Topography optimization of the lattice payload adapter for carrier rocket

R S Baldzhiev, A A Alekseyev and A V Azarov

1Bauman Moscow State Technical University, 2nd Baumanskaya str., b. 5, Moscow, 105005, Russia
E-mail: r.baldji@yandex.ru

Abstract. Current study is dedicated to the evaluation of the topology optimization method for the design of load-bearing aerospace structures. The subject of research was composite spacecraft attach fitting (adapter) which provides the interface between a spacecraft and a commercial launcher. Modelling of stress-strain state of the lattice payload adapter under operation conditions was performed. Compression strengths of structural ribs were defined together with the stiffness and buckling stability taken as the design constrains. By means of the topology optimization procedure optimal material distribution in the payload adapter was obtained. The workability of the adapter was proved by the confirmatory analysis.

1. Introduction
Currently there are several design approaches for the spacecraft payload attach fitting - adapter design, namely: sandwich panels, reinforced shells and lattice structures. Each variant has its certain pros and cons. However, lattice payload adapter with ribs manufactured from unidirectional carbon fiber reinforced plastic (CFRP) demonstrates highest weight efficiency (of all the above-mentioned variants) accompanied with high stiffness [1]-[3].

Recent advances in composite manufacturing technologies development allow switching from the traditional filament winding to the modern automated fiber placement (AFP) technology. AFP equipment combined advantages of both techniques — fiber placement and winding due to utilization of automated operational system and special software. Consequently, AFP allows obtaining products with intricate shapes [4]. Also composite parts with complex shapes can be achieved using emerging composite 3D printing technology [5]-[6]. Application of these new techniques enables to create optimal structures by varying ribs pathways (trajectory), their number and cross-section shapes.

However, a great number of variables make the design problem of lattice composite load bearing adapter quite complex and resource-consuming. Topology optimization method could overcome this issue. Topology optimization is the design approach that allows to define reasonable material distribution in a certain volume taking into account the design constraints that depend on the operation conditions and type of the applied loads [7]-[10]. Such analysis is performed by means of the well-known calculation method – Finite Element Method (FEM).

This paper aims to develop an optimal structure of the CFRP payload adapter of the carrier rocket by utilizing topology optimization method.

2. Object of the research
The lattice payload adapter (Figure 1) consists of several types of ribs made from unidirectional CFRP. The biggest amount of the ribs belongs to spiral type - 48 pairs of main (1) and 16 additional (2).
Circumferential ribs (3) are located at the intersections of the main spiral ribs. The adapter is mounted to the neighboring structures with the upper (4) and lower (5) frames. In the lower cross-section the adapter is connected with the upper stage of a launcher using 8 groups of bolts (Figure 2). The diameter of the lower frame is 2085 mm, of the upper – 1212 mm, the adapter height is 901.5 mm. Total weight of the structure is 64 kg. The geometry parameters of the structural ribs cross-sections are presented in Table 1.

3. Topology optimization of the lattice adaptor structure

3.1. Trajectory parameters determination

The input parameters for the topology optimization procedure were the adapter dimensions – upper and lower frame diameters, and positioning of the bolt holes on the lower frame. During the payload orbiting the adapter must withstand intensive compressive stresses while keep its dimensions and shape unchanged. Therefore strength and stiffness characteristics of the initial lattice structure were assumed as the constraints for optimization.

Modelling of the stress-strain condition of the adapter was conducted in order to define structure mechanical properties. Stress-strain analysis was conducted in Femap – Siemens PLM Software. The applied loads are presented in Table 2.

The modelling results (Figure 3) demonstrate that maximum compression strain in the ribs is 310 MPa, buckling coefficient of the ribs – 4.4, displacement under the axial load is 0.09 mm, while under side load – 0.13 mm. All the obtained results do not exceed the ultimate values for CFRP (Table 3), that indicates the structure operation capacity.
Table 3. Stress-strain state modelling results for the initial adaptor structure.

| Analysis type | Parameters                                      | Obtained value | Ultimate value |
|---------------|-------------------------------------------------|----------------|----------------|
| Strength      | Maximum compression stress in the ribs, MPa     | 310            | 450            |
| Buckling      | Buckling safety coefficient                      | 4.40           | > 1            |
| Stiffness     | Displacement under the axial load influence     | 0.09           | < 0.5          |
|               | Displacement under the bending moment influence  | 0.13           | < 0.5          |

Figure 3. Initial adaptor structure stress-strain analysis results: (a) compression stress fields; (b) buckling stability; (c) ribs displacement under the axial load; (d) ribs displacement under the side load.

3.2. Topology optimization

The 3D-model for the topology optimization as well as all geometry modeling was carried out using the Shape Design module of computer-aided design system Catia V5. This adapter model had the same overall shape as the initial adaptor, but by contrast to the original one the model had a solid wall (Figure 4). Topology optimization was conducted in the Optistruct module of the FEM program Altair Hypermesh with a great toolkit for a complex optimization analysis. The resulting structure after topology optimization after cleanup is shown in Figure 5. The geometrical parameters of the resulting ribs are presented in Table 4.
Figure 4. 3D-model of the adaptor for the topology optimization.

Figure 5. Optimized adaptor geometry after cleanup.

Table 4. The geometrical parameters of the resulting ribs.

| Structural element   | Cross-section dimensions, mm |
|----------------------|-------------------------------|
| Main ribs            | 12x30                         |
| Additional ribs      | 8x30                          |
| Upper frame          | 30x30                         |
| Lower frame          | 135x30                        |

The resulting lattice adapter had a maximum ribs thickness of 12 mm, and weight of 27 kg, that is almost twice lower than the initial structure weight. However, the resulting structure before cleanup had certain imperfections. Thus, it had numerous non-joint sections together with complex ribs shapes and different lengths (Figure 6). Consequently, for the further analysis, the geometry was modified leaving the basis concept provided by the topology optimization.

Figure 6. Topology optimization results: (a) adaptor geometry before cleanup; (b) geometry imperfections – non-joint section, complex ribs shapes and different lengths.

3.3 Optimized adaptor geometry verification and post processing

After the structure modification some elements were deleted and that is why a new stress-strain analysis of the modified structure was carried out (Figure 7). The results shown in Table 5 demonstrate that the elements displacements exceed the ultimate value and the structure needs to be stiffened. For this reason additional lateral stiffness ring (8x30 mm) was added to the intersections of the additional ribs (Figure 8). This lateral stiffness ring reduces the displacement down below the allowable value (Figure 9, Table 6).
Figure 7. Modified adapter structure stress-strain analysis results: (a) compression stress fields; (b) buckling stability; (c) ribs displacement under the axial load; (d) ribs displacement under the side load.

Table 5. Stress-strain state modelling results for the optimized adapter structure after modification.

| Analysis type  | Parameters                                      | Obtained value | Ultimate value |
|----------------|-------------------------------------------------|----------------|----------------|
| Strength       | Maximum compression stress in the ribs, MPa     | 393.43         | 450            |
| Buckling       | Buckling safety coefficient                      | 5.09           | > 1            |
| Stiffness      | Displacement under the axial load influence     | 0.31           | < 0.5          |
|                | Displacement under the bending moment influence  | 0.59           | < 0.5          |
Figure 8. Optimized adapter with the additional lateral ring.

Figure 9. Stress-strain analysis of the optimized adapter with the additional lateral ring: (a) compression stress fields; (b) buckling stability; (c) ribs displacement under the axial load; (d) ribs displacement under the side load.
### Table 6. Stress-strain state modelling results for the optimized adapter with the additional lateral ring.

| Analysis type | Parameters                                      | Obtained value | Ultimate value |
|---------------|-------------------------------------------------|----------------|----------------|
| Strength      | Maximum compression stress in the ribs, MPa     | 369.49         | 450            |
| Buckling      | Buckling safety coefficient                     | 6.72           | > 1            |
| Stiffness     | Displacement under the axial load influence     | 0.18           | < 0.5          |
|               | Displacement under the bending moment influence | 0.29           | < 0.5          |

The implementation of topology optimization enables to reduce the mass of the adapter for 45%. Thus, the initial structure mass was 53 kg, mass of the adapter without the additional lateral ring – 27 kg, mass of the adaptor with the additional lateral ring – 28.7 kg.

### 4. Conclusion

The research results demonstrate that topology optimization is a feasible instrument for aerospace lattice structures design. Utilization of this approach leads to the remarkable increase of weight efficiency. Nevertheless, the assumptions used during the optimal structure modification leads to the results deviations. Therefore the optimized geometry needs to be verified. However, the modified adaptor structure demonstrates 45% weight reduction that proves high potential of the described methodology.

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