HISTORY AND LESSONS LEARNT FROM THE DEVELOPMENT OF MECHANICAL SYSTEMS FOR DIFFERENT LAUNCH VEHICLES

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OVERVIEW

This paper summarizes the history of the mechanical developments – mainly load carrying structures but also payload adapters and shock attenuators – made by EADS CASA Espacio during the last thirty years for all the Ariane (from Ariane 1 to the last developments in Ariane 5), the Vega, the Soyuz and Rockot launch vehicles and tries to extract lessons learnt from technical (mass, load carrying, stiffness capability) and programmatic (develop-ment and production approach) point of view.

A discussion about the following topics will be included into the paper:

- Is it better to use composite materials everywhere? If not, what are the best suited cases for composites?
- What could be a goal for performance improvement with respect to the currently applied solutions?
- Could it be implemented in existing ELVs (Expendable Launch Vehicles) some mechanical solutions applicable to the challenge requested by the development of RLVs (Reusable Launch Vehicles), in terms of performance improvement?
- Are the conclusions obtained for launcher structures applicable to satellite structures?

PART I : MORE THAN THIRTY YEARS DEVELOPING LAUNCHER MECHANICAL ELEMENTS

1. THE FIRST ARIANE LAUNCHERS: ARIANE 1 TO ARIANE 3

During the year 1974 and as a consequence of the agreement reached (reference [1]) between the companies SNIAS (F) and CASA (E), the first development of launch vehicle flight elements was started in Spain: they were two load carrying structures of the Ariane 1 first stage:

- The Intertank Skirt was a cylindrical structure of around 4 meters of diameter and 2.7 meters of height, made using classical aeronautical metallic construction: aluminium alloy for skins, external stringers and internal longitudinal and circumferential reinforcements. Both interface rings with the two main tanks of the stage were optimized from already existing similar designs (as the one of the Blue Strike launcher -reference [1]-) changing the material from steel to aluminium alloy. All the elements were joined together by means of rivets.

FIG 1. Ariane 1 Intertank Skirt

- The Forward Skirt was also a cylinder with the same diameter but shorter: 1.5 meters was its total height. Materials and processes were similar to the ones used for the another skirt.

FIG 2. Ariane 1 Forward Skirt

Total development time for those two structures was less than three years up to their qualification tests made in 1977. It is important to state that NASTRAN finite element code was used for the first time in Spanish aerospace industry for this design.

Ariane 3 introduced auxiliary boosters attached to its first stage and the upper joint between the boosters and the launcher was made on to the Intertank Skirt. A general re-design – increasing skin thickness – and the implementation of an internal reinforcement circumferential box to withstand the local loads coming from the boosters were made. A new qualification test was made. In this case the development program up to qualification was made in less than two years.

2. THE FIRST COMPOSITE STRUCTURES: ARIANE 4

The use of liquid or solid propellant boosters attached to the Intertank Skirt of Ariane 4 implied another design update for this structure: better aluminium alloy was used, reinforcement of the box and additional attachment points were implemented. A new qualification test campaign was also made. This development was again made in less than two years.

Ariane 4 was the launcher implementing by first time composite (CFRP) structures in Europe, specially in the upper stages of the vehicle. This was the case of the Vehicle Equipment Bay Structure (see FIG. 3).

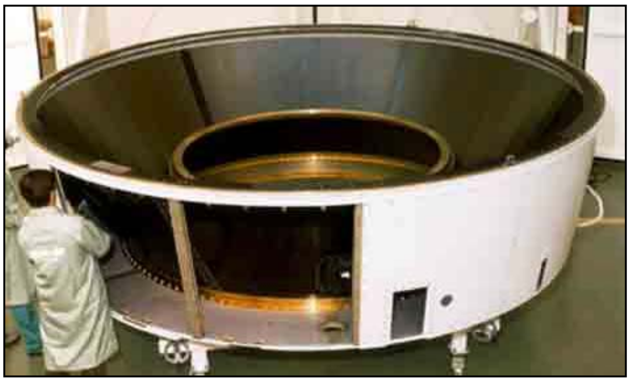

FIG 4. Ariane 4 Vehicle Equipment Bay

The VEB inner and outer cones were made of CFRP sandwich with interface aluminium rings at both ends bonded and riveted to the sandwich. The equipment platforms were aluminium sandwich panels and the external careenage panels were made of GFRP sandwich. The reinforcement ring placed at the upper interface plane (to withstand the important radial load of the fairing horizontal separation system) of the external cone was also made with CFRP sandwich with very thick faces.

A development team between MATRA SPACE and CASA was established to develop the VEB Structure: inner cone was developed by CASA and the rest was developed by MATRA. CASA manufactured and assembled the complete VEB Structure. In this case the development time was less than 4 years (1982-1986). Qualification tests were made at CASA Getafe Plant in 1986.

But Ariane 4 was also the first launcher where CASA reached a First Level Contractor role developing their first Payload Adapters. Three payload adapters corresponding to the three standard diameters were developed, using for all of them *marman* clamp separation systems from SAAB:

- 937-B Adapter was a CFRP sandwich structure with aluminium bonded and riveted rings.
- 1194-V Adapter was also CFRP sandwich with aluminium bonded and riveted rings.
- 1666-A Adapter was metallic – aluminium skin with riveted stringers and rings - .

The Payload Adapters geometry is always conical with a common lower interface (1920 mm diameter in the Ariane 4 case) and different upper interfaces corresponding to standard values. It is important to mention that 937-B and 1194-V were cocured structures: the CFRP sandwich cones were obtained as a single piece in one autoclave curing cycle: automation of CFRP structures was starting. A typical development time for any of those adapters was 2 to 3 years.

FIG 3. Ariane 4 1666A Payload Adapter

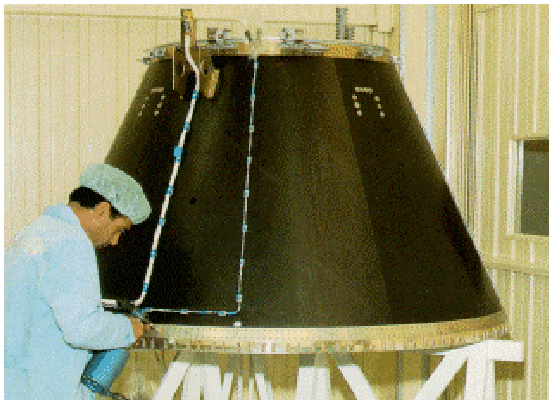

FIG 5. Ariane 4 937B Payload Adapter

3. ARIANE 5: UPPER PART STRUCTURES AND MECHANICAL SYSTEMS

With the starting of the development of Ariane 5, CASA reached a prominent role in the development of different structures and mechanical systems for the upper part of the launcher.

This is a list of the main developments in load carrying structures:

- VEB Structure composed by an external cylinder with a diameter of 5.4 meters and a height of 1.1 to 1.6 meters (depending on the versions), an internal cone passing from the outer diameter of 5.4 to the inner of 3.936 meters, interfacing with the EPS stage or the 3936 cone adapter and an equipment platform – aluminium sandwich panels – supported by the internal cone. There are five types of VEB Structures for Ariane 5:

1) **Type A:** The external cylinders (there are two of them separated by a ring containing a separation system) are metallic but made from machined aluminum panels with integral stringers riveted between them and to the interface rings. The internal cone is CFRP sandwich made from cocured sectors assembled by bonding and riveting and also bonded and riveted to the rings.
2) **Type B:** The external cylinders are made also in CFRP sandwich sectors. The main aim of this development was to reduce the structural mass.
3) **Type C:** For the ECA version of the launcher the separation system is included in another structure and, then, the lower cylinder disappears. The internal cone is reinforced to withstand bigger satellites.

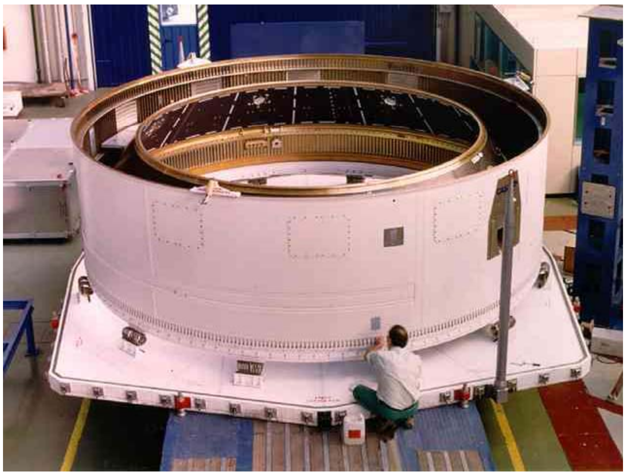

FIG 6. Ariane 5 VEB Structure Type A

FIG 7. Ariane 5 VEB Structure Type D

These three first VEB Structure developments strongly influenced by the launcher development itself and with many modifications in the requirements have filled a very long period: more than 14 years have passed between the starting of VEB Type A and the end of the development for VEB Type C.

4) **Type D:** This is a special development made for ATV launching where the complete primary structure has been redefined: both cylinders and the cone are made in a single cocured piece each one using automatic fiber placement technology. This new concept has been developed in shorter time: around 2 years up to the qualification recently pronounced.
5) **Type E:** Based on the type D VEB Structure a new and much more robust structure is currently being developed for the new ECA version of Ariane 5. This last VEB design started to be developed at the end of 2005 and the qualification test campaign is going to start in some weeks (April 2007).

- EPS Structure: this is a structure attached to the upper interface of the VEB cone (3936 mm diameter) and, by means of a cone provides a transition to the 2624 mm diameter. Another important function is to support the four propellant tanks and the engine of the EPS stage. It is made in CFRP cocured sandwich for the cone and the shear panels and aluminum alloy sandwich for the tank/engine support platform. The total height of the cone and platform is 1.16 meters. The rings and brackets connecting the different elements are metallic and bonded-riveted to the corresponding sandwiches. It has also a set of CFRP struts to support pressurization Helium tanks (not shown in fig. 5). The main development of EPS was made in 5 years (1991 to 1995) - several changes of requirements were taken into account -, although additional tests and analyses have been performed up to now in order to assess the robustness and margins in the structure.

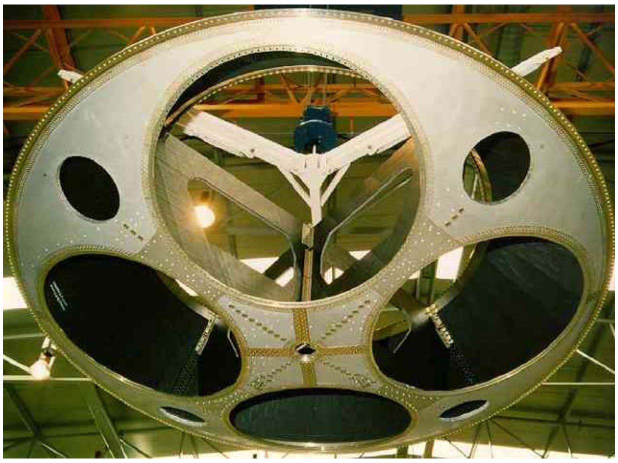

FIG 8. Ariane 5 EPS Structure

- ISS Structure: this is a skirt (similar to the ones developed for Ariane 1 to 4 in the first stage) connecting the VEB and the Hydrogen tank in the cryogenic version of Ariane 5. It has a diameter of 5.4 meters and a height of 2.9 meters. Being an upper part structure it has been made as a **cocured single**

piece CFRP sandwich, but using the automatic fiber placement technology in order to improve the quality and adjust the cost of the structure. It contains a pyrotechnic separation system integrated into its upper interface ring to separate the lower EPC stage from the upper ECA one. Development time in this case was three years. This was the very first CFRP sandwich structure made in Europe using fiber placement technique.

FIG 9. Ariane 5 ISS CFRP Sandwich

- 3936 Conical Structure: this a raising cone between diameters 3936 mm and 2624 mm (its total height is 0.783 meters) to be used instead of the EPS for the ECA version of Ariane 5. The fiber placement technology has been again applied and, in this case, the overall structure is obtained as a single piece from the curing: it is monolithic CFRP with both rings obtained machining thicker interface areas (see fig. 6). This was a short development: only 18 months.

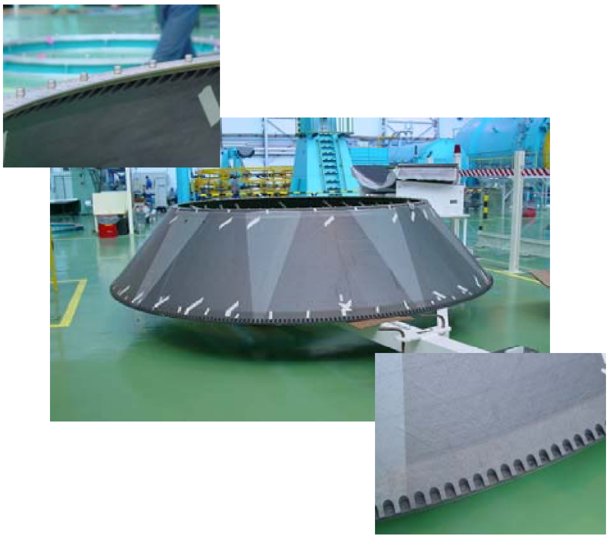

FIG 10. Ariane 5 3936 Cone with integrated CFRP rings

But together with those structure developments, EADS CASA Espacio continued and expanded their Ariane 4 expertise on Payload Adapters becoming the leading provider of those systems for the different versions of Ariane 5 launch vehicle. Taking into account the criticality of pyrotechnically induced shocks in Ariane 5 upper part, a new kind of mechanical systems has been developed: the shock attenuation systems. The main members of both families are as follows:

- Payload Adapters 937 B and 1194 VB5 similar to the Ariane 4 ones, but with the 2624 mm diameter lower interface (Ariane 5 standard). 1666V is a case were the shape is not conical (see fig. 7) but the structural concept is the same.

FIG 12. Ariane 5 1666V Payload Adapter

- The new 1194H adapter was developed aiming to launch the new heavy satellites appearing during the last years of the past century. This adapter had a structural design similar to the one of 3936 cone (monolithic CFRP automatically produced using fiber placement with integrated lower ring and the upper aluminum one bonded and riveted). A completely new separation system was developed for this adapter: CRSS allowed to increase the satellite mass and reduced significantly the shock induced by the clamp-band release.

FIG 11. Ariane 5 1194H Payload Adapter and one of the Shock Attenuators

- Thinking in future ECA versions of Ariane 5, a new family of Payload Adapters are being developed now: they are called PAS (Payload Attachment System) and two main members will be available for flight during the current 2007 year: PAS 1194 and PAS 937. The structure is the same for both models (1194 is obtained from 937 cutting it at the corresponding diameter) and similar to the one of 1194H, but a new shockless separation system has been developed for this family: LPSS is much more robust than its predecessors, has bigger load capability (satellites of more than 7 Tons can be launched with 1194 interface) and reduces the release shock spectrum by a factor of 5 with respect to CRSS.

FIG 13. Qualification Test of PAS 1194

- Concerning the Shock Attenuation Systems two types of them has been developed: one having two configurations (load carrying one and shock filtering one) called generically SAD (Shock Attenuation Device). Three different SAD have been flown: one with ENVISAT (SAD-6 blades), one with INSAT3A (SAD-3 blades) and one with MSG-2 (GSAD). The design is similar for the three cases: two aluminum rings (2624 mm interface diameter) are attached by a clamp band (CRSS type) during the loading phase of the Ariane flight. The separation system is released just before the shock event and the two rings are slightly separated and they continue being attached by a discrete number of points (blades) filtering the structural vibration modes produced by the pyrotechnic shock.
- The another type of shock attenuators are passive structures introduced in the shock propagation path to filter it by a local increase of mass (this is the case of MFD-C) or a local decrease of stiffness (this is the case of PSAD).

Development times for Payload Adapters and Shock Attenuators range from the minimum PSAD (3 months) to the maximum of 1194H (around three years but developing two versions of CRSS).

4. DEVELOPMENTS FOR ANOTHER LAUNCHERS: SOYUZ, ROCKOT AND VEGA

Based on the Ariane experience, several developments have been made for three main launch vehicles:

- For Rockot only separation systems CRSS 937 and 1194 have been made based in the existing Ariane concept but with a different band opening system (pyronut instead of pyrobolt cutter).
- For Soyuz different Payload Adapters have been made: 937 adapter uses a CRSS separation system on top of a CFRP sandwich adapter with a design similar to the 937B of Ariane (except the 8 interface brackets at the lower base of the cone) and there are two types of 1194 adapter for Soyuz: one is a metallic monolithic cone machined in a single piece and the another one has a similar structure to the one of the 937 adapter, being possible the use of any separation system: the classical marman-clamp or the CRSS one.
- Special mention is made to upper part VEGA developments:
    - AVUM and IS3 structures combine aluminum alloy cylindrical parts (1920 mm typical diameter) with aluminum sandwich structures for equipment or tank support. Total height of AVUM is xxx mm and IS3 is xxx mm high. IS3 contains a pyrotechnic separation system able to decouple the stages 2 and 3 of the launcher.
    - Payload Adapter for Vega is a CFRP monolithic cone with metallic rings, starting at 1920 mm standard interface and having 937 or 1194 satellite interfaces. Separation System is CRSS. The total height of 937 adapter is 1461 mm.

The three VEGA elements are currently under development with qualification expected in 2007 and first flight in 2008.

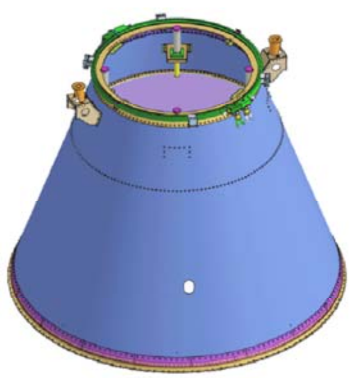

FIG 14. CAD model of VEGA 937 Adapter

PART II : SOME LESSONS LEARNT

1. DEVELOPMENT OF STRUCTURES

Looking at the different types of load carrying structures developed in the past thirty three years we have learnt that:

- **Composite structures are able to withstand much bigger loads with less mass (or reduce more the mass to withstand similar loads).** Only as an example: A5-ISS (fig. 5) is a cylinder bigger in size than A4-IT Skirt (fig. 1 left) - 5.4 m Ø and 2.9 m high for ISS compared with 4 m Ø and 2.7 m height for the A4-IT Skirt - , their total masses are similar (870 kg for ISS and 900 kg for A4-IT Skirt), but the maximum compression flux for the A4 Skirt was 198 N/mm and the A5 Composite Sandwich ISS is designed to withstand fluxes of 400-600 N/mm. Another example is the comparison between VEB Structure Type A and Type B the first one with metallic external cylinder and the second with CFRP sandwich one: structural mass 860 kg compared with 695 kg (see table 1).
- **Composite structures are strongly dependant from the design solutions and manufacturing processes** selected to apply on to them (basic material components – resin and fiber - lay-up, curing cycle, discontinuities, bonded areas, stress concentration around holes, etc…) and they must be carefully characterized and the overall process, including a "design for manufacturing" need to be controlled. Depending on the knowledge of the proposed design and processes and depending on the structural details, it is advisable to use a margin policy imposing minimum margins to different structural parts in order to increase the reliability.
- **Hand made composite structures, using sandwich construction and sectors to be assembled, with bonded and/or riveted metallic rings are much less robust than single piece, automatic layering, monolithic and integrated rings ones.** The lack of robustness comes from:
  - Higher number of parts to be assembled means higher complexity and number of uncertainty sources (any internal interface between parts to be assembled is by nature a source of uncertainty: bonding integrity, tolerances, tightening torques, etc…).
  - Hand made layering is less repeatable than automatic one.
  - Sandwich is more complex than monolithic.

  In the table 1 a comparison between the different models of VEB Structure for Ariane 5 is made: Type D and E have been designed to the shown loads, but with a margin policy of 50% in sandwich trying to cover any uncertainty. Type C has been qualified only to 85% of the load on cylinder and 60% on the cone (lack of robustness).

- **A less robust structure implies much higher development costs** (more test and analytical verifications to be done trying to characterize the uncertainties) **and also higher recurrent costs** (more inspections trying to limit the scattering).

	Mass [Kg]		Sizing Line Load [N/mm] (1)			
			Aft Cylinder			Fwd Cone
Model	Total	Struct.	Φ_{AVG1} (2)	Φ_{AVG2} (3)	Φ_{MAX} (4)	Φ_{MAX}
Type A	990.	860.	120.	230.	750.	270.
Type B	876.	695.	120.	230.	750.	270.
Type D	1080.	900.	–	240.	770.	450.
Type C	730.	560.	140.	375.	450.	500.
Type E	772.	600.	–	344.	391.	220.

(4) Limit flux
(4) Theoretical value (N, M & T)
(3) Envelope value taking into account EAP overflux
(4) Maximum flux

TAB 1. Ariane 5 VEB Structure Mass & Sizing Load Evolution

2. DEVELOPMENT OF PAYLOAD ADAPTERS

The table 2 shows a comparison of performances for the different payload adapters developed by EADS CASA Espacio in the last twenty years for Ariane launchers.

	Mass [Kg]	It can lauch payloads up to		Shock at 1000Hz (g)	Shock at 2000Hz (g)
		Mass (kg)	CoG (m)		
Ariane 4					
ACU 937B	60	4000	1.1	1000	3000
ACU 1194V4	75	4500	1.7	2800	4500
ACU 1666A	50	3900	1.85	2400	2700
Ariane 5					
ACU 937VB5	145	3200	1.3	2100	4000
ACU 1194V5	145	5000	1.2	2800	4500
ACU 1194H	160	6700	2.1	700	1900
ACU 1666V5	145	4500	2.0	2100	5800
PAS 937	153	4000	1.5	< 700	< 600
PAS 1194	156	7000	2.4	< 700	< 600

TAB 2. Ariane 5 Payload Adapters Mass & Typical Performances

The main conclusions and lessons learnt from those developments are as follows:

- **The mass of the adapter itself must not be the main concern for bigger launchers** (see the masses on the table 2, compared with the performances), like all the cases shown in table 2, corresponding to Ariane 5 (although a mass optimization is always requested), but it can be a critical parameter for smaller launchers like VEGA.
- The conclusions about the upper part structures are also applicable for the adapter structures: **robust designs with small number of components and quasi "all-composite" structures** (upper ring is yet metallic for satellite interface reasons) **are preferable**.
- **The separation system is a critical component of the adapters**: high performance and low shock separation systems are common nowadays (evolution

in the shock induced by the release of the separation system is impressive as the table 2 shows): the satellite manufacturers want standard interfaces but also comfortable environments, without forgetting that the main requirement of a separation system is the reliability.

- **The adapters must be easily "adaptable" to each satellite to be launched**: redefinitions of missions are very common: this factor has a direct implication in the way of designing and producing these systems: parameterization and standardization in design, modularity and fast reaction to changes in manufacturing and assembly are of a key importance in this case.

3. DEVELOPMENT OF SHOCK ATTENUATORS

Shock attenuation systems are closely related with Payload Adapters, because their main function is to provide a smooth environment to the payload from high frequency vibration point of view.

The main learning in this case is that the generalization is very difficult: only the principles on how to apply the attenuation (filtering by stiffness, mass or damping or any combination of them) are general, because the application is particular for each case: depending on the characteristics of the payload and the shock to be attenuated.

Some of the conclusions valid for the structures are not applicable here, i.e.: small number of connected pieces is against the guideline of having as much interfaces as possible between the shock source and the payload.

PART III : FUTURE DEVELOPMENTS AND CONCLUSIONS

FUTURE DEVELOPMENTS

1) Based in our experience the future developments of launcher structures must follow some guidelines:

- **CFRP integrated and automatic solutions are more robust and cheaper** than CFRP classical hand intensive ones from an overall point of view.
- **CFRP structures are more optimum in terms of structural mass**. So, if the mass is a critical concern (where is more a concern the mass than in a launch vehicle or a satellite?) CFRP must be used.
- Concerning the cost, if we compare automatic and integrated CFRP structures with metallic ones, and take into account the over-mass of these last ones, **all the upper part and load carrying structures of a launcher should be made with composite materials**.

  An effort to qualify composite tanks and another launcher parts should also be made thinking mainly in the criticality of the mass reduction for RLVs.

- Thinking in basic materials and, mainly from a procurement point of view, **a common effort of standardization of CFRP (and also metals) together with the aircraft industry (the main current consumer deciding the market orientation) is urgent and necessary.**
- **CFRP shells with integral stringers and frames, automatically produced combining fiber placement and RTM parts co-bonding can be an affordable solution both from technical and cost points of view**.

As an illustrative example about how much mass can be saved from a very optimized CFRP current structure, see table 3. We can see there that only 66% of the total structural mass is the CFRP sandwich part, that the aluminum rings mass is very high (specially the upper one containing the separation subsystem) or the important mass of rivets/screws. Thinking that part of the aluminum ring mass is due to the sandwich configuration and type of rings and it can be optimized, a realistic objective of mass improvement for this structure (passing from sandwich to skin reinforced with stringers and reducing to the minimum the ring mass) conserving or improving its performances could be around 15%.

If we think that not all the structures in the launcher are so optimized as the ISS (already made using fiber placement in a single piece), a goal of 20% mass gain for all the launcher structures could be feasible.

	Mass [Kg]
Ariane 5 ISS	
CFRP Sandwich Shell	576
Lower Ring	95
Upper Ring	113
Pyrotechnic Cord	11
Rivets / adhesive	28
Supports / Inserts	6
Wiring	13
Doors	12
Thermal Protection	51
Screws, Nuts & Washers	16
TOTAL	921

TAB 3. **Ariane 5 ISS Mass Budget**

- But not only the material or structural construction must be reviewed: **an innovation in the development approach, introducing also innovation into the loads and requirement definition process, is necessary [ref. 2].**

2) Concerning the Payload Adapters the two main guidelines are as follows:

- **To transform the adapters into comfortable "seats for the passenger" concentrating on them as much responsibility as possible concerning the reduction of shocks, vibrations and any other mechanical environmental loading passing from the launcher to the satellite.** Passive attenuators and dampers and more complex active or semi-active systems will be introduced into the future Payload Adapters.
- **To automate – as much as possible - the**

customization process of the adapters: this will reduce the cost and increase the flexibility in front of the customers.

3) The above mentioned future developments in launcher structures can also be applied to the satellite ones. In this case the complexity is bigger because we have many different types of satellites: a telecom platform – with a recurrence of several models per year – is different from a scientific one – having a single protoflight model only - but , at least in some particular cases the launcher experience can be particularly useful for satellites:
   - Central tubes of future satellites can also be made of CFRP monolithic or reinforced shell solutions using automatic manufacturing techniques (see figure 15).
   - Integration of different structural parts avoiding connections and mechanical interfaces must be a driving factor to improve robustness.
   - Shock attenuation methods applied in launchers can be also applicable to satellites to reduce shock loads coming from internal or external sources.
   - Some techniques under development, thinking in monitoring the health of launcher structures – fiber optic sensoring specially applicable to RLVs – can also be of application to satellites.

FIG 15. Central Tube for Eurostar 3000 Platform: Monolithic CFRP made using automated fiber placement

CONCLUSIONS

New Launch Vehicles are requesting dramatic improvements in mass and cost with respect to the current values. This is specially important for future RLVs.

Innovative approaches both, for structural concepts and development processes can reach these ambitious objectives, but a proof of concept is necessary.

We have an example to follow: Boeing company set the objective of gaining 20% of mass “carbonizing” their new 787 airplane. Now, based on this innovative approach, Boeing have recovered terrain against their competitor Airbus [ref. 3].

Why not thinking in a “Black Launch Vehicle”?. It can be, in a first step (proof of concept) an evolution of an existing ELV or a big stage of it. A set of developments aiming to apply in an efficient cost way CFRP on it could demonstrate the reachable performances, extensively applicable also to the future RLVs.

And what about a truly “black satellite”?

REFERENCES

[1] Llorca, M. A. “The History of the Ariane launcher in Spain” – 57th International Astronautical Congress – Valencia (2006)

[2] Martín, J. “Innovation in Structures Engineering for Future Launch Vehicles” – 7th International Symposium on Launcher Technologies - Barcelona (2007)

[3] Gómez Molinero, V. “General View of the Spacesystem Structures Evolution and Future Challenges” – European Conference on Spacecraft Structures, Materials & Mechanical Testing – Noordwijk (2005)