Estimated delamination of an elastic-plastic liner in a high-pressure metal composite vessel

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Abstract. To carry out delamination analysis in high-pressure metal composite vessels, a software approach is proposed in which the dynamic calculation algorithm is implemented in software systems. The algorithm is built on three points: the introduction of technological deviations (at the level of permissible defects), the determination of a three-dimensional stress-strain state, and a real-time solution. As a calculation program, LS-DYNA was selected in a dynamic formulation with the structure divided into 3D solid elements and unilateral constraint on the contact surface of the metal (liner) and composite shells was introduced. A geometrically and physically nonlinear problem is solved. The moment of liner delamination from the composite shell is determined by the change in the liner stress-strain state and by the liner deformable surface in time presented visually.

1. Introduction
The effectiveness of gas pressure vessels, widely used in transportation equipment, is determined by the bearing capacity and weight. A rational combination of these properties can be achieved in composite metal composite high-pressure vessels (MC HPV), in which a gas-tight metal shell (liner) is externally reinforced with a rigid composite shell. A feature of such vessels is the possibility of liner delamination from the composite shell, which refers to unacceptable defects [1]. Therefore, at the design stage of the MC HPV, it is necessary to evaluate the monolithicity (wholeness) of the vessel for its delamination. The delamination mechanism can occur both at the stage of MC HPV manufacturing (winding, heat treatment), and at the operation stage. The experimental search for the optimal parameters is expensive and difficult, which makes it relevant to develop calculation methods for assessing MC HPV monolithicity.

The aim of this work is to propose a software approach to MC HPV calculation containing information on delamination occurrence. The calculation should take into account the following points: the complex geometry of the vessel, the inhomogeneous and anisotropic properties of the materials and their non-linear deformation characteristics, the ability of the liner to move away from the composite shell, the conditions of power and heat loading, and temporal processes of deformation development. There are no algorithms covering the above requirements in the well-known publications on calculating MC HPV [2–4 and others]; and this does not allow us to study the liner delamination from the composite shell in the MC PV. A generalized algorithm that allows the inclusion of the stated requirements and is implemented in software systems is the proposed software approach, the basis of which is a dynamic analysis of the stress-strain state of MC HPV [5]. Let us
consider the approach as applied to the heat treatment problem of MC HPV, when both the liner and the composite shell are heated.

2. Design scheme
According to the proposed approach to calculating the MC HPV delamination, an analysis of its stress-strain state is made, which changes in time and determines the moment of the vessel solidity violation in the form of the liner delamination from the composite shell, and corresponding external loads are found.

The generalized algorithm of the program approach combines three points.

- Technological deviations in characteristic zones are introduced into the ideal vessel design. Technological deviations are understood as cut-outs in the liner and in the composite shell of shallow depth and dimensions in terms of acceptable defects. The characteristic zones in cylindrical MC HPV include end domes and the cylindrical part of the vessel.
- The spatial stress-strain state of the vessel is analysed which makes it possible to find all the components of the stress and strain tensors and displacement vectors and correctly set the conditions on the contact surface of the liner – composite shell.
- The deformation of the MC HPV is monitored in real time. The temporal process makes it possible to establish the beginning and further development of the liner delamination.

We will implement the algorithm in the LS-DYNA software package in a dynamic formulation. We represent the design of the vessel in three bodies: a composite shell, a liner, a rigid ring simulating a flange in the pole hole of the end dome. We will subdivide the bodies into 3D solid elements (figure 1) of the SHELL type for a composite shell and a liner, and of the SOLID type for a rigid ring.

![Figure 1. Finite element model of a metal composite high-pressure vessel.](image)

On the contact surface of the liner — composite shell, we will define a unilateral constraint normal to the surface and neglect the tangent interactions of the liner and the composite shell. We will introduce the layers of boundary finite elements in the liner and composite shell near the contact surface, in which we will place technological deviations (local cut-outs). The material of the composite shell is considered linearly elastic, and the liner material is elastoplastic. The problem of vessel deformation is solved in a geometrically nonlinear formulation. We will replace the multilayer composite shell with a quasihomogeneous orthotropic one with the given mechanical characteristics. We will transfer the thermal loads on the vessel by increasing the temperature of both the liner and the composite shell without taking into account changes in mechanical characteristics.

Presentation of calculation results is organized in two forms — graphic and visual. The graphic form shows the change in the stress-strain state with time, which provides a quantitative determination
of the moment of liner separation from the composite shell associated with a local buckling of the liner and the formation of local wrinkles on it.

The visual form of the deformable surface of the liner, with a conditionally removed composite shell, qualitatively illustrates buckling process of the liner under load, which leads to its delamination from the composite shell.

3. Analysis of the results
We will study the mechanical behaviour of the liner as a part of a cylindrical MC HPV during heat treatment. To do this, we will simultaneously increase the temperature of the liner and the composite shell according to the linear law from 0 °C, when the structure is not strained, to the temperature \( T_1 \) recommended for heat treatment of the composite shell. Let the vessel consist of an aluminium liner and a carbon-filled plastic shell wound around it. Then \( T_1 = 140 \) °C. MC HPV has dimensions and mechanical characteristics given in [6]. The ratio of the liner and the composite shell stiffnesses is such that the liner is deformed virtually surrounded by a rigid medium that does not lose its shape. At high heating temperatures, the liner bends locally (figure 2) and wrinkles occur on its surface (figure 3) in the areas where technological deviations exist. These wrinkles are caused by local buckling of the liner, and they are subdivided into circumferential and radial ones on the end domes and into the contour (turning into longitudinal) wrinkles on the cylinder [6].

![Figure 2. Local buckling of the liner.](image-url)
In the zones of wrinkles, delamination of the liner from the composite shell occurs. The moment of delamination of the vessel can be quantified by the graph of changes in circumferential stresses ($\sigma_y$) in the cylindrical part of the liner (figure 4) far from the zone of buckling, that is, where the stress state approaches a uniform one. When the structure is heated, the circumferential stresses in the liner (element No. 65626) initially increase; and at the moment the liner buckles, they begin to fall down. In the place of the curve break on the graph, there is the desired point, which determines the time and temperature of the liner delamination from the composite shell (figure 5). It was found that $\tau = 0.0045$ s, $T = 90$ °C.

**Figure 3.** Buckling wrinkles on the liner surface.

**Figure 4.** Graph of circumferential stresses $\sigma_y$ in the cylindrical part of the liner.

**Figure 5.** Complete displacement.
4. Conclusions
The program approach to the analysis of delamination of metal composite high-pressure vessels (MC HPV) is considered. It is shown that this approach, combining a dynamic calculation algorithm and software implementation, allows taking into account the geometric and mechanical features of the MC HPV and finding the moments of its monolithic form violation in the form of the liner delamination from the composite shell. Using the selected example of calculating a vessel with an aluminium liner and a carbon-filled plastic shell, the application of the LS-DYNA software package in a dynamic formulation with the subdivision of the structure into 3D solid elements is demonstrated. It was established that the liner delamination from the composite shell associated with the appearance of wrinkles of buckling on the liner occurred in the areas of technological deviations, where there were local small decreases in the thickness of the liner and composite shell.

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