INNOVATION IN STRUCTURES ENGINEERING FOR FUTURE LAUNCH VEHICLES • FACING THE 21ST CENTURY CHALLENGES

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OVERVIEW

The continuous strive for light, robust and affordable structural configurations for the future expendable and reusable launch vehicles obliges to reconsider the way things are being done. Novel structural configurations and manufacturing techniques are to be incorporated in the process. Efficient structural configurations definition and verification require the use of non-traditional analytical techniques.

The hurdles we might encounter are numerous. The excessive conservatism, totally legitimate in the past, that prevails in this industry and the existing risk averse mentality profoundly hinders the practical and industrial application of innovative concepts.

The necessary paradigm change is not dramatic, most of the concepts and techniques are already existing (with different maturity level), and, in some cases, have been applied to different projects. Adequately funneling all this can provide the needed technological leap forward.

Through all the years that EADS CASA Espacio has been actively involved in the development and production of primary structures for the Ariane, Soyuz/Starsem and VEGA launch vehicles, some of these innovative technologies have been incrementally applied. Structural configurations as unitized composite structures, composite iso-/ortho- grid panels and shells have been developed and, in some cases, applied to flight hardware. Manufacturing techniques as fiber placement and RTM co-bonding have demonstrated to provide a reliable, rapid and repetitive serial production of large structures.

The concept of uncertainty is present through all the structural verification process. The deterministic approach, presently prevailing, considers ‘extreme situations’ in ‘worst-case scenarios’, applying factors to ‘guarantee’ structural integrity. Non-deterministic approaches deal with ‘typical situations’ in ‘realistic scenarios’. These approaches bring the engineering closer to the reality. Tools for reliability-based structural verification are available. Their use, replacing the deterministic MoS computations, would allow for the design of more efficient and robust structures.

This paper will provide an overview of all these novel technologies for structures engineering, giving practical examples of their use and proposing an application scenario for future launch vehicle structures.

1. INTRODUCTION

To achieve a low-cost access to space, the future launch vehicles must be lightweight, fully reusable and easily maintained. The economic viability of the RLV (Reusable Launch Vehicle) depends to a large extent on achieving target empty weight of the vehicle.

In order to minimize weight and cost, innovative concepts, adequate materials and manufacturing processes, and refined analytical techniques are required for the major structural components.

The cost-effective manufacturing of large composite structures, required for a RLV, is necessarily based on automated processes. The **A**utomated **F**iber **P**lacement (AFP) technology is the most promising fabrication method for rapid and cost-effective composite part manufacture.

The different technologies that are needed are being developed. This development is intended to attain the sufficient level of maturity to apply them to actual structures. Bearing this objective in mind, EADS CASA Espacio has been gradually developing and implementing new design concepts. An important outcome of this continuously evolving innovation process is the all-composite structure. This all-composite structure is a fully integrated component. A conical skirt of the Ariane 5 Launch Vehicle is produced in a single piece with important benefits in terms of cost and mass in comparison with the conventional design concepts.

The innovation process continues either as incremental innovation (improvement of the integrated ring concept of the unitized CFRP conical skirt) or as radical innovation (iso-grid shells for future launch vehicles).

2. INNOVATION IN STRUCTURES ENGINEERING

2.1. Innovation Initiatives

Paraphrasing [2], structural design should be a creative process. Innovation is the “life-blood” of better designs.

One of the most misunderstood innovation initiatives was NASA’s ‘Faster, Better, Cheaper’. Fostering this initiative, Dan Goldin was looking for a bold change in the way things were being done. He wanted the limits of the technology to be pushed. This initiative wanted to promote the utilization of new technologies.

As described in [6], any new technology goes through three phases. The first is that of naïve euphoria – unrealistic expectations resulting from overreaction to immature technology. The second is cynicism, or frustration associated with unmet expectations. The third is that of realistic expectations – gradually realizing the true benefits from the technologies (see FIG 1).

This evolution is to be born in mind by all the parties involved in the development and practical application of any innovation.

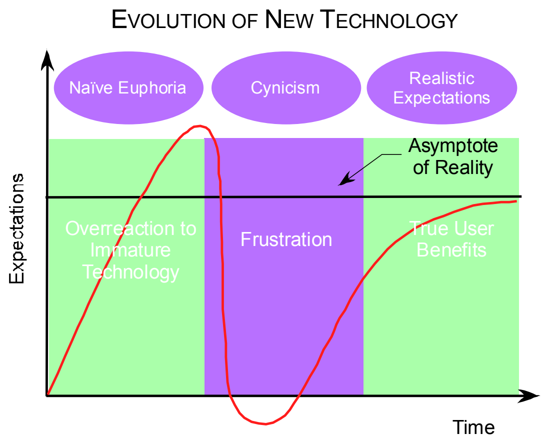


FIG 1 – Evolution of New Technology

Any of the multiple facets of structural engineering is a candidate for innovation. Structural concepts, analytical methodology, materials technology, testing approach, … Trying to adequately cover all of them in a single paper is totally impossible. This paper will focus in innovation related to structural concepts and analytical verification methodologies.

As reported in [3], " 'Better, faster, cheaper' does not mean a trade-off among the three, but rather innovation and good technical judgment so that resources are applied to those factors that eliminate the most risk in each."

The emphasis is shifting from design for performance at any cost to design for affordability.

2.2. Innovation and Risk. Travel Companions

The history of composites teaches us that innovation will be the norm for a long time to come. The presence of applicable service experience will be the exception and uncertainty is a concept we will have to learn to contend with in risk management..

Innovation challenges the structural safety, because "the validating service experience" is not available. To compensate this lack of service experience, explicit safety constraints are introduced into the structural design process – robustness. This additional safety constraints often penalize the proposed innovative design.

The uncertainties commonly associated to innovation are directly translated into additional risks. Some risks have to be taken, but not blindly. Risks are to be managed. Unexpected incidents can occur when working on the boundaries of the state-of-the-art, squeezing to the limit the existing technologies and being eager to innovate. By learning from those incidents we are building a solid foundation to tackle the next challenge.

If we don't recognize and accept this, we, engineers, will become overly risk averse, losing our capability to make decisions and producing the stagnation of the technology.

2.3. Need for a Paradigm Shift

Lockheed Martin Skunk Works is widely recognized as the example to follow with regard to innovation in the aerospace industry ('skunk works' and innovative design are practically synonyms). One of their postulates was that standard specifications inhibit new technology and innovation. The present tendency in the space industry is the over-specification and the bias towards well proven concepts. Real requirements and 'desirements' are mixed up, limiting the innovation possibilities.

All those aspects precluding innovation in structural engineering are to be questioned. Non traditional approaches are to be followed and risks have to be taken. A cultural change is in order.

3. INNOVATION IN STRUCTURAL CONCEPTS

EADS CASA Espacio has always been striving for an effective utilization of advanced composites in space vehicle structures. The permanent obsession for mass reduction makes to the launch vehicle and spacecraft structures the perfect candidates for the use of composite materials. The future launch vehicles structures would profit from all this experience.

An important step towards the weight reduction is the direct consequence of the use of advanced composite material for the different structural components. The cost of manufacturing composite structures has been the biggest obstacle for its widespread use. This is because of design and manufacturing approaches that use composite materials in the conventional 'metals fashion' of assembling large numbers of mechanically fastened parts ("black aluminium designs").

A fully coordinated design approach involving larger, integrated components to maximize producibility, quality and design efficiency is needed to fully exploit the weight and cost benefits of composites.

Low-cost composites manufacturing processes include tow placement, resin transfer molding, … A promising structural concept for low-cost automated manufacturing is advanced grid stiffened structures, which evolved from early iso-grid stiffening concepts and feature a lattice of rigid, interconnected grids.

3.1. Motivations for Innovation in Launch Vehicle Structures

The arrival of the carbon fiber to the aerospace industry opened great expectations with respect to the potential mass savings that could be attained. The upper structures of the launch vehicles were excellent candidates for the use of this innovative material. The saving of one kilogram of mass directly implied the possibility of increasing the payload mass in one kilogram. The ideal of the all-composite structure soon appeared as one of the objectives. But the materials and processes were not in line with this objective.

Materials engineering, and manufacturing techniques and processes had to evolve. Composites design technology suffered from a lack of maturity due to the incomplete understanding of the damage mechanisms and structural failure modes.

The important benefits in terms of mass and cost reduction that would be directly derived from the use of innovative materials and structure concepts spurred EADS CASA Espacio to a deep involvement in the development of these new technologies and their incorporation into the standard design processes once it was considered the sufficient level of maturity was attained. This new technologies development and their subsequent transition to the production programs is based on collaborative engineering. Engineers from all the related disciplines (materials, analysis, design, manufacturing and quality assurance) work together in all the phases of the technology development and implementation.

The feasibility of the future Reusable Launch Vehicle (RLV) strongly depends on the availability of light and low cost primary structures. The continuous implementation of innovative concepts will allow to attain this final objective. An important achievement in this direction is the development and use of automated processes that help to reduce production and quality control costs.

3.2. Clearing the Path Towards the All-Composite Structure

To arrive to the production of the all-composite structure has been the result of a continuous effort to develop and implement innovative design concepts and production processes. The manufacturing of sandwich panels using the cocuring technology since the mid 1980's, the development of the Resin Transfer Molding (RTM) Technology during the 1990's, and the incorporation of the automated production process (Fiber Placement) have cleared the path towards the production of the all-composite structure (FIG 2).

All these technologies, innovative at their time, were gradually applied to the production of primary structures of the Ariane family of launch vehicles. The EPS-, VEB-Structures and Payload Adapters benefited from these technologies. Cocuring is used for all the sandwich panels of those structures, allowing for the manufacturing of some of the shells in a single piece with evident benefits in terms of mass and cost. RTM is used to produce the USR's of the payload adaptors and was investigated as an alternative to the metallic interface rings. Ring diameters of up to 2624. mm have been produced. FIG 3 shows some of the components that have been produced using the RTM technique. Important lessons were learned following the extensive development and testing campaign that was performed in the frame of the EPS-Structure program. The replacement of metallic rings interfacing with the propellant tanks by RTM rings was investigated. Although, at that time, the level of readiness of the technology was not considered sufficient, those investigations allowed to acquire the required level of knowledge (analytical techniques, design practices, ...) to consider this technology as a promising candidate for future applications. An important lesson that was learned at that time is that the simple replacement of metallic components by composites without modification of the designs strongly limits the possibilities offered by the composite materials. To fully benefit from the use of composites, conventional metallic components design practices have to be revised and adapted to the full potential of the composite materials.

The fiber placement is presently the standard manufacturing technique for new developments. Interstage Structure (part of the ESC-A), 3936 cone and 1194H payload adapter are being produced by using this innovative manufacturing technique (see FIG 4). In fact some of these developments could not have been viable without this new technique. Conventional hand lay-up would have resulted in excessively expensive products, and, in the case of large structures, impossible to manufacture without running out the outlife of the material. AFP has become the standard manufacturing process for the CFRP launch vehicle structures. New versions of structures originally produced 'by hand' are being produced by AFP (case of the Ariane 5 VEB-Structures).

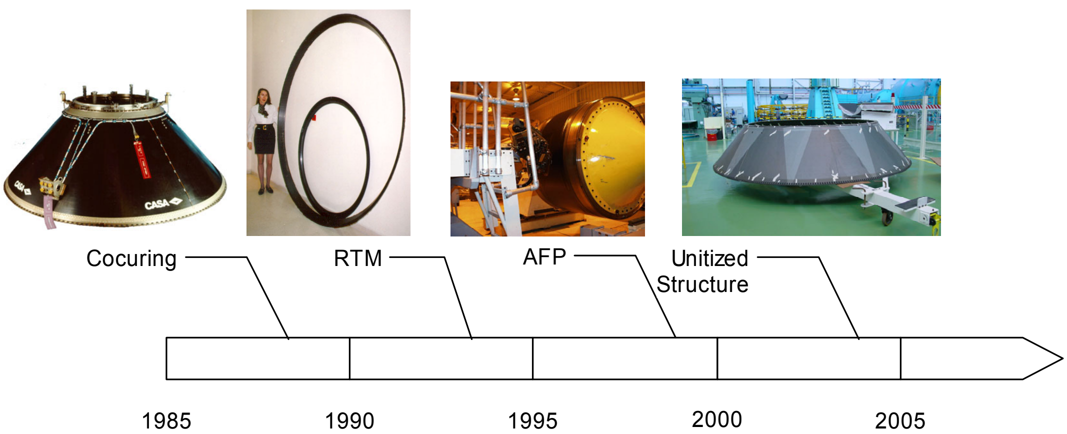


FIG 2 - Composites Structures Technology Evolution at EADS CASA Espacio

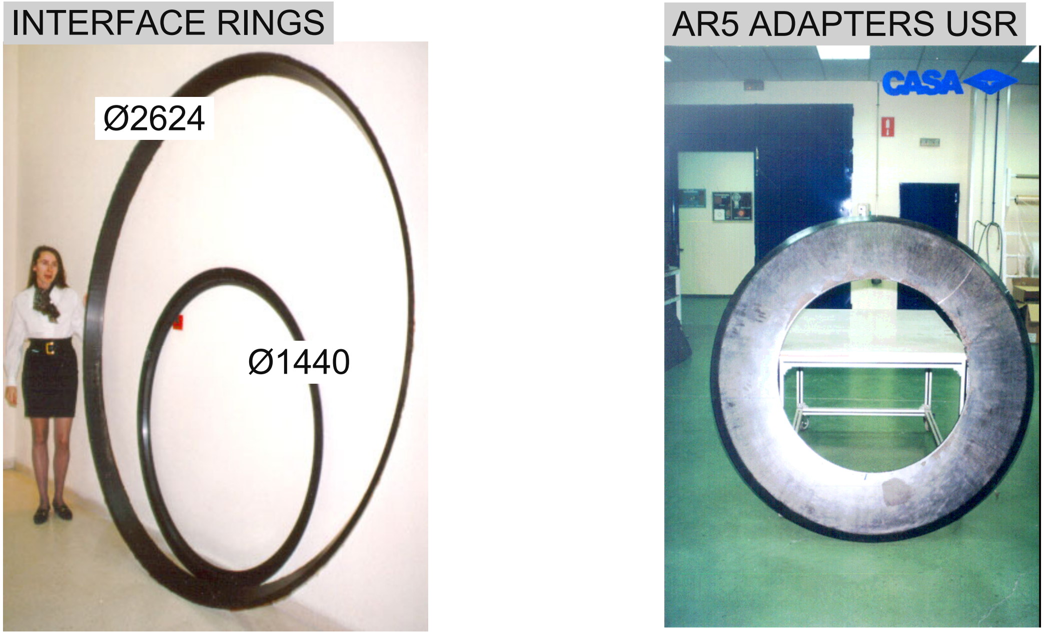


FIG 3 - Launch Vehicle Structural Components Manufactured by RTM Process

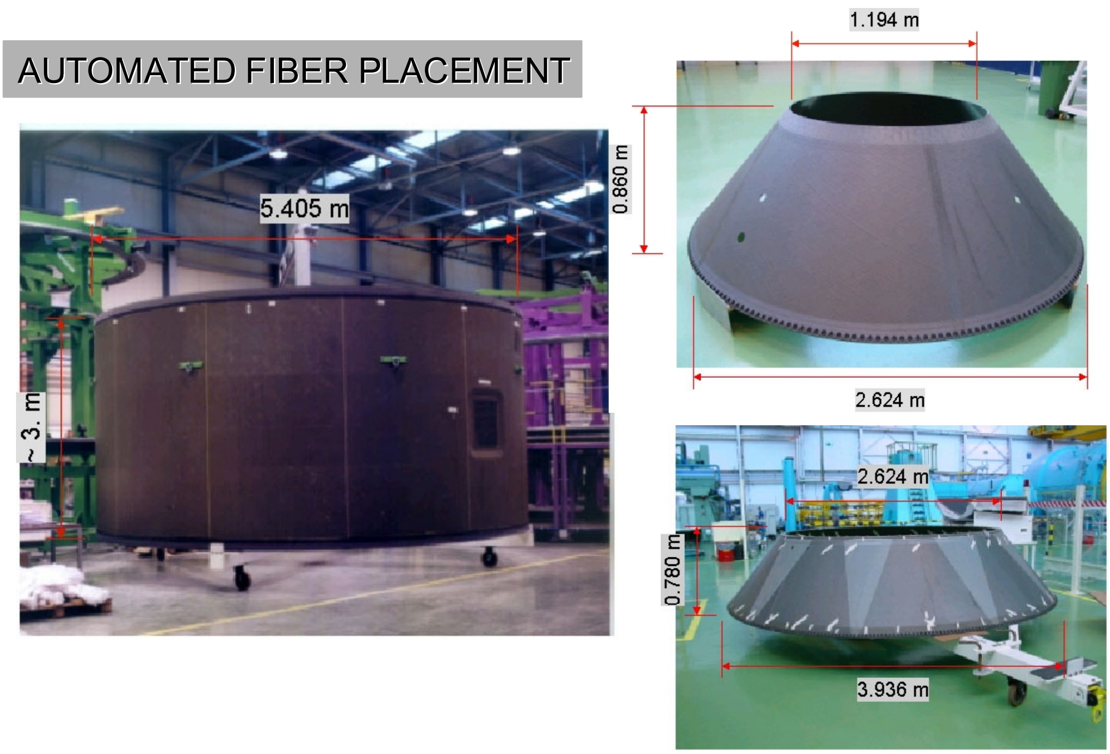


FIG 4 - Launch Vehicle Structural Components Manufactured by AFP Process

3.3. The All-Composite Structure

The integration of the interface rings to the shell was an important stage in the pursuit of the all-composite structure. The 1194H adapter was identified as an adequate candidate to implement this new structural concept.

To industrialize a new structural concept is necessary to demonstrate the advantages it offers with respect to the conventional concept being used up to that moment. To accomplish this, an extensive trade-off between the two candidate configurations is normally performed. This trade-off concluded in the interest that offered the new concept and pushed forward its development.

The interface ring was integrated into the shell. The capabilities of the Automated Fiber Placement technology allowed for the integration of the ring with the associated benefits of reduction in the number of parts and fasteners, and simplification of the assembly steps (essential for cost reduction).

The use of the building-block approach and the practice of the collaborative engineering along the different phases of the structure development minimized the potential risk inherent to the implementation of new concepts.

The use of the building-block approach (FIG 5) was invaluable to augment the knowledge (analysis, design, manufacturing, ...) of the technology and to anticipate potential problems. The performance of the successful full-scale testing (October 2001) provided the final validation of the structural concept.

This development of the 1194H payload adapter was an important contribution to the increase in the level of maturity of the used technologies. The next step was the production of an all-composite structure. The selected structure was the 3936 ESC cone.

The 3936 ESC cone is a conical structure with a Ø3936 aft diameter and a Ø2624 forward diameter. Its total height is 780 mm. Aft and forward interfaces are to be bolt-connected to adjacent structures. The ring integration technology already proved in the 1194H is applied to both interfaces. FIG 6 shows the 3936 ESC structure, zooming in on the aft and forward integrated rings.

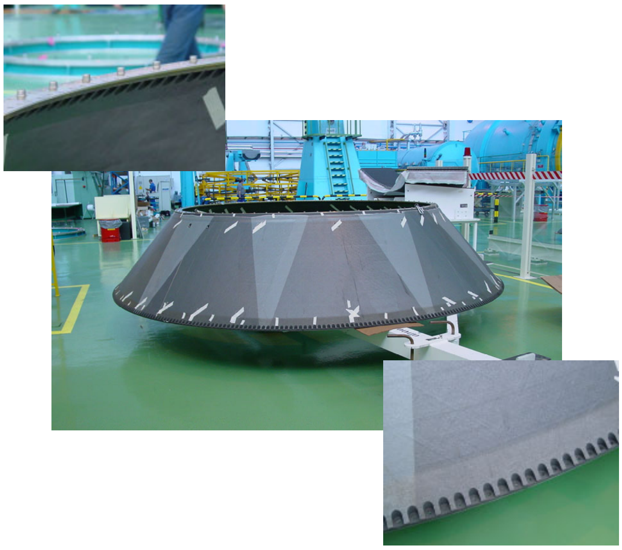


FIG 6 - The All-Composite Structure (3936 ESC Cone with Integrated CFRP Rings)

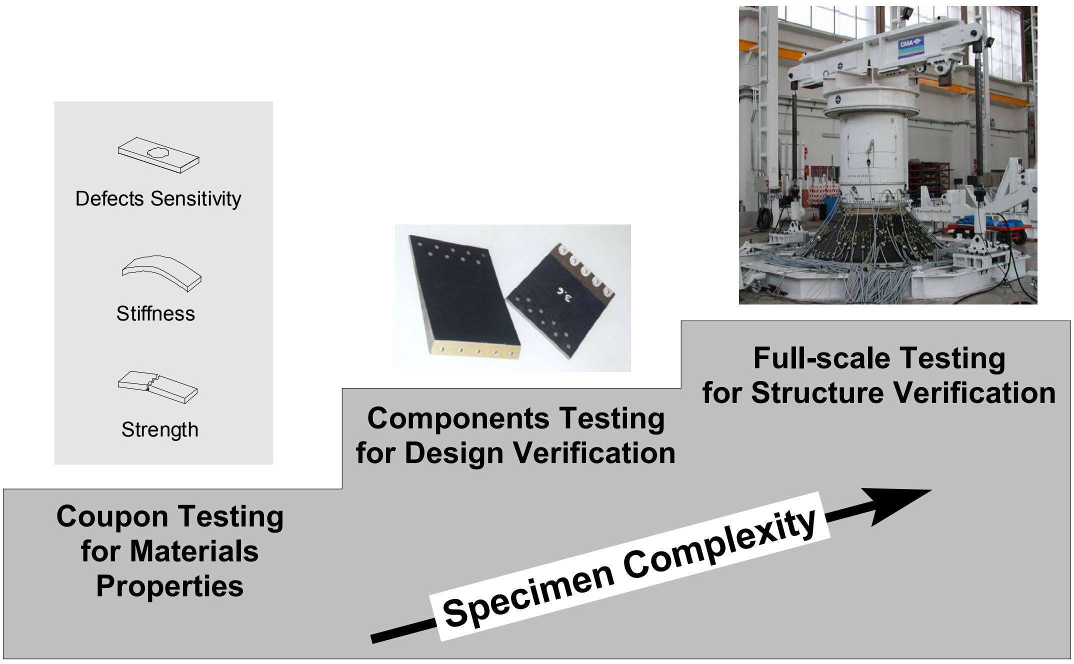


FIG 5 - Building Block Approach for Composite Structures Development

3.4. More Recent Structural Concepts

RTM technology is being incorporated into the all-composite structure integrated rings to improve manufacturability considerations without impairing the structure performance. This represents a clear example of incremental innovation.

In the frame of the preparatory activities for future European reusable launch vehicles, a more radical type of innovation is being probed. Automated manufacturing techniques and iso- or ortho-grid shell concepts are being investigated to achieve the necessary efficiency gains in terms of mass and cost (FIG 7).

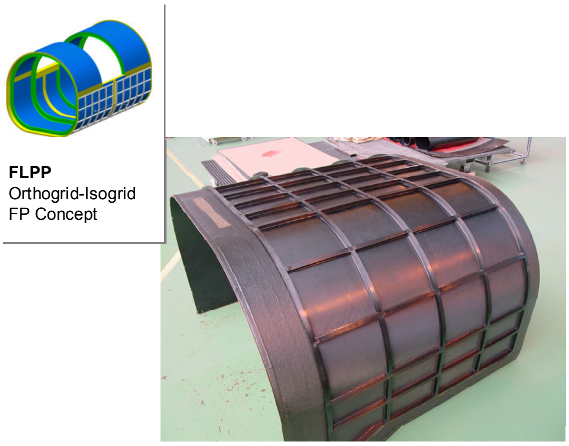


FIG 7 – Structural Concept for Future Launch Vehicles (Technology Demonstrator)

4. INNOVATION IN STRUCTURAL ANALYSIS APPROACH

As somebody said,

Structural Engineering is the art of using materials (that have properties which can only be estimated) to build real structures (that can only be approximately analyzed) to withstand forces (that are not accurately known).

The concept of uncertainty clearly emerges from previous definition.

The traditional way of facing the presence of uncertainties has been by applying factors. Load enhancement, capability 'knockdown', and safety factors are applied to guarantee a 'safe' design. These factors tending to overestimate the effect of the applied loading and underestimate the structure capability. Sometimes, these factors are applied without a second thought about their applicability for the problem in hand. Factors that have been proven adequate for traditional design processes could be inadequate for new technologies.

Moving from deterministic design to robust/probabilistic design methods amounts to an admission that uncertainty exists and has a significant impact on system performance.

4.1. Criticism of the Factor of Safety Approach

The use of the factor of safety is validated by the 'service experience'. Nevertheless, this use (associated to following a deterministic approach) is being questioned. Reference [7] reports some quotes criticizing that its use is hindering real progress in structural design.

"The factor of safety was a useful invention of the engineer a long time ago that served him well. But it now quite outlived its usefulness and has become a serious threat to real progress in design." – *D. Faulkner*

"The times of straightforward structural design, when the structural engineer could afford to be fully ignorant of probabilistic approaches to analysis, are " definitely over." – *A.M. Lovelace (1972)*

"As a person who was brought up on factors of safety and used them all his professional life, their simplicity appeals to me. However, if we are to make any progress the bundle has to be unbundled, and each of the constituents correctly modeled…" – *A.D.S. Carter (1997)*

4.2. Deterministic vs. Non-Deterministic Analysis Approach

In the traditional deterministic approach, 'extreme situations' in 'worst-case scenarios' are analyzed. The non-deterministic innovative approach deals with 'typical situations' in 'realistic scenarios.'

The deterministic methodology that is being used to size the structures has been shown to be a sound approach to derive the structure design. The deterministic approach simplifies the load environment (limit loads) and the structure resistance (minimum guaranteed values) and considers some safety factors to size the structures. The inherent conservatism of this approach has an associated mass/cost penalty.

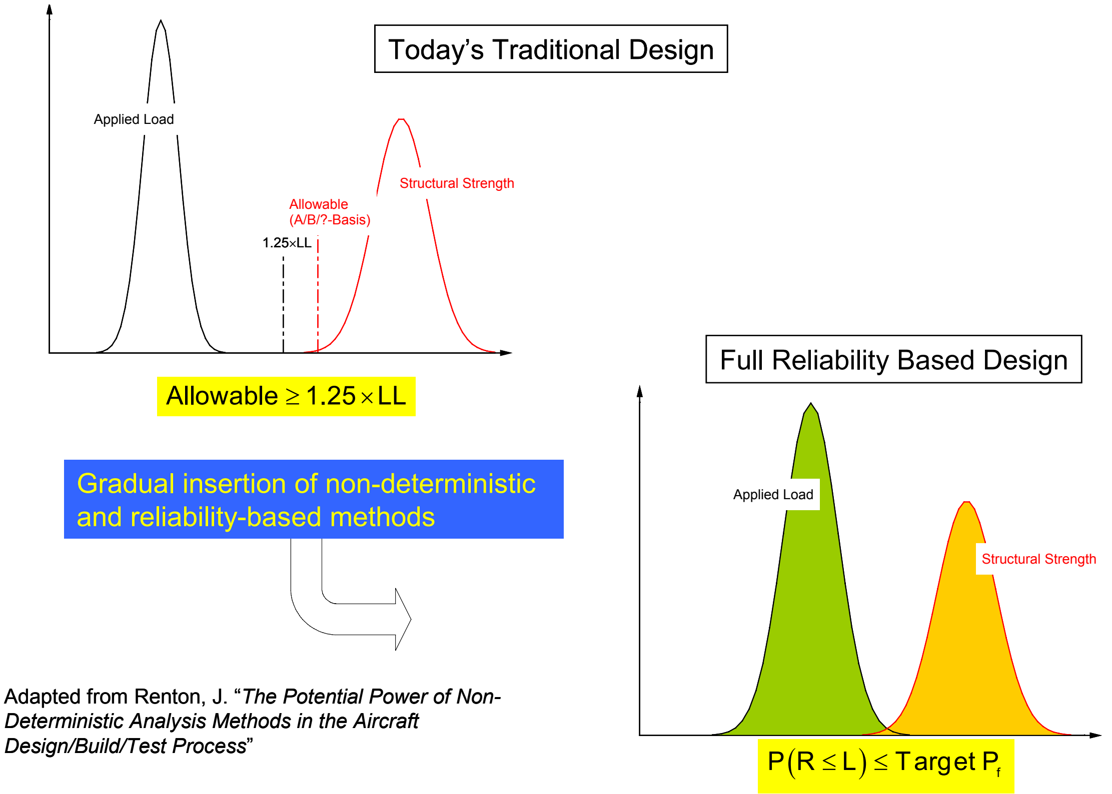
The stochastic approach does consider the actual interaction among the different load components and the structure resistance. Statistic distributions are used to characterize each one of the definition variables. No additional assumptions are needed in order to combine load components. The margin of safety calculation is replaced by the Probability of Failure (PoF).

The probabilistic design brings the engineering closer to the reality. Scatter, randomness, uncertainties are part of the reality and cannot be ignored. Tools to manage this are commercially available. Many structures engineering software developers (MSC.Software, ANSYS, …) are incorporating probabilistic considerations. Other industries have already shifted to non-deterministic approaches as the common approach to follow. It is time for the space industry to follow suit.

Deterministic approach was justifiable when analysis were performed 'by hand' or with limited computer power. The advent of the modern computer has not fully modified the approach for doing things. An important increase in knowledge could be acquired by efficiently using the computer resources, performing realistic simulations of the structure response accounting for all the potential uncertainties. This knowledge is fundamental for a correct management of the risks inherent to the new technologies that are needed for the production of affordable launch vehicle structures.

different. For instance, thrust load is less scattered than transient load (see TAB 1).

The strength characteristics of each item composing the structural component also differ. For this example, let's



Adapted from Renton, J. "*The Potential Power of Non-Deterministic Analysis Methods in the Aircraft Design/Build/Test Process*"

FIG 8 – Deterministic vs. Non-Deterministic Analysis Approaches (adapted from [7])

assume two different items with strength CoV of 4% and 8%.

4.3. An Illustrative Example

The best way of illustrating the inherent limitations of the traditional margin of safety concept is by means of an example.

Type of Load	CoV
Thrust	5%
QSL	30%
Transient	60%

TAB 1 – Loading Statistics (CoV)

Let's consider an structural component of a space vehicle. The component must withstand the simultaneous application of thrust, QSL (quasi-static load) and transient loadings. The relative participation of any of these three loadings in the limit stress of different items of the components can vary. For some items, thrust load can account for 90% of the stress, while in other item this participation can be of 30%. The statistics parameters (CoV, …) associated to each of these loads is also

Assuming a margin of safety equal to 0.0 (traditional approach), the probability of failure (PoF) is computed for structural items with different participation from the three loading types and different variability in the strength capability (CoV of 4% and 8%). TAB 2 summarizes the obtained results (normal distribution is assumed for loads and strength).

MS_{ULT} = 0.0				
Participation	Thrust	0.6	0.9	0.3
	QSL	0.3	0.1	0.3
	Transient	0.1	0.0	0.4
PoF	CoV – 4%	1.7E-13	2.3E-13	1.1E-9
	CoV – 8%	1.2E-8	1.6E-7	2.4E-8

TAB 2 – Probability of Failure (MS_{ULT}=0.0)

Considering PoF=1.6E-7 (the higher value in TAB 2) as a target, different 'acceptable' margins of safety are derived (see TAB 3).

PoF = 1.6E-7				
Participation	Thrust	0.6	0.9	0.3
	QSL	0.3	0.1	0.3
	Transient	0.1	0.0	0.4
MS	CoV – 4%	–0.15	–0.13	–0.09
	CoV – 8%	–0.07	0.0	–0.05

TAB 3 – ‘Acceptable’ Margin of Safety (PoF=1.6E-7)

The MS does not provide a reliable indicator of the criticality of the different structural items. The same margin of safety could correspond to PoF differing in some orders of magnitude.

Elaborating a little bit further this example, we could assume a structural item with a capability characterized by a CoV equal to 12% and fully (100%) stressed by the thrust load (CoV = 5%). In this case, a $MS_{ULT}=0.$ corresponds to a PoF=4.5E-5. To get a PoF=1.6E-7 (reference for TAB 3), a $MS_{ULT}=+0.37$ would be needed.

4.4. Advantages of a Probability-Based Design

Relative to a conventional factor of safety design, a probability-based design has the promise of producing a better engineered structure. Specific benefits are well documented in the literature,

1) A more efficiently-balanced design results in weight savings and/or an improvement of reliability.

2) Uncertainties in the design are treated more rigorously.

3) Because of an improved perspective of the overall design process, development of probability-based design procedures can stimulate important advances in structural engineering.

Experience, in other industries, has shown that adoption of a probability-based design approach has resulted in significant savings in weight. In civil engineering, mass savings from 5% to 30% (10% being typical) are being estimated. Similar saving could be expected for aerospace structures.

With respect to reliability aspects, the first improvement comes from the possibility to quantify it.

5. CONCLUSIONS

Innovation is essential for the evolution in the structures engineering technologies required for affordable and reliable reusable launch vehicles. This need for innovation is clearly stated in [4]: “The biggest cost reduction will come from modernizing current launch vehicle technology by using innovative, and efficient composite design and manufacturing concepts”. Conventional concepts correspond to mature technologies. Conventional design and manufacturing processes are optimized and no important cost benefits are to be expected.

Innovation in different areas is needed. The innovation in structural design and analytical verification methodologies have been explored in this paper.

In the area of structural design, the efficient use of composite materials is, presently, the only way of approaching to the required mass and cost targets guaranteeing the viability of the RLVs. For more than twenty years, EADS CASA Espacio has been involved in a continuous innovation process, still on-going, aimed to produce the most efficient launch vehicle structure. The paper has described in detail the most important milestones of this process.

The traditional analytical verification approaches have to be challenged. Non-traditional approaches taking into account uncertainties, scatter, … are mature for practical application. A firm willingness, at all the different levels, is the only thing is missing. A cultural change could be necessary.

Innovation should become the norm in the space industry and not the exception.

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A previous version of this paper was presented in the 7^TH International Symposium in Launcher Technologies (April, 2007 in Barcelona – Spain). The contents of the paper has been revised and extended for this version.

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