Chapter 20
Payload Adapter Made from Fiber-Metal-Laminate Struts

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Abstract In comparison to other transport systems, launch vehicles are characterized by relatively light but extremely valuable payloads. The launcher's upper stage structures, e.g. payload adapter and fairing, offer the highest weight saving potential. An effective weight reduction can only be achieved by the combined utilization of high performance materials and adapted construction methods. To improve the structures damage tolerance a new hybrid lay-up has been developed, which combines the properties of both, steel and carbon fiber reinforced plastics (CFRP). This chapter presents a preliminary design of a payload adapter as a framework, which is based on the high performance material properties of unidirectional CFRP-steel-laminates, offering a considerable weight saving potential.

20.1 State-of-the-Art Construction Technologies for Payload Adapters

Previous adapters used in launcher structures are made of metal, fiber reinforced plastic (FRP) or a combination of both materials. The adapter 1666A of the 'ARIANE 4', for example is an aluminium semi-monocoque construction, Fig. 20.1a, whereas CFRP is used for the adapter 1,194 V, Fig. 20.1b. The latter is designed as a sandwich-construction with aluminium frames. Similar material combinations can be found in the 'ARIANE 5', in which the VEB (Vehicle Equipment Bay) type A is made of CFRP as sandwich, Fig. 20.2a. Monolithic CFRP adapters are also used for this launcher, Fig. 20.2b.

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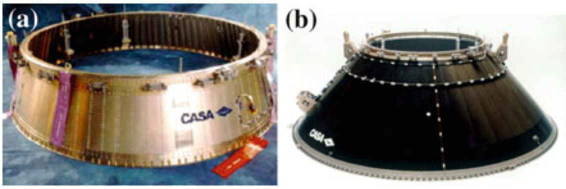

Fig. 20.1 **a** Adapter 1666A and **b** 1,194 V of ‘ARIANE 4’ [1, 21]

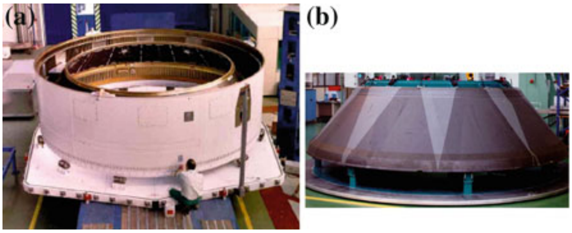

Fig. 20.2 **a** VEB structure type A with adapter and **b** monolithic CFRP adapter of ‘ARIANE 5’ [1, 21]

Fig. 20.3 **a** CFRP-lattice structure adapter and **b** aluminium adapter of ‘Proton-M’ [2]

CFRP-sandwich structures are also used in the Russian launcher ‘Soyuz’ [1]. For many years, CFRP-lattice-structures for adapters have been successfully used in Russian aerospace [2, 3–5]. Figure 20.3 shows a (a) CFRP lattice-structure adapter and (b) aluminium adapter with a variable wall thickness of the Russian launcher ‘Proton-M’. Weight- and cost savings up to 60% can be achieved by utilizing a CFRP-lattice structure compared to a metallic [2].

However, in all these examples metal and CFRP are combined on a structural level and not on a material scale. Fiber metal laminates have not been found in adapters for launcher structures so far.

20.2 Current Fiber Metal Laminates

Research on fiber metal laminates has been done for more than 40 years to improve the material performance of the individual constituents [6, 7]. The well-known material GLARE (**Gla**ss Fiber **Re**inforced Aluminium) is a combination of layers of glass fiber reinforced plastic (GFRP) which is used in the upper fuselage of the ‘AIRBUS A380’. The use of glass fibers considerably reduces the risk of fatigue compared to monolithic aluminium [7].

Local reinforcement of joining areas is another important discipline for fiber metal laminates [6, 8–11]. Fiber laminates, especially highly orthotropic laminates,

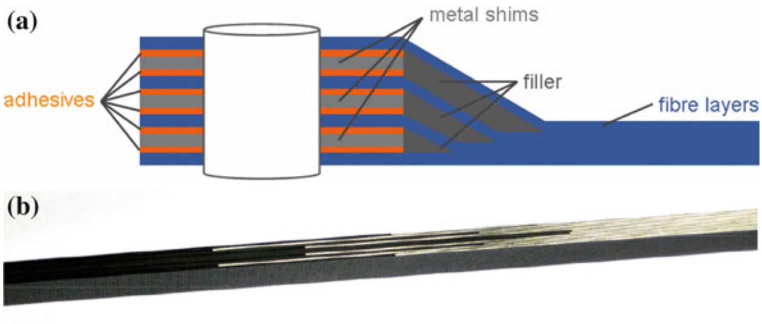

Fig. 20.4 **a** Transition zones with and **b** without eccentricity [11]

are characterized by low bearing and shear capabilities. Therefore, a local laminate built-up at the joining area is necessary to increase the load capacity of the laminate, Fig. 20.4a. Secondary stresses and eccentricities due to thickening on one side are the unfavourable consequences.

Another solution to improve the low bearing strength of fiber laminates is the local reinforcement technique characterized by the gradual substitution of specific composite plies by high-strength metal foils, cf. Fig. 20.4b. This approach eliminates any laminate thickening and secondary stress and consequently reduces the size and weight of fastening elements [11]. The transition region between the pure composite and the metal reinforced coupling region reaches a coupling efficiency (ratio of transition strength to strength of basic composite) of up to 100% [8, 10–12]. This leads to an increase of the specific strength of the bolted joining of up to 41% compared to pure CFRP [11].

20.3 Framework Design for an Upper Stage Adapter

In the following a VEB-structure as a V-ring construction with an adapter in framework design is investigated. As a consequence of the framework design the struts, serving as main structural elements, are only loaded in longitudinal direction. This allows a unidirectional alignment of all carbon fibers as long as damage tolerance needs are sufficiently satisfied. Thus, struts with quadratic and circular cross sections are investigated (Fig. 20.5).

20.4 Fiber Metal Laminates Increase Degree Capacity Utilization of CFRP-Strut

In a variety of aerospace applications, the industry’s increasing requirements for higher structural efficiency compete with the fundamental requirements for damage tolerance. Especially, when high specific uniaxial mechanical properties are desired,

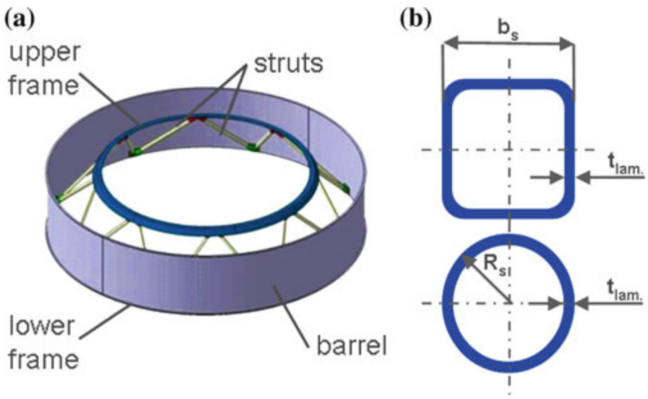

Fig. 20.5 **a** V-ring with adapter as framework design using struts with **b** quadratic and circular cross section

notch and impact sensitivity properties drastically limit the fiber fraction in load direction since laminates are created by stacking sequences with various orientations. Additionally, the thickness of equally orientated layers is limited to reduce crack distribution.

As a result, stiffness and strength per unit weight of the laminate for a given direction are lower than the corresponding values of a unidirectional composite. Particularly buckling endangered longerons and struts with high stiffness requirements suffer a loss of their lightweight potential due to the reduced residual strength capability.

Conventional fiber metal laminates, for example those described in the patents of Kolesnikov [12] and Westre [13] contain metal-layers with a thickness of 0.08–1.0 mm and therefore relatively high metal fractions impair the weight efficiency of the laminate.

Recognizing these limitations, a new laminate lay-up has been developed to improve the CFRP performance [14]. This new laminate consists of metal layers with a thickness of less than 0.08 mm and unidirectionally aligned fiber layers which are stacked as alternating layers of metal and fiber. Hence, stiffness and strength in the 0°-direction are not reduced in comparison to the use of variant fiber directions. The metal layers deflect inter-fiber-fracture in zones of delamination; they serve as crack arrest layers and the energy dissipation is elevated due to the increase of the delamination area as a consequence of an increased number of interfaces within the laminate. Transverse stiffness and strength are increased compared to unidirectional laminates while the specific stiffness in the 0°-direction is higher compared to common multi-axial CFRP laminates (Fig. 20.6).

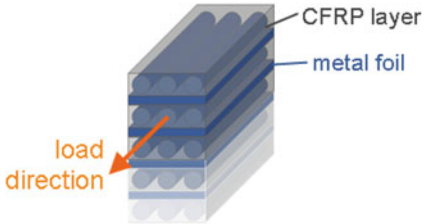

Fig. 20.6 Unidirectional fiber metal laminate [22]

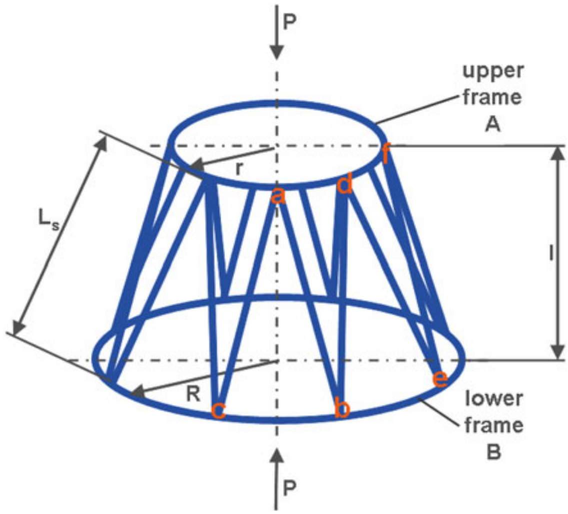

Fig. 20.7 Geometrical relations for framework adapter

20.5 Analytical Preliminary Design of Framework-Design

The local and global buckling of the structure is estimated for the preliminary design and the bending moment in the frame is investigated. Based on these results, different adapter configurations are compared.

20.5.1 Geometrical Relationships of Struts in a Conical Framework

Figure 20.7 shows the proposed conical framework structure [15] for the adapter.

The length L_s shown in Fig. 20.7 is determined by

$$L_S = \sqrt{R^2 + r^2 + l^2 - 2Rr\cos(\pi/n)} \quad (20.1)$$

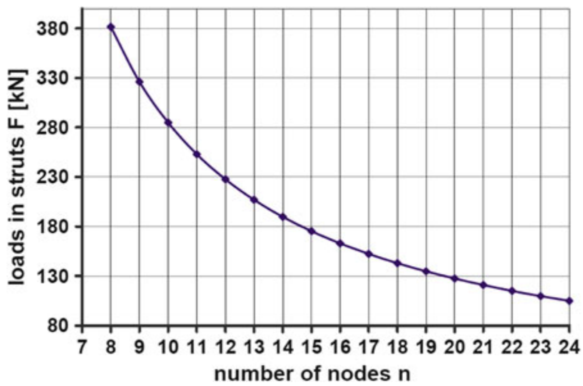

Fig. 20.8 Strut loads as a function of the number of nodes

The normal forces in the struts F of a conical framework due to the load P are

$$F = \frac{PL_S}{n2l} \tag{20.2}$$

The graph in Fig. 20.8 shows the relation between strut forces and the number of nodes for a given load case. Increasing the number of nodes from 8 (equals 16 struts) to 24 (equals 48 struts) reduces the normal strut forces by a factor of 3.64.

20.5.2 Estimation of Local and Global Buckling Stress of Struts

The global and local buckling stresses of struts with a square cross section, as shown in Fig. 20.5(b), are estimated as follows [16, 17]:

$$\sigma_{buckl.global} = \frac{\pi^2 E_1 I_{\min}}{A_S (\nu L_S)^2} \tag{20.3}$$

$$\sigma_{buckl.\text{local}} = \frac{\pi^2 t_{lam.}^2}{6b^2}\left(\sqrt{\tilde{E}_1 \tilde{E}_2} + \tilde{E}_1 \mu_2 + 2G_{12}\right) \tag{20.4}$$

$$\tilde{E}_1 = \frac{E_1}{(1 - \mu_1 \mu_2)} \tag{20.5}$$

$$\tilde{E}_2 = \frac{E_2}{(1 - \mu_1 \mu_2)} \tag{20.6}$$

For struts with a circular cross section, the global and the local buckling stresses according to [15, 18, 19] are

$$\sigma_{\text{buckl.global}} = \nu \frac{\pi^2}{2} E_1 \left(\frac{R_S}{L_S}\right)^2 \tag{20.7}$$

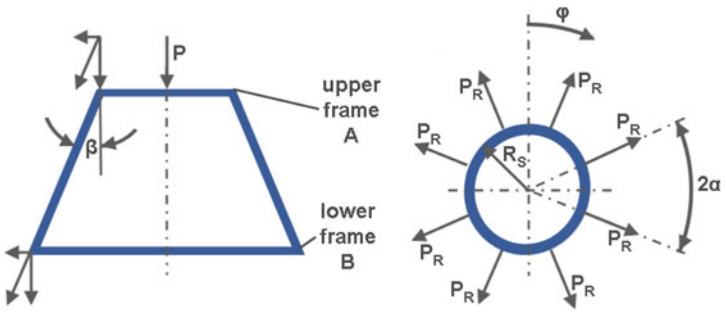

Fig. 20.9 Radial loads in adapter frames

$$\sigma_{buckl.\mathrm{local}} = \frac{1}{\sqrt{3(1-\mu_1\mu_2)}}\sqrt{E_1E_2}\frac{t_{lam.}}{R_S}\sqrt{\frac{\sqrt{E_2/E_1}+2G_{12}(1-\mu_1\mu_2)/E_1+\mu_2}{2\sqrt{E_2/E_1}+E_2/G_{12}-2\mu_2}} \quad (20.8)$$

The effective buckling length factor $v = 1$ that, represents a simple support of a bar is used for the calculation of the global buckling stress with Eqs. (20.3) and (20.7). The non-axially symmetric buckling-stress is estimated with Eq. (20.8).

20.5.3 Radial Loads in Frames

As a consequence of the conical adapter shape, radial loads P_r (Fig. 20.9) act in the nodes a, b, c, d etc. (Fig. 20.7).

The radial loads P_r are given by

$$\mathrm{P}_r = \frac{P}{n}\tan\beta \quad (20.9)$$

The relation of radial loads P_r in frame B as a function of the number of nodes is given in Fig. 20.10. Increasing the number of nodes from 8 (equals 16 struts) to 24 (equals 48 struts) reduces the radial loads P_r by factor 3.

20.5.4 Maximum Bending Moment in Frames

The radial loads $\mathrm{P_r}$ generate a bending load in frame B. According to [16] and [20] for $0 \le \varphi \le \alpha$ (see Fig. 20.9) the bending moments in frame B are estimated by:

$$M = \frac{P_rR}{2}\left(\frac{\cos(\varphi)}{\sin(\alpha)} - \frac{1}{\alpha}\right) \quad (20.10)$$

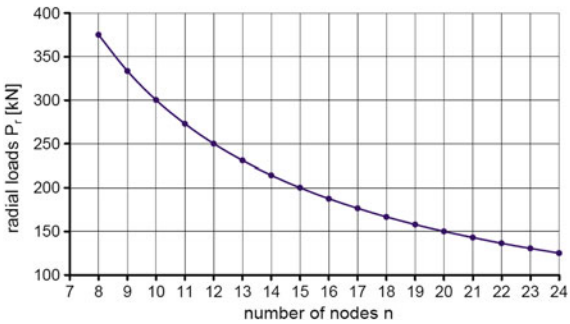

Fig. 20.10 Radial loads in frame B as a function of the number of nodes

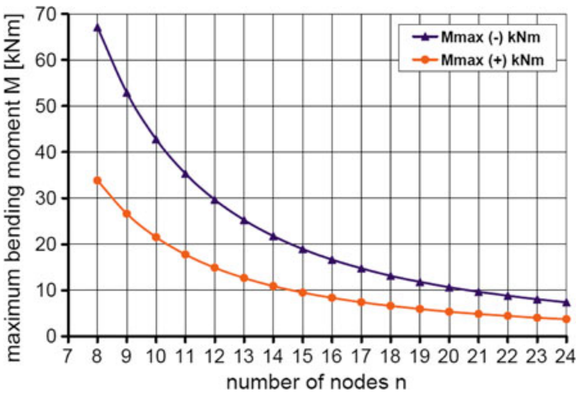

Fig. 20.11 Maximum bending moments in frame B as a function of the number of nodes

in which the angle α is

$$\alpha = \frac{\pi}{n} \tag{20.11}$$

The positive maximum bending moments in frame B occur at angles $\varphi = 0, 2\alpha, 4\alpha \ldots$:

$$M_{\max}^{(+)} = \frac{P_r R}{2}\left(\frac{1}{\sin(\alpha)} - \frac{1}{\alpha}\right) \tag{20.12}$$

The negative maximum bending moments in frame B prevail at angles $\varphi = 1\alpha$, $3\alpha, 5\alpha \ldots$:

$$M_{\max}^{(-)} = \frac{P_r R}{2}\left(\cot(\alpha) - \frac{1}{\alpha}\right) \tag{20.13}$$

The maximum bending moments in frame B as a function of the number of nodes are given in Fig. 20.11. Increasing the number of nodes from 8 (equals 16 struts) to 24 (equals 48 struts) reduces the maximum bending moment almost by a factor of 7.

Table 20.1 Weight reduction compared to CFRP-sandwich reference; V_M: metal volume fraction

Configuration	1	2	3	4
Description	CFRP 76.5/ 23.5/	CFRP-titanium	CFRP 75/25/0	CFRP-steel
Metal volume fraction (%)	0	1.74	0	3.1
Cross sections struts (mm)	Quadratic 49 × 49	Quadratic 45 × 45	Circular radius: 28.2	Circular radius: 30.1
Thickness laminate (mm)	2.125	2.29	2	1.29
Weight reduction (%)	25.2	24.5	29.4	36.9

20.5.5 Weight Saving Potential of Framework Configurations

Detailed investigations prove that the total weight is nearly independent of the number of nodes for the considered node numbers in the previous calculations. However, based on the considerable reduction of the bending moments in frame B for increased node numbers, n = 22 nodes are selected for further investigations. A further increase of the node numbers seems unnecessary since the maximum bending moment asymptotically approaches a lower limit.

The weight reduction of the struts is regarded as a primary optimization parameter. Struts of pure CFRP and unidirectional CFRP-steel-laminates are investigated based on a classical optimization method. Laminate thickness, strut diameter and lay-up are systematically varied to reach a similar safety margin against compression failure as well as local and global buckling in the struts.

Therefore, two different unidirectional fiber metal laminates (CFRP-titanium and CFRP-steel) with following parameters were investigated:

- thickness of CFRP-layer (prepreg): $t_{CFRP} = 0.125$ mm
- thickness of titanium- and steel-layer: $t_{titan} = t_{steel} = 0.01$ mm
- fiber orientation in CFRP layer: exclusively in the direction of the applied load (unidirectional)
- metal volume fraction V_M: 1.43% up to 7%

Following the described optimization method, the total weight of the adapter was calculated for different configurations of the derived bending loads in frames A and B using the given material parameters. The four most promising configurations are listed in Table 20.1, whereas the weight reduction is given in comparison to a reference CFRP-sandwich construction. Therein no coupling elements are considered, neither for the framework nor for the sandwich design.

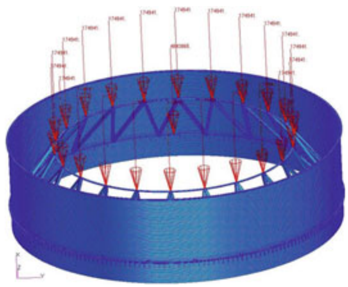

Fig. 20.12 External load application

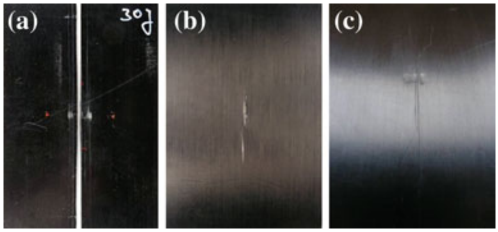

Fig. 20.13 (**a**) Damage after 30 J impact; UD (**b**), [62.5/25/12.5] (**c**); [92.5/7.5St/0]

20.6 FEM Analysis for Preferred Framework Configuration

The intention of the FEM-calculation is the validation of the analytical solutions for the framework and the sandwich design of the adapter. MSC software PATRAN (pre- and post-processing) and NASTRAN (Solver) was used for the simulations.

The 44 struts of one of the framework configurations are modelled with beam-elements. The connection between beam and barrel is modelled with RBE3 elements. The loads are applied to the nodes according to Fig. 20.12.

The FEM-results show a good agreement with the analytical solutions.

20.7 Experimental Investigation of Unidirectional CFRP-Steel-Laminates

Compression-After-Impact (CAI) examinations with 30 J impact were performed at CFRP-UD-laminates, CFRP-62.5/25/12.5-laminates and CFRP-UD/steel-laminates with different metal volume fractions using metal foils of 0.05 mm thickness. The UD-laminates showed catastrophic failure after impact, whereas the residual strength after impact could be tested for the other lay-ups, see Fig. 20.13.

The CFRP-UD/steel-laminates showed higher values for residual compression strength and demonstrated an elastic modulus increased by 65% compared to the CFRP-62.5/25/12.5 reference laminate (Fig. 20.14).

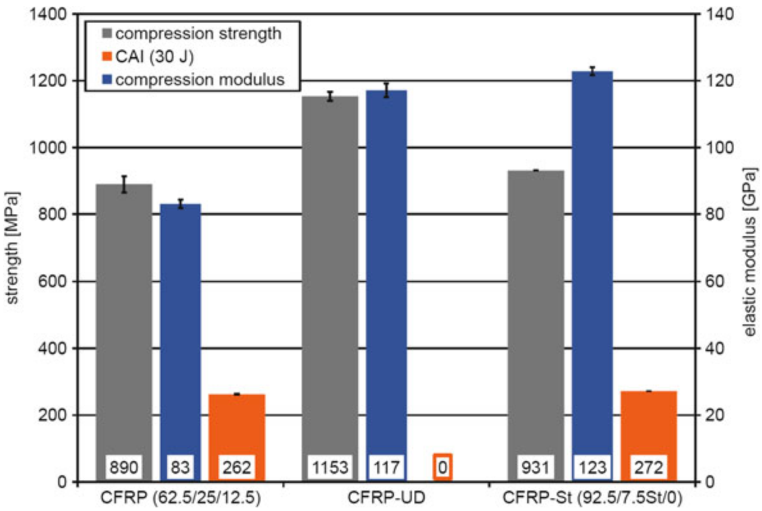

Fig. 20.14 Compression properties

20.8 Conclusion

Advantages in weight efficiency of an adapter in framework design compared to a sandwich design could be shown analytically. The results were validated by a numerical simulation showing very similar values. The weight efficiency can be improved by using unidirectional CFRP-steel-laminates. However, damage tolerance properties have to be proven for these novel materials. Experiments for a steel thickness of 0.05 mm showed promising results, but thinner foils offer a higher potential for the regarded adapter.

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