Studying rigidity of the welded liner - composite shell construction

Anton V Egorov

Spacecraft and Launch Vehicles Department, Bauman Moscow State Technical University, 5 Second Baumanskaya Street, Moscow, 105005, Russian Federation

E-mail: antegor177@mail.ru

Abstract. The mechanical behaviour of an aluminium welded liner in a cylindrical metal composite vessel of high pressure made by winding on a linear carbon-filled plastic tape with tension is investigated. The resulting pressure of the wound composite shell on the welded liner is simulated by cooling the shell. It is believed that the weld is obtained by friction welding and has characteristics that are reduced in relation to the base material of the liner. The problem is solved in a geometrically and physically nonlinear formulation using a 3D solid element model, taking into account technological deviations and in real (current) time. The calculations were performed in the LS-DYNA software package in a dynamic formulation. It is shown that liner delamination from the sheath starts from the side of the circumferential weld in the area of technological deviations.

1. Introduction

The two-layered cylindrical liner–composite shell designs, in which a liner refers to metal shells, and a composite shell (sheath) means their tight surrounding medium, are used in various industries. In aerospace engineering, such structures are part of the highly efficient in mass and load-carrying capacity of gas cylindrical metal-composite high-pressure vessel (MC HPV). The result of the optimization of design solutions of the MC HPV for space technology was the use of a welded liner in the middle cylindrical part of the MC HPV and high modulus carbon-filled plastic in the outer power shell (sheath). The girth weld is performed by friction stir welding, the holder – by winding on a linear carbon-filled plastic tape with tension.

In the manufacture and operation of the MC HPV, due to its two-layer, the separation between the liner and the casing is possible. Since the multi-layer carbon-fibre sheath is rigid, internal local radial displacements may appear in the liner, i.e. local buckling may occur (unacceptable defect).

The purpose of this work is to investigate the circumferential weld effect on the deflections of liner surrounded by an elastic composite shell in the manufacture of MC HPV.

2. Model of deformation

The production process of MC HPV consists of two stages. At the first stage, a metal liner is manufactured; at the second stage, the composite tape is wound onto the liner with tension. The resulting multilayer composite shell presses on the thin-wall liner and is capable of deforming it with the formation of internal folds, which indicates buckling of the liner. Therefore, large displacements may
occur in the liner, exceeding the thickness of the liner, which must be provided for in the deformation model of the welded liner-composite shell structure.

For large displacements leading to a local change in the shape of the liner, plastic deformations may occur in it, which should also be taken into account in the deformation model of the structure. Since there is a girth weld in the cylindrical part of the liner, it becomes necessary to reflect its distinctive properties in the deformation model of the structure: geometry and mechanics.

For this purpose, experimental studies were carried out [1] on friction welding of two plate-like aluminium specimens 2.5 mm thick. Friction welding was performed using a new disk tool (figure 1) when forming the weld root [2] and using a core tool to obtain a full-length (in height) weld.

![Figure 1. Scheme of disc friction welding:1-filler lining; 2 - disc tool; 3 - aluminium plates.](Image)

According to the experimental-calculated analysis, the width of the heat-affected zone (figure 2), equal to 10 mm, was obtained. It is of this size that the width of the weld in the deformation model of the structure was assigned. According to the results of testing samples of welded joints of plates, the mechanical characteristics in the weld zone were established:

\[ \sigma_{pr} = 130 \text{ MPa}; \quad \sigma_{0.2} = 152 \text{ MPa}; \quad \sigma_t = 331 \text{ MPa}; \quad \delta = 16\% . \]

By these parameters, a deformation diagram was constructed, similar to the diagram constructed in [3] for the AMg-6 alloy.

![Figure 2. Heat-affected zone of the welded joint.](Image)

At the start (tool entry) and end (tool exit) of friction welding with mixing, we take into account the lowering of the weld and here, in a small area, on the contact surface of the liner and composite shell, also take into account technological deviations in the form of local starved spot, which is inherent in real structures. The form of technological deviation (sector of the ring) will be chosen in accordance with the recommendations [4] for calculating buckling of the cylindrical liner.

Carbon fibre shell believe orthotropic with reduced mechanical characteristics [3]. Stress-strain and flexural stiffness of the composite shell is an order of magnitude higher than that of the liner. This leads to a special behaviour of the structure, when small radial displacements of the shell correspond to large displacements of the liner in a small area where there are technological deviations.
Thus, the model of deformation of the welded liner – composite shell structure should be geometrically and physically nonlinear, three-dimensional, with one-sided connection of the liner and the composite shell on the contact surface.

3. Method of calculation
Calculation of the rigidity of the welded liner – composite sheath will be performed in the LS-DYNA software package in a dynamic formulation using 3D solid elements. In the finite element model (figure 3) of the structure, we reflect its main features. With the help of specially introduced boundary elements on the shell and liner, we will define a local starved spot on the contact surface by cutting out a number of elements.

![Finite element model of the structure.](image)

**Figure 3.** Finite element model of the structure.

The weld seam is also modelled with 3D solids, but with its lower mechanical properties, which are different from those of the liner base material. With the help of the boundary elements on the weld we set for it a local lowering of the seam. The overall dimensions of the finite element model are assigned so that the conditions for thinness of the wall and the length of the structure are fulfilled:

\[ \frac{D}{h} = 100-300; \quad D/L \leq 10, \]

where \( D \) is the diameter of the contact surface, mm; \( h \) is liner thickness, mm; \( L \) is the length of the cylindrical part of the structure, mm.

Such conditions correspond to real composite shells. The papers [5-8] are devoted to their analysis. The stability of a ring liner surrounded by a rigid medium was studied in [9-12].

4. Analysis of the results
Let us consider the deformation of the structure of a welded liner – composite shell with the following parameters: \( D = 364 \text{ mm}; \ h = 2.2 \text{ mm}; \ L = 50 \text{ mm} \). As an external load, we set the negative temperature of the shell and take into account that a thermal insulator is placed (conditionally) at the border of the liner – shell so that the liner is not cooled. Compressing, the shell presses on the liner and there are compressive circumferential deformations in it. According to the corresponding circumferential stresses \( \sigma_\beta \) (figure 4) in the zone with a stressed state close to homogeneous, it is possible to establish the moment of liner delamination from the composite shell and of the liner buckling. Local liner deflections occur at the time \( \tau = 2 \times 10^{-4} \text{ s} \); at the same time, critical stresses \( \sigma_\beta = -179 \text{ MPa} \). Knowing these stresses, according to the method described in [3], it becomes possible to estimate the liner deformation in a specific vessel when winding a composite tape with tension on the liner, i. e. to answer the question of whether there will be the loss of stability of the liner in the manufacture of MC HPV.
Figure 4. Circumferential stresses distribution in the liner with time.

In our design case, the liner peels off and buckles (figure 5). The liner is skewed in the delamination zone towards the weld, which has lower mechanical characteristics with respect to the liner base material. However, if the tension in the liner from tape winding is less than the obtained critical stress, then there will be no buckling of the liner in the manufacture of the MC HPV.

Figure 5. Form of liner buckling at time 0.01 s.

5. Conclusions
The considered deformation of the aluminium welded liner design – carbon-fibre composite shell showed that the shell, rigid in comparison with the liner, does not change its initial cylindrical shape and has small radial displacements when it is cooled. However, in some cases these displacements are sufficient for the liner to deform with the formation of a local internal deflection, indicating a local buckling of the liner. Outside this zone, the stress state of the liner is close to homogeneous. This makes it possible to trace in time the change in circumferential stresses in the liner and from them to establish the moment of delamination of the liner and the composite shell.

On the basis of the result obtained and knowledge of the circumferential stresses in the liner [3], when a composite tape with tension is wound onto it, it is concluded that the liner is behaving mechanically whether it will buckle or not. According to the conducted numerical analysis, it was established that the weld reduces the value of the critical load on the liner, surrounded by a rigid medium. According to the results of the study, the dependence of the stability of shape of the structure on the rigidity of the shell, liner, and weld was revealed.

The 3D solid element model of the structure deformation and the LS-DYNA software package used in the dynamic formulation allowed us to obtain results adequate to the goal of estimating the effect of the weld on liner deflections in the manufacture of MC HPV by means of winding.

References
[1] Egorov A V and Vermel’ V D 2017 Formation of the temperature field during friction disk welding of aluminum sheets Aviation Industry Journal 3 27-31
[2] Kaschuk N M, Shtrikman M M, Egorov V N and Egorov A V 2013 The method of friction
welding by a rotating disk Rospatent 30 2496621

[3] Egorov V N and Egorov A V 2019 Estimation of the allowable pressure of metal liner pressure testing when winding a composite shell Engineering Journal: Science and Innovation 2(86) doi: 10.18698/2308-6033-2019-2-1854

[4] Egorov A V 2017 Buckling of cylindrical shells in rigid medium Engineering Journal: Science and Innovation 9 doi: 10.18698/2308-6033-2017-9-1670

[5] Vasiliev V V 2009 Composite pressure vessels: Design, analysis, and manufacturing (Blacksburg: Bull Ridge Publ.)

[6] Marzbanrad J, Paykani A, Afkar A and Ghajar M 2013 Finite element analysis of composite high-pressure hydrogen storage vessels J. Mater. Environ. Sci. 4(1) 63-74

[7] Zheng J Y, Liu X X, Xu P, Liu P F, Zhao Y Z and Yang J 2012 Development of high pressure gaseous hydrogen storage technologies International Journal of Hydrogen Energy 37 1048

[8] Liu P F, Chu J K, Hou S J, Xu P and Zheng J Y 2012 Numerical simulation and optimal design for composite high-pressure hydrogen storage vessel: A review Renewable and Sustainable Energy Reviews 16 1817

[9] El-Sawy K 2013 Inelastic Stability of Liners of Cylindrical Conduits with Local Imperfection under External Pressure Tunnel. Undergr. Sp. Tech. 33 98-110 doi: 10.1016/j.tust.2012.09.004

[10] Silveira R A M, Nogueira C L and Gonzalves P B 2013 A numerical approach for equilibrium and stability analysis of slender arches and rings under contact constraints International Journal of Solids and Structures 50 147-59

[11] Vasilikis D and Karamanos S A 2014 Mechanics of Confined Thin-Walled Cylinders Subjected to External Pressure Applied Mechanics Reviews ASME 66 010801

[12] Vasilikis D and Karamanos S A 2010 Buckling design of confined steel cylinders under external pressure Journal of Pressure Vessel Technology 133(1) 331-41