 mm thickness and a casing layer of rubber with 2 mm thickness.

2. The problem statement
The purpose of this article is to estimate the strength characteristics of a rubber-cord pipe as a result of a numerical study [2] of the stress-strain state (SSS) of a rubber-cord casing (RCC) resulting due to the internal overpressure. For this, models of the RCC and the side connection in the contact area with the flange are investigated by the method of finite element analysis in ANSYS software [3].

3. Theory
While studying the strength characteristics of the branch pipe, the presented work considered two types of material of the RKO structural elements: orthotropic - for modeling a rubber-cord material and isotropic - for modeling rubber [4]. The initial data of the considered materials of the branch pipe rubber-cord casing are given in table 1.

Table 1. Casing materials specifications

| Criteria                        | Value  |
|---------------------------------|--------|
| Modulus of elasticity $E_c$, MPa| 130000 |
| Tensile modulus when 1 % elongation, MPa | 35000 |
| Poisson ratio                   | 0.4    |
| Density, kg/m$^3$               | 1450   |
| Tensile strength, MPa           | 2650   |
| Cord diameter, mm               | 0.6    |
| Force at rupture, N             | 750    |

| Criteria                        | Value  |
|---------------------------------|--------|
| Modulus of elasticity $E_r$, MPa| 3.0    |
| Poisson ratio                   | 0.49   |
| Coefficient of elongation, %    | 525    |
| Nominal strength at elongation, MPa | 22.82 |
| Density, kg/m$^3$               | 1150   |

For a numerical study and calculation of the stress-strain state of the pipe, we determine the average values of the mechanics properties of the reinforcing layer [5]. For a multilayer an-isotropic casing, the modulus of longitudinal elasticity for an orthotropic material is determined by formula:

$$E_1 = [1 + (n-1) \cdot \varphi] \cdot E_r,$$

where $n = E_c/E_r$ is reinforcement power; $\varphi = \pi d^2 n/4hl$ is ratio of reinforcement is equal to the ratio of reinforcement cords area to the total area of the layer; $\varphi = 0.193$.

The averaged elastic modulus in the isotropy area is.
\[ E_2 = \frac{[1 + (n - 1)\varphi]E_c}{(\varphi + n(1 - \varphi))[1 + (n - 1)\varphi] - (n\nu_r - \nu_c)^2\varphi(1 - \varphi)} \]

where \( \nu_r \) and \( \nu_c \) is Poisson ratio of rubber and cord.

Density of the rubber cord material, consisting of cords with density \( \rho_c = 1450 \text{ kg/m}^3 \) and rubber with density \( \rho_r = 1150 \text{ kg/m}^3 \), is determined according to the equation

\[ \rho = \rho_c \cdot \varphi + \rho_r (1 - \varphi) \]

The branch pipe is determined with \( K = \frac{[\sigma_c]}{\sigma_r} \), where \( K \) is casing reserve factor; \( [\sigma_c] \) is cord reserve factor; \( \sigma_r \) is maximum stress in the boundary disturbance area. The safety factor of the most loaded layer of the branch pipe casing was 16.4.

4. Simulating

For calculation in the ANSYS software, it is necessary to create a finite element model of the object under study. For this purpose, we considered the structure of the rubber-cord casing of the branch pipe (figure 4).

There is a sealing rubber layer (1) on the side of the inner cavity, which is a protective element against the harmful effects of the medium for the load-bearing frame (2, 3), made on the reinforced cords at 54.4° angle to the pipe axis. The power frame perceives the forces from the internal pressure of the working fluid pumped through the pipeline. There is a covering layer of rubber (4) outside, which protects the power frame from mechanical damage and aggressive environmental factors.

Based on the previously published findings of the applicability of various finite element models of rubber-cord structures, a three-dimensional cylindrical casing reinforced with beam elements is considered as a calculation model in the ANSYS software [6]. Metal flanges are represented by three-dimensional elements with steel properties (modulus of elasticity is \( E = 2 \times 10^{11} \text{Pa} \)).

As RCC is a multilayer casing, the issue of creating an integral calculation model and combining layers was solved by imposing contact conditions on adjacent surfaces. In this case it is possible to obtain load bearing characteristics of the interaction of layers.

5. Calculation results

The research problem of RCC and structural elements of the vibration-insulating pipe stress state is solved in an axisymmetric setting based on the finite element method. ANSYS software demonstrates visually the stress-strain state of the model as a whole and shows the distribution of stresses and strains in single layers of casing and metal elements of the model of the branch pipe under study [7]. The SSS calculation is carried out under boundary conditions, when one of the flanges is rigidly fixed, and the condition of limiting displacements is imposed on the other.
We investigate the stress-strain state of a branch pipe loaded with internal pressure of 1 MPa. The greatest forces in cords are 122.22 N. Since the density of the cords is 10 times less in this model than in the real one, then in fact one cord is like ten in a real branch pipe. Therefore, the force on the cord in the real pipe is 12.2 N. At the maximum cord breaking load of 750 N, the safety margin of the branch pipe casing along the cord was 61. The forces in the cords of the inner layer turned out to be greater than that of the outer one and are evenly distributed along the entire length of the pipe (figure 5).

\[ \text{Figure 5. Forces in cords} \]

It turned out in the course of study, that if we do not take into account the stresses arising at the edge of the casing (where the side area should be modeled), then the highest stresses of 0.2-0.4 MPa arise in the reinforced layers along the entire length of the casing and in the cover layer at the edge of the contact zone with the flange (figure 6).

\[ \text{Figure 6. Stress diagrams at the contact between the cover layer and the branch pipe flange} \]

The strength of the bonds between the layers can be estimated from the output parameters of the contact. Frictional Stress parameter is the most indicative; it shows the shear stresses that occur between layers. Standart stresses displayed by the Pressure parameter in this issue are positive (they act on the compression of the contact pair), therefore they cannot destroy the contact pair and will not be considered. As a result of calculating the stress-strain state of the RCC finite element model, stresses and strains values were obtained layer by layer: in the inner sealing layer, cords, a rubber layer between the cords, a cover rubber layer. For example, color diagrams of shear stresses arising in the contacting layers between the cover layer and the flange are shown in figure 7. The stress concentration occurs at the edge of the casing-flange contact and is about 0.1 MPa.
6. Discussion of the results

As a result of the numerical study, there is an increase in stresses observed, both in the contact zone of the casing with a flange and in the central part of the casing. In this regard, it would be recommended to research the contact zone of the casing with the flange, as during the branch pipe operating, stresses concentrated at a parametric distance of approximately 72 mm from the end edge can cause fatigue cracks to appear in the rubber layer.

The task of ensuring reliable tightness of the side connection of the branch pipe for a long-term operation becomes urgent. Sealing filler made in the form of a rubber chamber meets the requirements in terms of construction. Its finite element model was created to determine the stress-strain state of the sealing filler from the action of internal pressure and compression by metal flanges. A diagram of a branch pipe and an enlarged view of a contact zone model of sealing filler with a flange are presented in figure 8. The calculation was carried out in the ANSYS software, while a branch pipe with 150 mm nominal diameter was loaded with 10 MPa internal pressure.

Displacement of flange (1) by 0.015 m was simulated before contacting with the stationary part (2). The stresses caused by the contact interaction of the flange elements and the sealing filler are presented in the diagram in figure 9.
Figure 9. Stress diagrams of the contact interaction of the filler with the flange

The maximum stresses reach 7.9 MPa in the corners of the groove for the sealing filler and it is presented in figure 9. This is due to the fact that there are no radius forms of the groove in these places. Compressive stresses of 3 MPa occur in the right flange element. The magnitude of the resulting stresses is explained by the high stiffness characteristics of the metal parts of the pipe flange.

7. Conclusions

Based on the modeling and finite element calculation in the ANSYS software, there were studied strength characteristics of a vibration-insulating pipe based on the rubber-cord casing. According to the resulting stresses of the branch pipe, it was determined that the highest values take place in the central part of the casing, where the inner layer of the rubber-cord casing is the most loaded, and areas with boundary disturbance, the contact area between the casing and the flange. The maximum deformation of the rubber sealing filler was 2.5 MPa. The maximum stresses were about 2 MPa, and in the flange metal - about 8 MPa, which is due to the greater rigidity of the metal flange. The discovered stress surges are due to the fastening of the flanges into the cylindrical casing (there are no displacements along all axes), therefore, bending moments occur as a consequence of the boundary disturbance.

Thus, while studying the contact interaction of the sealing filler with the flanges, it is noted that the stresses are insignificant in the rubber mass, and this is explained by the fact that rubber has relatively low stiffness in comparison with the metal parts of the pipe flange.

In conclusion, it can be noted that as a result of the analysis of the stress-strain state, it becomes possible to predict the performance indicators of the structures of reinforced casings, and these aspects should be taken into account when vibration-insulating pipes are designed and operated on.

8. References

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