PROCEEDINGS

# SC AEROSPACE INDUSTRY CONFERENCE AND EXPO 2015

# ACE ‘15 TECHNICAL SYMPOSIUM

EDITORS:
RAMY HARIK
MICHAEL VAN TOOREN
ZAFER GÜRDAL

ISBN: 978-0-692-49924-5

## LETTER FROM THE EDITOR

# MANUFACTURING THE FUTURE

Innovation in composites is leaping boundaries and creating more uncertainty and difficulties for the product lifecycle parameters and management of multiple trades, mainly in the aerospace and automotive domains. Design of new structures to further meet the cost, quality and time trinity is encountered with unprecedented challenges of materials and manufacturing. The first edition of the SC Aerospace Conference and Expo Technical Symposium (ACE '15) reinforced the need of collaboration across all involved disciplines: Design, Performance, Analysis, Manufacturability, Testing and Certification.

The creation of quasi-isotropic structures (black aluminum), the integration of analysis within design, tests on new steering determination path are all, while being innovative design endeavors, hindered by the materials and manufacturing domains progress. The product lifecycle chain is being rethought by integrating defects and damage early on in the design process. Obliviously traditional design feature recognition and optimization needs to continue to evolve, however, the concept of Design for Manufacturing is prevailing as a must passage to the production of successful next generation products.

ACE '15 shed the light on the importance of thermoplastics and the need to better understand how manufacturing processes can profit from the advantage thermoplastics can influence new composites. The grafting of thermoset-thermoplastic is one of those many innovations. Finally, a vital step is the integration of post manufacturing defects, damage growth and repair techniques to keep pushing forward the manufacturing of the future.

—Ramy Harik

TABLE OF

# CONTENTS




**CORRESPONDENCE TO**

Ramy Harik
harik@mailbox.sc.edu

WEDNESDAY AUGUST 26, 2015

# SESSION I: CHALLENGER

## 01 THERMOPLASTIC COMPOSITE MATERIALS: PAST, PRESENT AND FUTURE

**Jim Mondo**[1,2]
[1]TenCate Advanced Composites, Morgan Hill, CA, United States
[2]Product Manager, Thermoplastic Composites

### ABSTRACT

To make it to next generation air vehicles, materials need to offer an advantageous edge: It has to be lighter and/or reduce the complexity of composites manufacturing. Evidently, the prior benefit needs to meet or exceed the design specifications. TenCate believes in the potential of thermoplastics and has established an advanced thermoplastics composites business unit with annual capacities reaching over four million lbs for tapes and laminates, and producing above ten million parts. The goal to grow the thermoplastic business is continuously achieved through the creation of collaborations with multiple industrial and academic institutions. To justify the usage of TP materials, one must demonstrate weight savings, higher mechanical performance, reduced environmental knockdowns and enhanced toughness. Multiple examples such as the G650 tail elevator are shown. Finally, manufacturing of new material and innovation in the processing are equally paramount to the usage of new materials. Though thermoplastics have come a long way, there is still a lot of innovation to be made, and multiple manufacturing techniques are presented.

## 02 BEYOND BLACK ALUMINUM – OPTIMIZATION OF COMPOSITE STRUCTURES

**Robert N. Yancey**[1,2], yancey@altair.com; Ming Zhou[1], zhou@altair.com; Jeffrey Wollschlager[1], jaw@altair.com; Warren Dias[1], warren@altair.com
[1]Altair Engineering, Troy, MI, United States
[2]Vice President of Aerospace and Composites

### ABSTRACT

The challenge with analyzing composite structures has led to the common design process in the industry referred to as "black aluminum" design. This process refers to creating a laminate that has isotropic material properties in the plane of the laminate and is often referred to as a quasi-isotropic design. The vast majority of the laminate test data available is on quasi-isotropic test articles. A quasi-isotropic design eliminates the design variable of material orientation and allows the designer to just worry about shape, thickness, and materials as their design variables which is more in line with the design process for metal structures. Composites are attractive because they have a high stiffness-to-weight ratio, but they can also provide directional mater-ial properties, which can provide significant advantage. If we look at the composites in nature such as bone structure or trees, they are not designed as quasi-isotropic structures, but they have highly directional stiffness that give the item stiffness and strength only where it is needed. Given the large number of variables available to the designer of a composite structure, numerical optimization methods are required in order to really design efficient composite structures that have the stiffness and strength where required. Fortunately, numerical optimization methods are available now that can help designers sort through all of the variables and get to an optimized design in terms of weight and performance. Examples of this process will be presented for an open-hole tensile coupon and an aircraft door surround.

**Keywords:** Design Optimization, Composite Structures, Free-Size Optimization

### 1 INTRODUCTION

Structural optimization has seen accelerated deployment throughout all industries in the past decade, largely due to the recognition that tremendous efficiency gain can be achieved at concept design stage through topology optimization. For metal structures, a two-phase design process has become well established, where at Phase-I topology optimization is applied to generalize design concept, while design details are further optimized using sizing and shape optimization at Phase-II. For composite structures, the added design freedom prompts a modification of the process leading from concept to design details. While different forms of composite materials exist, the predominant usage is composite laminate where thin plies of various orientations are stacked together to form a shell structure. In recent years, the authors have developed a three-phase optimization process for composite laminate design optimization [1-2]. The target of the first phase is the material distribution in terms of orientation and thickness. This is achieved through free-size optimization where thickness of each 'super-ply' of a unique fiber direction is allowed to change freely throughout the structure. As a result thickness contour of each fiber orientation is obtained. A discrete interpretation of the thickness contour results in concept design of ply layout and thickness. Then in Phase-II the interpreted ply-based structural model is further optimization under all design constraints with discrete design variables representing the number of plies of each ply patch. During Phase-III, ply stacking optimization is performed to refine the design according to detailed manufacturing constraints. It should be emphasized that manufacturing constraints are considered throughout all three optimization phases. Some previous work on composite laminate optimization by others is cited in [3-6].

## 2 APPLICATION

The 3 stage optimization process is applied to 2 structures. The first is a simple open-hole tensile coupon. This is a simple load case and is a common test article so a good example of the application of the technology. Even with the simple load case, the results are not intuitive. Given a thorough examination of the results, the ply shapes generated do make sense but it would be difficult for even the most experience composite design engineer to develop these shapes on their own. An overview of the process and results are shown in **Figure 1**. The results do show a potential for a 30% weight reduction in this simple test article with the same failure load as a constant thickness test coupon.

The second example is on an actual aircraft structure. The application is a door surround model with an internal pressure load. The study starts with an aluminum door frame. Using traditional composite design methods to replace the aluminum structure with a quasi-isotropic constant thickness composite laminate design, a weight savings of 14% can be realized. We use the displacement of the aluminum frame as the design constraint making sure the composite structure yields a similar displacement. This is a significant weight savings and often this alone can justify the added expense of composite materials. Using the 3 phase composite structure optimization, an additional 20% of weight savings can be realized. The structure is still constrained to meet the same displacement requirements to match the aluminum door.

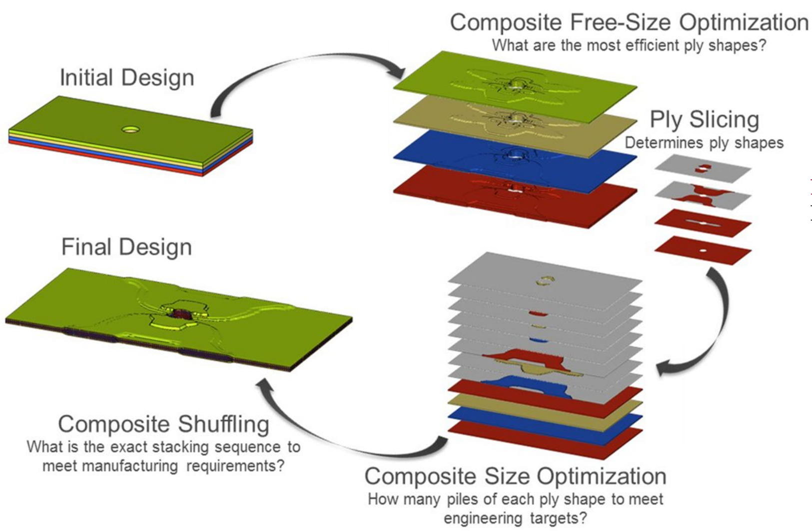



**Figure 1.** Results of 3-stage Composite Optimization Process Applied to an Open-Hole Tensile Coupon.

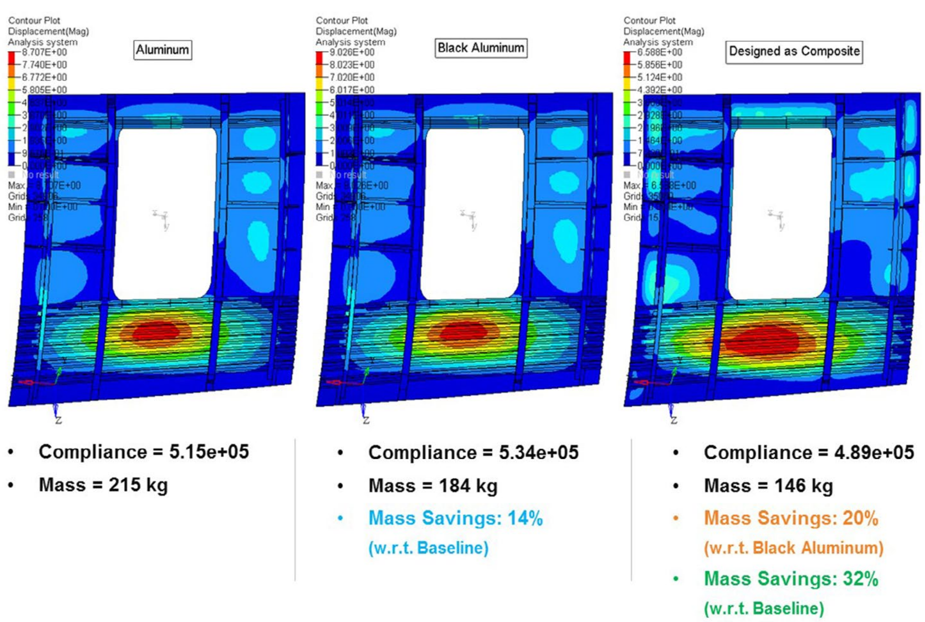



**Figure 2.** Results of 3-stage Composite Optimization Process Applied to an Aircraft Door Surround.

## 3 SUMMARY AND CONCLUSIONS

Design optimization methods can be a valuable tool for the designer in developing the best possible design for the intended application. In the Aerospace industry, as with all other industries, a balance is required between design function, cost, reliability, certification, and manufacturing complexity. Mathematical optimization tools can provide great insight which is often non-intuitive that can aid the organization in balancing all of the requirements with as much information as possible. It is often the case that design decisions made early that rely on incomplete information can lead to significant problems downstream and can add cost, time, and resources to resolve. The goal of design optimization is to provide additional information early in the design so that downstream problems are avoided.

## 4 REFERENCES

[1] Zhou, M., Fluey, R., Willmet, T.: Multiple phase optimization of composite structures. *Proc. 9th US National Congress of Computational Mechanics*, San Francisco, July 2007.

[2] Zhou, M., Fluery, R., Dias, W.: Composite design optimization – from concept to ply-book details. *Proc. 8th World Congress of Structural and Multidisciplinary Optimization*, Lisbon, Portugal, June 2009.

[3] Stegmann, J., Lund, E., Discrete Material Optimization of General Composite Shell Structures. *International Journal for Numerical Methods in Engineering*, **62**, 2009-2027, 2005.

[4] Liu, D., Vassili V. Toropov, V.V., Zhou, M., Barton, D., Querin, O.: Optimization of Blended Composite Wing Panels Using Smeared Stiffness Technique and Lamination Parameters. *Proc. 51st AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Orlando, Florida, April 2010

[5] Gürdal, Z., Haftka, R.T., Optimization of Composite Laminates. Optimization of Large Structural Systems, NATO ASI Series, Vol. 231, Editor G. I. N. Rozvany, Kluwer Academic Publishers, 623-648, 1993.

[6] Gürdal, Z., Haftka, R.T., Hajela, P., Design and Optimization of Laminated Composite Materials, Wiley-Interscience, 1999.

# 03 TOWARDS NANOSCALE ENGINEERING OF THERMOPLASTIC-EPOXY COMPOSITE INTERFACES

**Igor Luzinov[1,3]**, luzinov@clemson.edu; Tugba Demir[1,3]; Michel van Tooren[2], jvantooren@cec.sc.edu
[1]Department of Materials Science and Engineering, Clemson University, Clemson, SC, United States
[2]McNAIR Center for Aerospace and Innovation Research, University of South Carolina, Columbia, SC, United States

## ABSTRACT

Thermoplastic and epoxy based carbon composites can be combined in a single structural element to allow fusion bonding based assembly of the elements. It is obvious that the properties, reliability, and functions of the element are, to a great extent, controlled by the strength of the interface being formed at epoxy-thermoplastic phase boundary. Therefore, successful application of this concept in primary aircraft structure is based on reliable and predictable strength of the bond between the thermoplastic zones (called implants) and the epoxy zones in each structural element. To this end, we have studied how nanoscale layer of epoxy-containing macromolecules grafted to the surface of thermoplastic PEKK based implants (prior to the assembly) affects the PEKK-epoxy composite adhesion. We found that, in fact, the level of interfacial adhesion can be significantly increased with the polymer grafting. The presented method of the adhesion enhancement is expected to be also applicable to PEEK, PEI and PPS based implants.

**Keywords:** Adhesion, Composite Manufacturing, Aerospace Structures, Materials

## 1 INTRODUCTION

Since thermoset (not reusable, non weldable), and thermoplastic (reusable, weldable) polymers offer very different advantages regarding physical properties and related manufacturing options, it is advantageous to have zones of thermoplastic composite and zones of thermoset composite in a single structural element (**Figure 1**) **[1]** . It is expected that this hybrid polymer approach will result in lighter, stronger and less expensive composite parts. However, poor understanding of reliable bonding between thermoplastics and thermoset materials has limited the use of multi-polymer composites in aerospace structures. To this end, we have investigated employment of intermediate nanoscale interfacial layers for bonding of thermoplastic parts to thermoset parts in a hybrid polymer composite component.

## 2 MAIN IDEA

The idea involves the pretreatment of the thermoplastic implants using polymer grafting to create surfaces that allow reliable bonding of the implants to epoxy based composites in a hybrid polymer composite component. In essence, to activate polymer surfaces the thermoplastic substrates (pre-treated with corona and/or plasma) are modified with a nanoscale anchoring layer of epoxy containing macromolecules (**Figure 2**) [poly(glycidyl methacrylate)

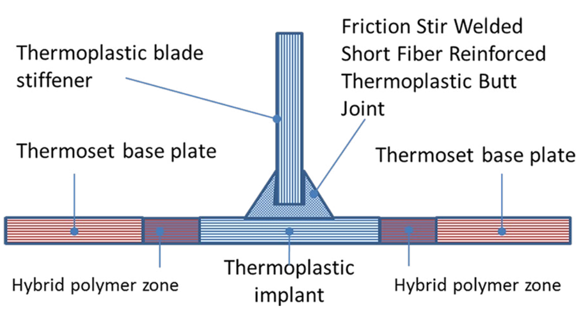
(PGMA), its copolymers, or epoxidized polybutadiene (EPB)] **[2-4]**. The polymers contain numerous epoxy groups, which, upon mild temperature activation, are known to be highly reactive.5 The anchoring layer is self-cross-linked via epoxy groups, providing its stability. At the same time, a large number of unreacted epoxy groups are available for further reactions. Therefore, this treatment creates significant number of epoxy groups on the thermoplastic surfaces. These groups are capable to react with thermoset epoxy matrix to ensure strong adhesion between the thermoplastic and thermoset materials.

In our experiments, we showed that for PEKK based implants used in an epoxy base a reliable and predictable bond can be created using a three step approach involving surface modification with a nanoscale layer of epoxy-containing macromolecules. Step one is the activation of the PEKK surface with corona or plasma treatment. The second step of the process is the creation of a nanoscale anchoring layer of epoxy containing macromolecules such as PGMA on the PEKK surface. The third step is combining the pretreated with the layer thermoplastic composite implant with the epoxy based composite material. Specifically, in the presented research epoxy-carbon prepreg is used for the epoxy part. The unreacted epoxy groups in the anchoring layer react with the epoxy in the prepreg and ensure high, predictable and reliable adhesion between the thermoplastic and thermoset materials. In our investigation we demonstrated that strength of PEKK/epoxy interface can be significantly increased with the treatment (**Table 1**).

| Samples | Max load (N) | % of Strain at max load | Tensile Stress (MPa) at max load |
|---|---|---|---|
| Epoxy-PEKK | 763.4±154.2 | 2.3±1.4 | 79.1±16.1 |
| Epoxy-Plasma treated PEKK | 900.4±241.2 | 1.9±0.45 | 82.7±25.14 |
| Epoxy-PGMA coated PEKK | 1359.1±204.9 | 2.2±0.32 | 132.5±20.1 |

**Table 1.** Results of mechanical testing of adhesive joint between epoxy-carbon fiber prepreg and PEKK film filled with carbon fibers. The results presented for original PEKK film, the film treated with plasma and with plasma/PGMA layer.

**Figure 1.** Butt-joint for thermoplastic matrix composite stiffened shells.




## 3 CONCLUSIONS

We demonstrated that level of interfacial adhesion between PEKK and epoxy prepreg can be significantly increased with the polymer grafting of nanoscale layer of epoxy-containing macromolecules to PEKK surface. The presented method of the adhesion enhancement is expected to be also applicable to PEEK, PEI and PPS based implants.

## 4 REFERENCES

[1] Van Tooren, M. J. L. Method for bonding a thermoplastic polymer to a thermosetting polymer component. Patent: WO2012161569 A1, Nov 29, 2012, 2012.

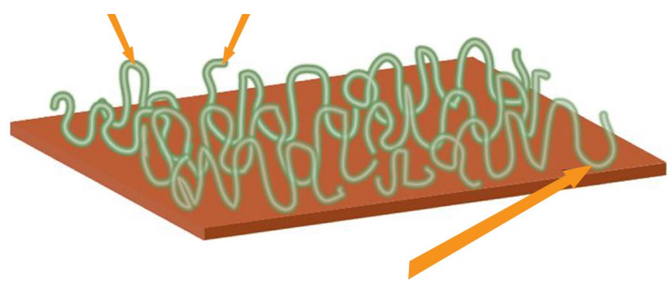
[2] Luzinov, I. A.; Swaminatha Iyer, K. L.; Klep, V. Z.; Zdyrko, B. V. Surface graft modification of substrates, US patent 7,026,014 B2, Apr. 11, 2006. 2006.

[3] Zdyrko, B.; Luzinov, I., Polymer Brushes by the "Grafting to" Method. *Macromolecular Rapid Communications* **2011,** *32* (12), 859-869.

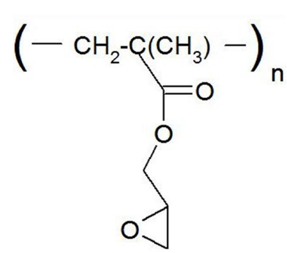
[4] Galabura, Y.; Soliani, A. P.; Giammarco, J.; Zdyrko, B.; Luzinov, I., Temperature controlled shape change of grafted nanofoams. *Soft Matter* **2014,** *10* (15), 2567-73.

[5] Zdyrko, B.; Iyer, K. S.; Luzinov, I., Macromolecular anchoring layers for polymer grafting: comparative study. *Polymer* **2006,** *47* (1), 272-279.

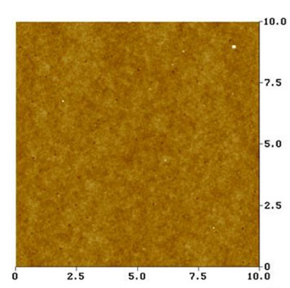
**Figure 2.** Schematic representation of reactive polymer attached to a thermoplastic substrate.



(2a). Chemical structure of PGMA



(2b). AFM image showing topography of PGMA layer deposited by dip-coating on silicon wafer.



(2c). Size - 10x10 µm.

# 04 WING AEROSTRUCTURAL OPTIMIZATION USING SIMULTANEOUS ANALYSIS AND DESIGN STRATEGY

**Michel van Tooren[1],** jvantooren@cec.sc.edu; Ali Elham[2], a.elham@etudelft.nl
[1]McNAIR Center for Aerospace and Innovation Research, University of South Carolina, Columbia, SC, United States
[2]Delft University of Technology, Delft, Netherlands

## ABSTRACT

This paper presents a wing aerostructural optimization using simultaneous analysis and design (SAND) strategy. The aerostructural analysis was performed using an aerostructural analysis tool based on quasi-three-dimensional aerodynamic analysis and finite beam element structural model. Although using SAND for optimization results in a large number of design variables and constrains, in this case about 1000 design variables and about 1600 constraints, it relaxes the need for discipline feasibility in each iteration, so increases the efficiency of the optimization. The results showed about 5% reduction in aircraft fuel weight, by optimizing the wing platform and airfoils shape and the wingbox structure simultaneously.

**Keywords:** Aerostructural optimization, Adjoint sensitivity analysis, Simultaneous analysis and design

## 1 INTRODUCTION

A multidisciplinary design optimization (MDO) problem can be formulated using different strategies. The MDO strategies determine how different disciplines are connected to each other and how the optimization problem should be solved. Different monolithic as well as distributed MDO strategies have been developed **[1]**. Selection of the MDO strategy for an MDO problem is a challenge. Some strategies make the analysis easier but the optimization more difficult, and some do the opposite. Some authors tried to benchmark different MDO strategies using simple test problems **[2-3]**. However the efficiency of an MDO strategy is strongly affected by the nature of the problem. In this study the simultaneous analysis and design MDO strategy is used for wing aerostructural optimization. In the following sections the concept of SAND is explained first, and then the application of SAND for wing aerostructural optimization is presented.

## 2 SIMULTANEOUS ANALYSIS AND DESIGN

An MDO problem can be formulated as follows using SAND strategy:

$$\begin{aligned} &\min \quad f(x, y(x,\bar{y})) \\ &w.r.t \quad x, \bar{y} \\ &s.t. \quad h(x, y(x,\bar{y})) = 0 \\ &\qquad c(x, y(x,\bar{y})) \le 0 \\ &\qquad R(x, \bar{y}, y(x,\bar{y})) = 0 \end{aligned}$$

*Equation 1: SAND formulation.*

In this formulation, $f$ is the objective function, $h$ and $c$ are the equality and inequality constraints of the original problem respectively and $R$ is the residuals of the governing equations of all disciplines. The design vector includes both the original design variables $x$ and the state variables $\bar{y}$. Using SAND strategy the discipline feasibility is not required at each optimization iteration, instead the optimizer is asked to satisfy the governing equations.

## 3 WING AEROSTRUCTURAL ANALYSIS

For wing aerostrcutural analysis the method presented by Elham and van Tooren **[4]** is used. In that method the wing drag is predicted using a quasi-three-dimensional (Q3D) aerodynamic analysis and the wing structural deformation and structural failure criteria are predicted using a finite beam element model. In a Q3D approach the viscous compressible drag of a wing can be computed by a combined use of an inviscid 3D solver (a vortex lattice method in this case) and a viscous 2D solver. More details of the method is presented in reference **[4]**. In that method four governing equations should be satisfied:

$$\begin{aligned} R_1 &= AIC\,G - V \\ R_2 &= Ku - f \\ R_3 &= L - nW \\ R_4 &= C_{l_{inv}} - C_{l_{visc}} \end{aligned}$$

*Equation 2: Governing equations of the aerostructural analysis using Q3D approach.*

The first and the second equations are the governing equations of the aerodynamic (a vortex lattice method) and the structure respectively. The third equation is needed to fine the proper angle of attack to have the wing total lift equal to the design weight multiplied by the load factor. The fourth equation is related to the Q3D analysis. It forces the viscous and inviscid analysis to be consistent. The state variables in this case are the vorticities $\Gamma$, the displacements $u$, the wing angle of attack $\alpha$ (to satisfy the $R_3$) and the downwash angles $\alpha_i$ (to satisfy $R_4$).

## 4 OPTIMIZATION FORMULATION

An Airbus A320 like aircraft wing is considered for the optimization. The design variables are the thickness of the wingbox structure at 10 spanwise positions (40 design variables), the shape of the airfoils at 8 spanwise positions (160 design variables) and the shape of the wing planform (6 design variables). Two surrogate design variables are used for the aircraft fuel weight and aircraft maximum take-off weight. So 208 design variables are used for the original problem. Six different load cases are used for wing structural and aerodynamic analysis. In total 785 state variables are defined for all the load cases. So in total, 993 design variables are used in SAND formulation. The original problem has 642 inequality constraints on structural failure, wing loading and aileron effectiveness and two equality constraints on the two surrogate variables. 993 equality constraints are added to satisfy the governing equations. So in total 1637 constraints are defined. The aircraft fuel weight is defined as the objective function. The SNOPT optimization algorithm **[5]** is used to solve the problem.

## 5 OPTIMIZATION RESULTS

**Table 1** summarizes the results of the optimization. The pressure distribution on the wing for the initial and the optimized wing are shown in **Figures 1** and the wing planform geometry is shown in **Figure 2.** From **Table 1**, one can observe that about 5% reduction in the aircraft fuel weight is achieved. About 2.7% reduction in the aircraft maximum take-off weight (MTOW), more than 12% reduction in the aircraft wing structural weight and about 9% reduction in the wing drag are the other achievements of the optimization.

| | MTOW [kg] | $W_{fuel}$ [kg] | $W_{wing}$ [kg] | $C_{D_{wing}}$ |
|---|---|---|---|---|
| Initial | 73500 | 17940 | 8791 | 0.0180 |
| Optimized | 71532 | 17059 | 7705 | 0.0164 |

**Table 1.** Characteristics of the initial and the optimized aircraft.

## 6 REFERENCES

[1] Martins, J.R.R.A, and Lambe, A.B., "Multidisciplinary Design Optimization: A Survey of Architectures," AIAA Journal, Vol 51, No. 9, September 2013, pp. 2049-2075.

[2] Tedford, N.P., and Martins, J.R.R.A., "Benchmarking Multi-disciplinary Design Optimization Algorithms," Optimization and Engineering, Vol. 11, No. 1, 2010, pp. 159–183.

[3] Kodiyalam, S., "Evaluation of Methods for Multidisciplinary Design Optimization (MDO), Phase I," NASA CR-1998-208716, Sept. 1998.

[4] Elham, A., van Tooren, M.J.L, " Coupled Adjoint Wing Aerostructural Optimization using Quasi-Three-Dimensional Aerodynamic Analysis," AIAA Aviation conference, June 2015, Dallas, TX, USA.

[5] Gill, P., Murray, W., and Saunders, M., "SNOPT: An SQP Algorithm for Large-scale Constrained Optimization," SIAM Review, Vol. 47, No. 1, 2005, pp. 99-131.

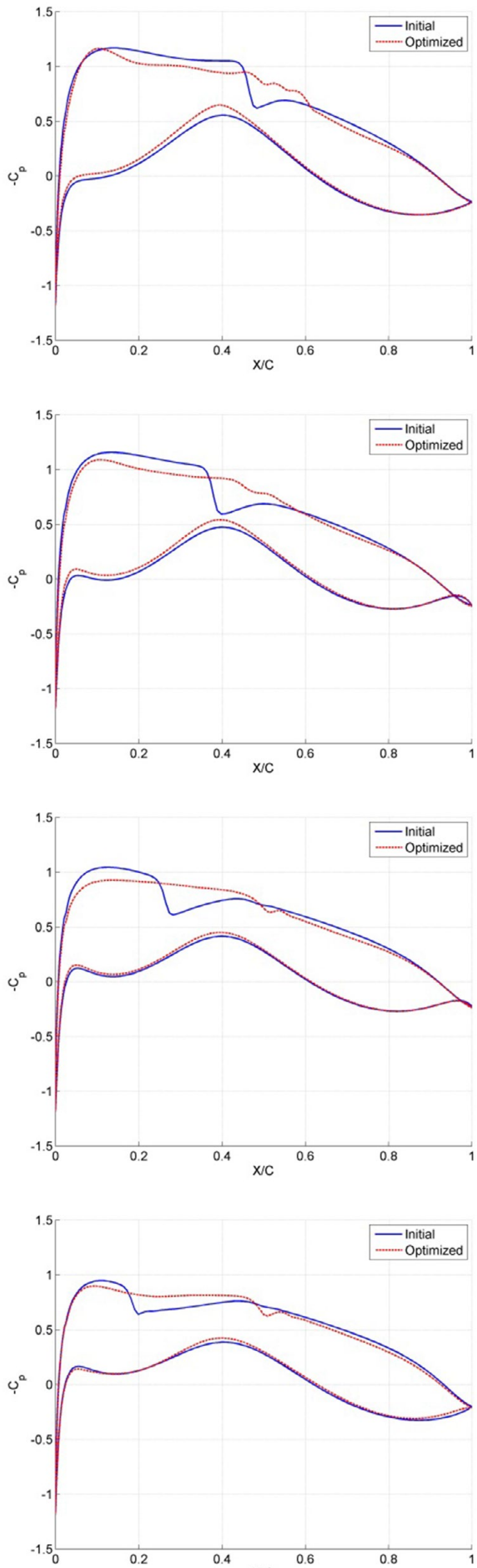



**Figure 1.** Pressure distribution at y/2b = 0.14 (top), 0.43 (second from top), 0.71 (second from bottom), 0.86 (bottom).

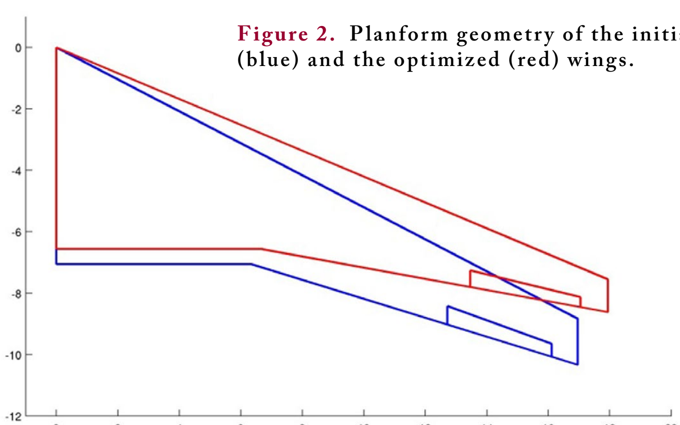


**Figure 2.** Planform geometry of the initial (blue) and the optimized (red) wings.

WEDNESDAY AUGUST 26, 2015

# SESSION II: MCNAIR

## 05 THERMOPLASTIC COMPOSITES FOR AEROSPACE APPLICATIONS

**Alexander Rubin**[1,2], alexander.m.rubin@boeing.com
[1]The Boeing Company, Chicago, IL United States
[2]Senior Technical Fellow

### ABSTRACT

The key drivers for implementation of thermoplastics composites for aerospace structures will be addressed in this presentation. Typical design requirements for commercial and military aircraft, the status of thermoplastic applications at Boeing, as well as the development approach for thermoplastic composite materials, processes, and applications, will be examined. The presentation will include selected examples of the Boeing Company's R&D partnerships in the area of thermoplastic composites and the challenges for future applications.

**Keywords:** Thermoplastic Composites, Aerospace Structures, Materials, Manufacturing, Automation

### 1 INTRODUCTION

The paper examines current materials, processes and aircraft applications of thermoplastic components; and identifies key technologies needed to increase design space and applications. Thermoplastic composites have some advantages over thermosets that can be explored for selected aircraft structural components. These advantages include increased weight savings opportunities vs. thermosets due to better hot/wet interlaminar shear and interlaminar tension properties, and improved durability primarily to reduced damage size for the same impact energy and improved compression strength after impact and $G_{1c}$ & $G_{2c}$ properties. Thermoplastics also offer improved fire, smoke and toxicity resistance properties over thermoset composites

The key advantages of thermoplastics are the cost saving for part production because of improved part fabrication cycle, potential cost efficient joints, and infinite material shelf life. Since thermoplastic components offer the above mentioned cost advantages and proven weight advantages over metallic components, multiple opportunities have been explored and found application on both commercial and military aircraft replacing metallic substructure.

### 2 THERMOPLASTIC MATERIALS AND PROCESSS DEVELOPMENT FOR AEROSPACE STRUCTURES

The challenges for the composite materials today are to satisfy multiple criteria and requirements:

- Structural performance (high stiffness, toughness, notched compression)
- Multi-functional performance (electrical & thermal conductivity, acoustic performance, chemical resistance)
- Expanded design space & optimization
- Improved analysis & modelling techniques (dimensional analysis and control, structural analysis and modelling)
- Enhance processability (reduced variability, increase throughput, alternative processing methods, affordable & scaleable manufacturing processes)
- Increased focus on life-cycle cost (better corrosion resistance, low cost repair techniques)
- Development and certification speed

Various thermoplastic materials are available on the market and are used in the Aerospace Industry today: both continuous and discontinuous fiber composites, standard and intermediate modulus fibers impregnated with PPS, PEI, PEKK, PEEK polymers. The key to successful implementation of thermoplastic composites is to understand and utilize advantages thermoplastics offer to optimize materials, processes and properties for a specific application (see **Figure 1**).

Current research in thermoplastic materials covers many areas, i.e. thermoplastic matrices properties and producibility, materials for direct digital manufacturing, toughening of thermosets, surfacing and carrier material, and many others. Although thermoplastic composites have been used in selected aerospace applications for many years on military and commercial aircraft utilizing injection molding, compression molding, press forming and welding processes, the broad implementation of structural components has not yet taken place.

Recent improvements in materials and processes may become a catalyst for adoption of thermoplastic composites for more structural applications. A significant number of thermoplastic components have been implemented on the Boeing 787, Phantom Eye (see **Figure 2**), other aircraft and the number of applications may increase on the future aircraft.

In order to achieve an appropriate weight, cost, and rate balance and compete with other technologies including advanced thermosets, advanced metallic structure, and hybrid structures the advantages of thermoplastics discussed in the introduction section must be fully utilized. A big part in this trade will be innovative joining processes which will give thermoplastics a distinct advantage (see **Figure 3**).

The implementation of innovative joining techniques for thermoplastics results in reduction (or even potential elimination) of fasteners and drilling operations and reduction of assembly cycle times. An induction welding process was recently demonstrated on the Phantom Eye Rudder by KVE Composites group (see **Figure 4**). Multiple welded components were implemented in production by Stork Aerostructures. They are also exploring several co consolidation techniques using innovative joint configurations.

Many opportunities are being evaluated by several manufacturers in the area of automated fiber placement and in-situ consolidation of thermoplastic components. With improvements of AFP materials and processes, as well as process modeling techniques, these fabrication

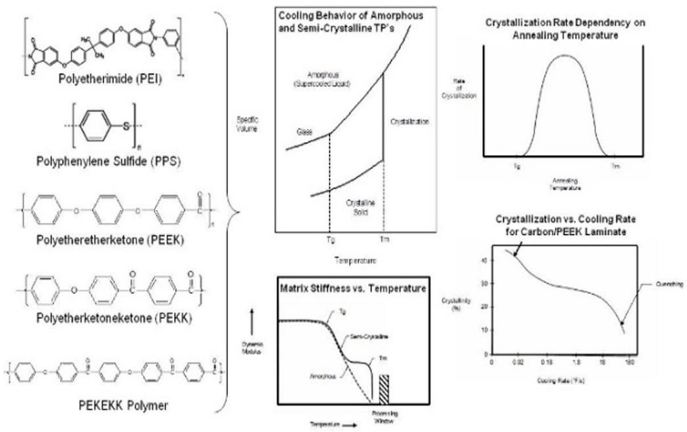
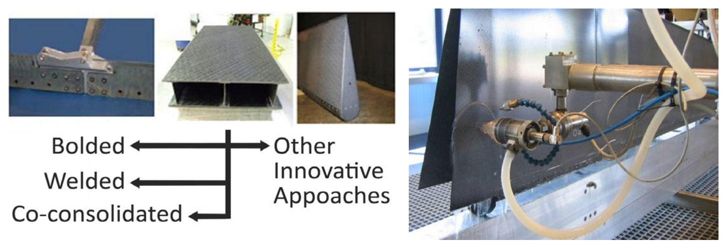



**Figure 1.** Material/process/properties optimization is a key to competitive thermoplastic structures.

**Figure 2.** Phantom Eye thermoplastic AS4D/PEKK wing struts and T300/PPS rudder.

processes look very promising for the design space that is dominated by thermoset composites today. Examples of the integrated composite structural components fabricated by AFP techniques are shown in **Figure 5**.




**Figures 3 & 4.** Induction welding process for thermoplastics.

Recent developments under a US Department of Energy GO-18135 contract performed by the Industrial Team which included Boeing, showed the basic feasibility for large scale induction consolidation and joining of thermoplastic composites using smart susceptors technology (see **Figure 6**). These initial development efforts have verified the key fundamental technical soundness of making large parts and joining integrated thermoplastic composite structures along with reaching the needed cycle time for automotive applications.

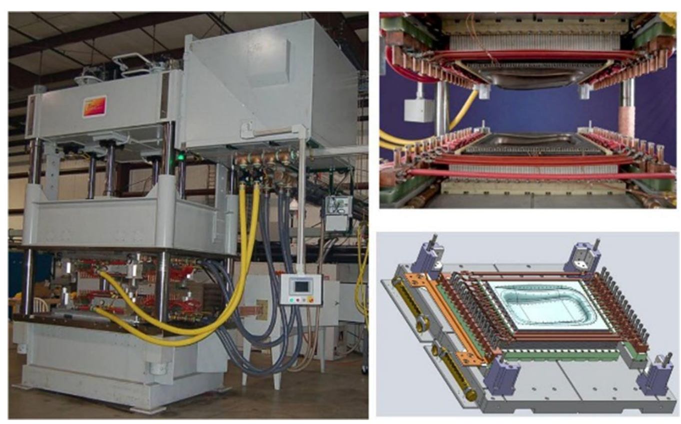


**Figure 5.** Advanced fiber placement processes.

However, implementation risks still exist in scale-up and joining for wind energy and aerospace components and cycle time for automotive parts. These risks will need to be reduced and process maturity further validated via process/component demonstration before implementation. With the high performance and cost expectation required for Aerospace Components much research and innovation is needed in the area of composites in general, and specifically in the area of thermoplastic composites. Boeing conducts many R&D projects internally and participates in several R&D Consortia and universities around the world, including University of South Carolina.

## 3 CONCLUSIONS

Weight, cost, noise, flammability, thermal, production rates drive requirements for Aerospace Components. Thermoplastic composites have performance and processing advantages over thermosets and metallic structure and are winning trade studies for specific applications. As an Industry, we need to continue aggressive materials and processes development research to further optimize cost/performance, keep capturing aerospace applications and unleash the true potential of thermoplastic composites.

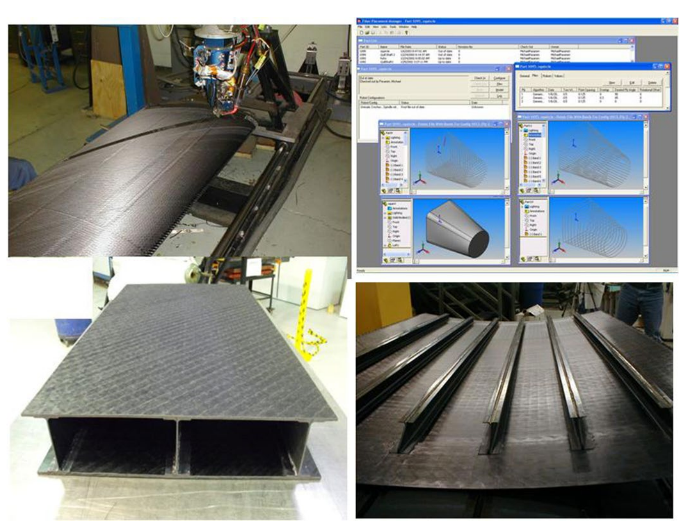


**Figure 6.** Magnetic/induction coil press consolidation and joining (right).

# 06 ADDITIVE MANUFACTURING OF ADVANCED COMPOSITE STRUCTURES

**David Hauber[1,2],** dhauber@automateddynamics.com; Robert Langone[1], rlangone@automateddynamics.com
[1]Autromated Dynamics, Schenectady, NY, United States
[2]Vice President of Engineering

## ABSTRACT

Rapid prototyping was invented over 30 years ago and has finally achieved widespread acceptance. We are now moving from rapid prototypes to additive manufacturing of functional structures. The next step is to additively manufacture advanced composite structures. Although manufacturing of composite structures is inherently additive in nature, it is not widely accepted as additive manufacturing because you can't simply push "print" and get a completed structure. However, there are several technologies that are converging to address this limitation.

There have been several attempts to-date to extend existing additive manufacturing technologies such as FDM (fused deposition modeling) to include composite materials. However, they all miss the critical insight of advanced composite structures: fibers must be aligned in the direction of the load paths. Short fiber filled polymers or 2D layered composite structures do not produce advanced composite structures, they merely improve bulk properties. What is needed is a means to additively manufacture 3D composite fiber architectures. This paper will discuss several possible approaches.

Automated fiber placement of thermoset composites was invented over 40 years ago and is now widely accepted for the manufacture of advanced composite structures. However, expensive tooling and post processes such as autoclaves are required. In-situ automated fiber placement of thermoplastic composites uses inexpensive tooling, eliminates these post processes, and can be considered an additive manufacturing process for advanced composite structures. This paper discusses recent advances in the additive manufacturing of tooling and completed structures using this process.

**Keywords:** Additive Manufacturing, Advanced Composites, Thermoplastic Composites, Automated Fiber Placement, In-situ Consolidation, Rapid Prototyping, 3D Printing

## 1 INTRODUCTION

Additive manufacturing (AM) with isotropic materials is now well established. There have been several attempts to extend AM with composite materials. MarkForged uses continuous fiber reinforced PA (polyamide) filament in modified FDM equipment to build 2D layered structures. This places fibers in 2D layers providing in-plane strength which is only useful for a limited applications such as the tension strap for which it was originally invented. ORNL (Oak Ridge National Labs) extrudes short fiber filled ABS (acrylonitrile butadiene styrene) pellets in their BAAM (big area additive manufacturing) workcell that recently made headlines by "printing" a car.

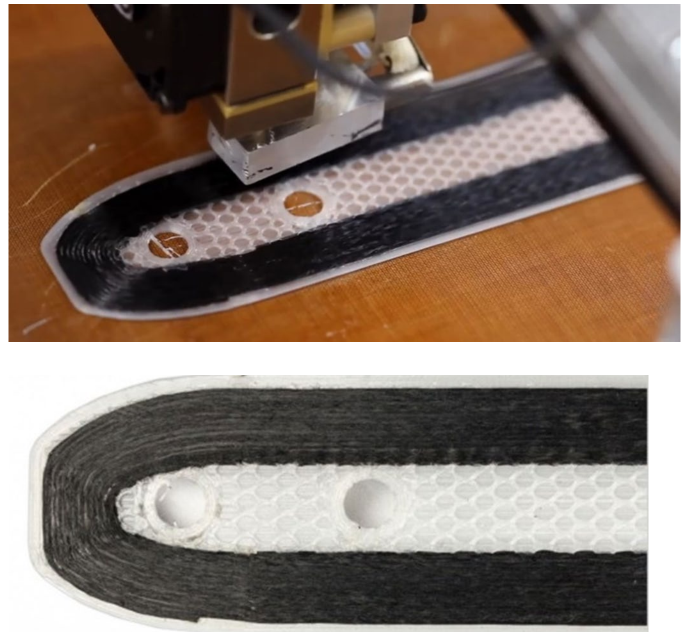


**Figure 1.** MarkForged carbon/PA tension strap.

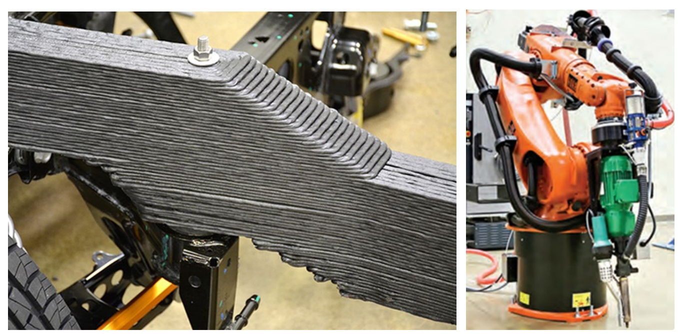


**Figure 2.** Extruded short fiber filled ABS frame of the ORNL BAAM Cobra car and robotic extruder.

However, 30% short fiber filled polymer only improves bulk properties providing little or no directional reinforcement and poor Z-axis (normal to the build plane) strength. There is a need for technologies to place continuous fibers in the direction of load paths. It is easy to envision how FDM could be used with a multi-axis robot to place continuous fiber in three dimensions. Existing rapid prototyping software or CAM software is not capable of this but AFP software is. In-situ automated fiber placement (AFP) of thermoplastic composites (TPC) consolidates continuous fiber reinforcement in three dimensions not just 2D layers. The follwoing figures illustrate the author's work with in-situ AFP of TPC on an additively manufactured core. The core may remain in the tool as a structural element or can be washout tooling. The follwoing figures show washout tooling from Stratysis with IM7/PEEK fiber placed over it using Automated Dynamics AFP equipment. This process uses commercial off the shelf (COTS) technology including the software.

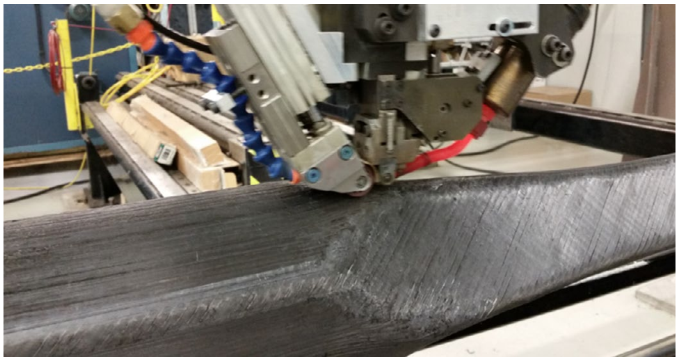


**Figure 3.** In-situ Automated Fiber Placement on an additive manufactured core.

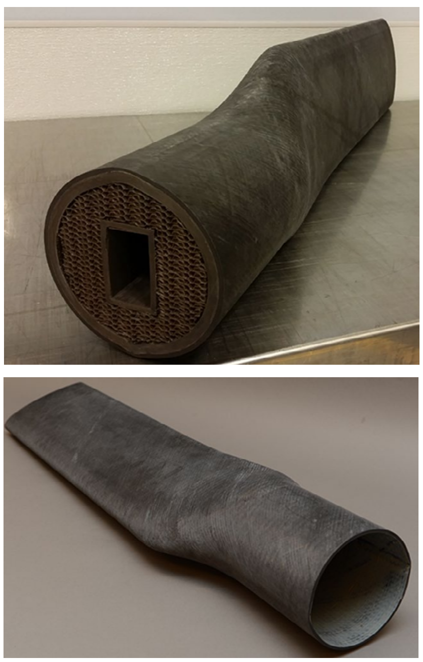


**Figure 4.** Additively manufactured advanced composite structure before (top) and after (bottom) core is washed out.

## 2 CONCLUSION

Additive manufacturing of isotropic materials is now an established technology. The range of applications is being extended using short fiber filled polymers, higher throughput print heads, and larger machines. There have been several attempts to additive manufacture continuous fiber reinforced composites with FDM. However, these attempts only provide strength in two dimensions. Advanced composite structures require continuous fibers aligned in the direction of the load paths in three dimensions. In-situ automated fiber placement of thermoplastic composites achieves this goal. The combination of additive manufactured tooling with in-situ automated fiber placement of thermoplastic composite achieves the goal of a truly additively manufactured advanced composite structures.

# 07 FEATURES RECOGNITION FOR MANUFACTURING KNOWLEDGE MANAGEMENT

**Julien Le Duigou[1,2],** julien.le-duigou@utc.fr; Christophe Danjou[1,2], christophe.danjou@utc.fr; Alexandre Durupt[1,2], alexeandre.durupt@utc.fr; Benoit Eynard[1,2], benoit.eynard@utc.fr
[1] Sorbonne Universités, Université de Technologie de Compiègne, France
[2]Mechanical Engineering Systems, Mechanical Laboratory

## ABSTRACT

Aeronautic industry faces more and more difficulties to manufacture good parts the first time. It mainly comes from the complexity of shapes and the use of new materials like Titanium. To be able to improve their manufacturing know-how, knowledge management applied to manufacturing is a promising way. This article exposes a solution to ensure Manufacturing Knowledge Management from CNC machines to CAD/CAM systems. The main goal is to capitalize knowledge from the CNC machine and to reuse it in the CAD/CAM systems. Based on STEP-NC standard, we propose ontology as the knowledge database. This ontology is filled by validated STEP-NC files, i.e. STEP-NC files which allowed manufacturing a right part. This knowledge database is then used in three ways: feasibility analysis based on manufacturing features recognition from CAD system, automated filling of cutting parameters and toolpath strategies of the manufacturing features and CAM decision aided support.

**Keywords:** Manufacturing Feature, Knowledge Based System, STEP-NC.

## 1 INTRODUCTION

Nowadays, aeronautic industries face great challenges like weight reduction. They have to use new materials like Titanium and Inconel and manufacture complex shapes for aerodynamic or for mechanical purposes (e.g. isogrid). Manufacture such parts is extremely difficult and no default is acceptable. To be able to manufacture the right part the first time, companies need to capitalize and reuse all their manufacturing knowledge, nowadays distributed among production engineers, post processors (PP) and operators.

One of the main difficulties for knowledge sharing and reuse is the lack of interoperability of the numerical chain through CAD/CAM/PP/CNC. Indeed the information contained in CAD files is damaged when transferred to the CAM system, except if both systems are from the same editor. Otherwise, the file has to be translated into a standard format, like STEP (ISO 10303 AP242), and loss the features information to become a dead solid. The same loss of information is also created between the CAM file and the Post Processor, where CLFile or APT is transformed into G-Code (ISO 6983). The most important fact is that none of the possible modifications made at one step of the design process can be integrated into the previous step due to those interoperability issues.

## 2 STATE OF THE ART

To be able to use a single format for all the numerical chain, a new standard was launched in 2002, call STEP-NC (led by two standards: the Application Reference Model ISO 10649 and the Application Interpreted Model ISO 10303 AP238). STEP-NC encompass the geometry definition of the part, the PDM meta data, but also the necessary data for manufacturing i.e. manufacturing features, toolpath strategy, cutting parameters… in a readable format directly by the controller of the machine. This deletes the Post Processor step by moving the knowledge of the PP for one part into the STEP-NC file and for the other part directly into the controller.

STEP-NC, even if not yet implemented in the controllers of CNC machines, it has been widely explored in academic research for manufacturing information feedback (Campos and Miguez, 2011; Wu and Wang, 2015; Xu, Wand and Rong, 2006), cutting parameters optimization (Ridwan and Xu, 2011; Zhao, Xu and Xie, 2008) and features recognition, like Borgia, Matta and Tolio (2013), which proposed a method for features automatic recognition based on STEP-NC Working Step.

One of the main lacks of STEP-NC is still the interoperability issue (Newman et al., 2008): How to use this standard to enable capitalizing manufacturing knowledge and its reuse in CAD and CAM? This paper proposes an approach that aims to enable early feasibility analysis into CAD, CAD/CAM automated transformation and decision aid support for toolpath strategies and cutting parameters based on manufacturing features recognition and STEP-NC.

## 3 PROPOSAL

To be able to capitalize and reuse cutting knowledge, a framework integrating OntoSTEP-NC, an ontology based on STEP-NC standard (Danjou, Le Duigou et Eynard, 2015a), and Closed Loop Manufacturing, an approach to integrate the information contained in validated STEP-NC files into the ontology (Danjou, Le Duigou et Eynard, 2015b) (**Figure 1**) have been proposed in previous works.

The information contained into a validated STEP-NC file is integrated into OntoSTEP-NC. Then, when a CAM programmer looking for the cutting parameters and toolpath for a specific manufacturing feature, the database (an implementation of OntoSTEP-NC into a Virtuoso XML database) is called through SPARQL directly from the CAM system, and the most appropriate manufacturing features and their related information are send depending of the material, the tool and the feature dimensions (point 3 in **Figure 1**).

To be able to go further and to directly allow information feedback to the CAD, we now propose to enrich this first proposal by integrating manufacturing features recognition. The geometrical features are compared and combined or discomposed to obtain known manufacturing features (that already exist in the database) (point 1 in **Figure 1**). Then the different manufacturing features can be automatically completed with cutting information and toolpath contained in the database for a proposition to the CAM programmer (point 2 in **Figure 1**).

If no manufacturing feature can be found in the database from the geometrical feature, a warning advices the CAD designer that a feasibility issue could exist, and he can directly contact the CAM programmer to ensure the validity of his proposed feature.

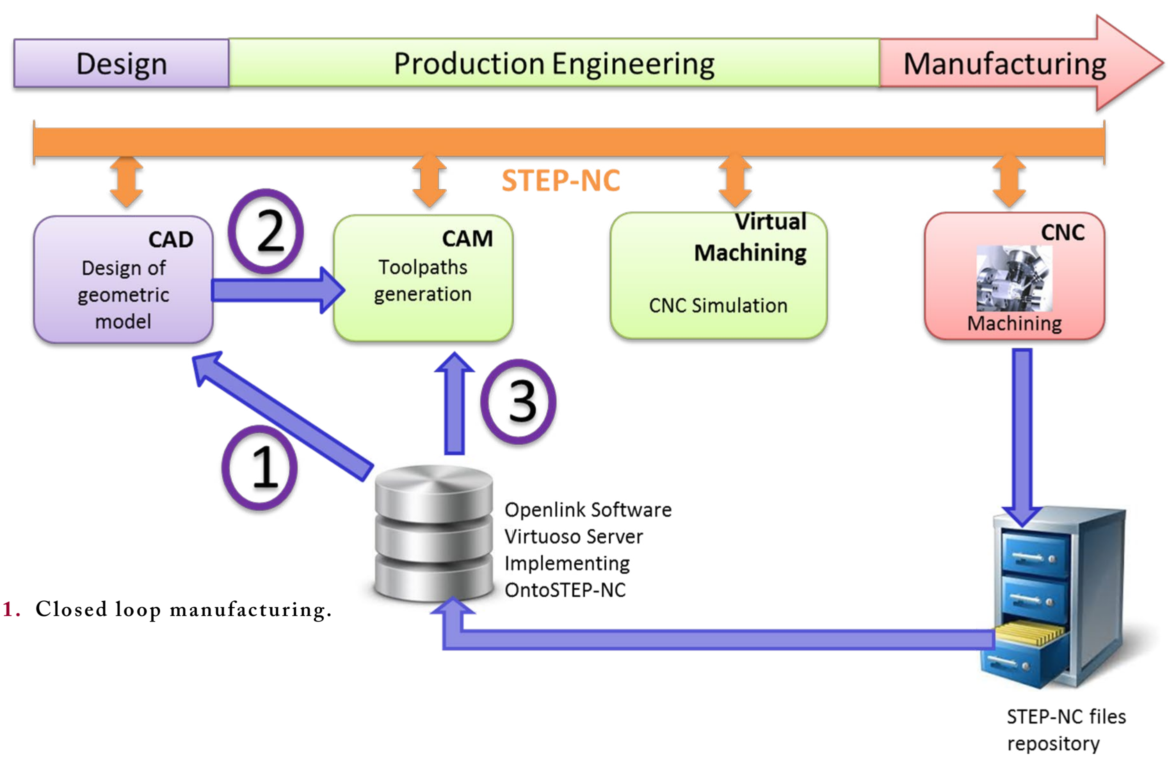



**Figure 1.** Closed loop manufacturing.

## 4 CONCLUSIONS

Aeronautical industry needs to better manage their cutting knowledge to face today's manufacturing challenges. This paper proposes an approach based on STEP-NC and ontology to capitalize and reuse this knowledge. This knowledge is then used for feasibility analysis at CAD level, cutting parameters and toolpath strategy filling at manufacturing features level between CAD and CAM and CAM decision aid support. The proposal is implemented on OntoSTEP-NC Virtuoso database and CATIA V5 CAD/CAM. Aeronautical cases are under evaluations. The use of STEP-NC as a basis for manufacturing knowledge management is validated and further developments are planned for features recognition and CAM automation.

## 5 REFERENCES

[1] Borgia, S., Matta, A., Tolio, T. (2013). STEP-NC compliant approach for setup planning problem on multiple fixture pallets. *Journal of Manufacturing Systems,* 32(4), 781–791.

[2] Campos, J.G., Miguez, L.R. (2011). Standard process monitoring and traceability programming in collaborative CAD/CAM/CNC manufacturing scenarios. *Computers in Industry,* 62(3), 311–322.

[3] Danjou, C., Le Duigou, J., Eynard, B. (2015a, April). *OntoSTEP-NC : une approche ontologique pour la capitalisation des connaissances en usinage*. 14ème Colloque National AIP-Primeca, La Plagne, France.

[4] Danjou, C., Le Duigou, J., Eynard, B. (2015b). Closed-Loop Manufacturing process based on STEP-NC. *International Journal on Interactive Design and Manufacturing*. http://dx.doi.org/10.1007/s12008-015-0268-1

[5] Newman S.T., Nassehi A., Xu X.W., Rosso, R.S.U.Jr., Wang, L., Yusof, Y., … Dhokia, V. (2008). Strategic advantages of interoperability for global manufacturing using CNC technology. *Robotics and Computer-Integrated Manufacturing,* 24(6), 699–708.

[6] Ridwan, F., Xu, X. (2011). Advanced CNC system with in-process feed-rate optimisation. *Robotics and Computer-Integrated Manufacturing,* 29(3), 12–20.

[7] Xu, X.W., Wang, X.V. (2015). A collaborative product data exchange environment based on STEP. *International Journal of Computer Integrated Manufacturing,* 28(1), 75-86.

[8] Xu, X.W., Wang, L., Rong, Y. (2006). STEP-NC and function blocks for interoperable manufacturing. *IEEE Transactions on Automation Science and Engineering*, 3(3), 297–308.

[9] Zhao, F., Xu, X., Xie, S. (2008). STEP-NC enabled on-line inspection in support of closed-loop machining. *Robotics and Computer-Integrated Manufacturing,* 24(2), 200–216.

# 08 EFFECT OF DEFECT ON STRUCTURAL INTEGRITY BY TAPE LAYUP MANUFACTURING PROCESSES

**Frank Abdi[1,3],** Mohamad R. Talagani[1], Zafer Gürdal[2]
[1]AlphaSTAR Corp, Long Beach, CA, USA
[2]McNAIR Center for Aerospace and Innovation Research, University of South Carolina, Columbia, SC, United States
[3]Chief Scientist

## ABSTRACT

The use of composites in aircraft structures requires an accurate assessment of effects of known manufacturing defects such as gaps, fiber waviness, and disbonds. Relying on test and NDE Non destructive Evaluation) alone to evaluate such effects is costly, time consuming, and can delay entry of aircraft into market. Test validated advanced De-homogenized computational multi-scale and multi-physics damage tolerance approach is proposed to: **a)** determine the location size and distribution of cracks resulting from the tape lay up manufacturing processes; and **b)** evaluate the effects of manufacturing defects; on Durability and Damage Tolerance (D&DT). The work is motivated by the desire to reduce testing during the certification of the aircraft composite structure. The effect of defects in Aircraft structures by Tape Layup manufacturing processes can reduce the mechanical strength, and buckling properties due to: **1)** formation of threshold crack size and; **2)** void shape/size/distribution and fiber waviness may results from the surface gap (**Figure 1**); **3)** proper single/multiple Teflon insertion tests needs to be designed between skin and stringer. The approach is effective at various levels of the building block of structures for a composite wing and fuselage aircraft structure.

The work presented in this paper evaluated effects from multiple defect characteristics including delamination size, location, and number on stability of composite panels subjected to compression and shear loadings. This provided a framework for test guidance and for designing a test article capable of showing the real effects of disbonds as it may take place during manufacturing or in-service. Sawicki and Minguet evaluated the effects of overlap/ gap presence on notched and un-notched laminate compression strength using specimens containing defects of defined size and locations. They reported strength reductions up to 27% in laminates containing gaps and overlaps at least 0.03" (0.762 mm) wide. Their study determined that further reductions in strength were not observed when wider defects were present. The compression strength reduction for un-notched and notched laminates was the same and was mainly caused by out-of-plane waviness induced by the defects on the subsequent plies. Similarly, Hsiao and Daniel investigated through analysis and experiments the effects of fiber waviness on compressive strength of composite laminates. Their work also concluded that in unidirectional composites the compression strength is degraded seriously with increasing fiber waviness due to interlaminar shear failure.

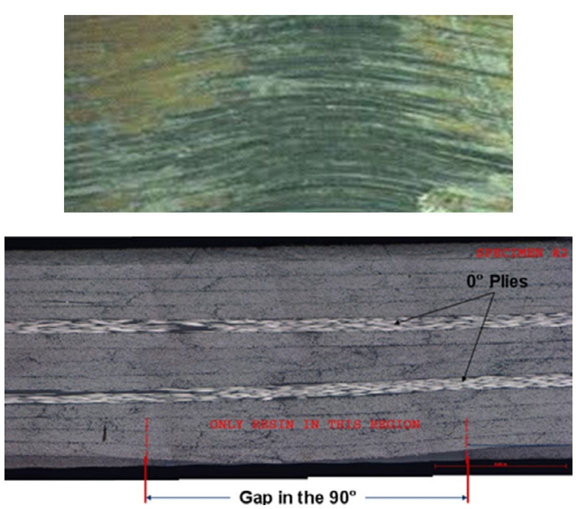
Multi-Scale Modeling for gap and overlap were developed: **(1)** The first is determination of gap location and the size due to tape layup overwrapped on geometry and formation of crimp, cracks and

subsequent layup fiber waviness, and resin rich/void. The analysis will determine the location of gap that may be compared with NDE/AE (Non destructive evaluation, and Acoustic emission); **(2)** The second is the use of Micro-mechanics based analytical procedure used for defect and overlap modeling and use of mathematical based wave geometry to determine laminate knockdown in strength and stiffness; and **(3)** The third is finite element based and Multi-scale Progressive Failure Analysis (MS-PFA) models a cross section of the laminate with defects to generate lamina mechanical properties inclusive of the gap defect (**Figure 2**). The approach, utilizes the damage and fracture evolution as it can be deployed to evaluate any structure where the defect may exist regardless of the complexity of the structure.

Next, the MS-PFA analytical procedure used for defect modeling is compared with building block test validation. The analytical approach was first validated with test data for laminate with defects. Then it was applied to the evaluation of notched laminates and stiffened panels. The results for notched laminates, like in the test, indicated that initially the gap reduced the strength of notched laminates, but its effect diminished as the gap size grew. Gaps in stiffened panels were found to have minimal effect on stability and strength. Beside gap defects, composite flat panels with delaminations in form of disbonds were modeled and analyzed to evaluate their effects on stability response. Structural analysis and test of the flat panels indicated that initial delamination can adversely affect the stability of composite panels once the disbonds reached a critical size (**Figure 3**). Finally the Fuselage structure crimp angle, crack location is determined (**Figure 4**).

**Keywords**: Composite Effect of Defects; Gap and Overlap; Material Characterization and Degradation; Durability and damage tolerance; fiber waviness; Multi-Scale Progressive Failure Analysis; composite strength and stability analysis; crack threshold size and Crack Growth; stiffened Panel and Fuselage Barrel

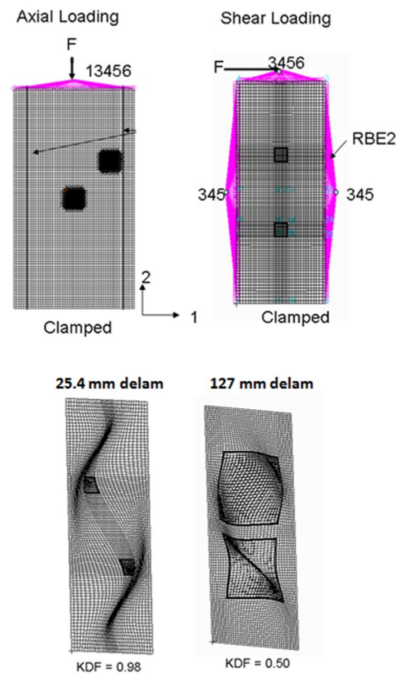
**Figure 1.** Defects observed in composite aircraft structures.




(1a). Micrograph of a composite laminate showing fiber waviness (top).

(1b). Composite laminate scan with gap in 90 degree ply (bottom).

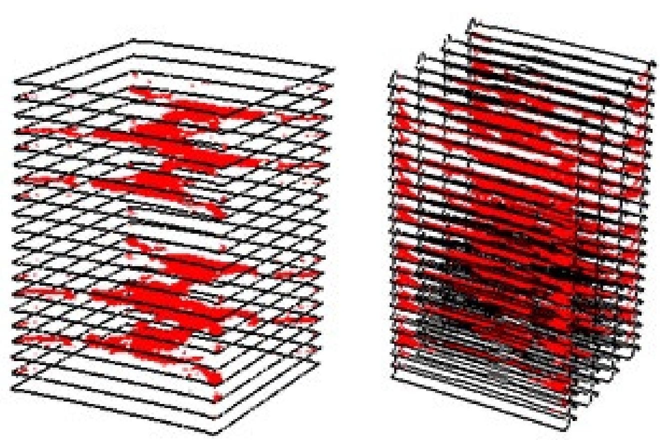
**Figure 2.** Gap and over load effect on buckling and stability.




(2a). Finite element models for axial compression and shear buckling with initial delamination (top).

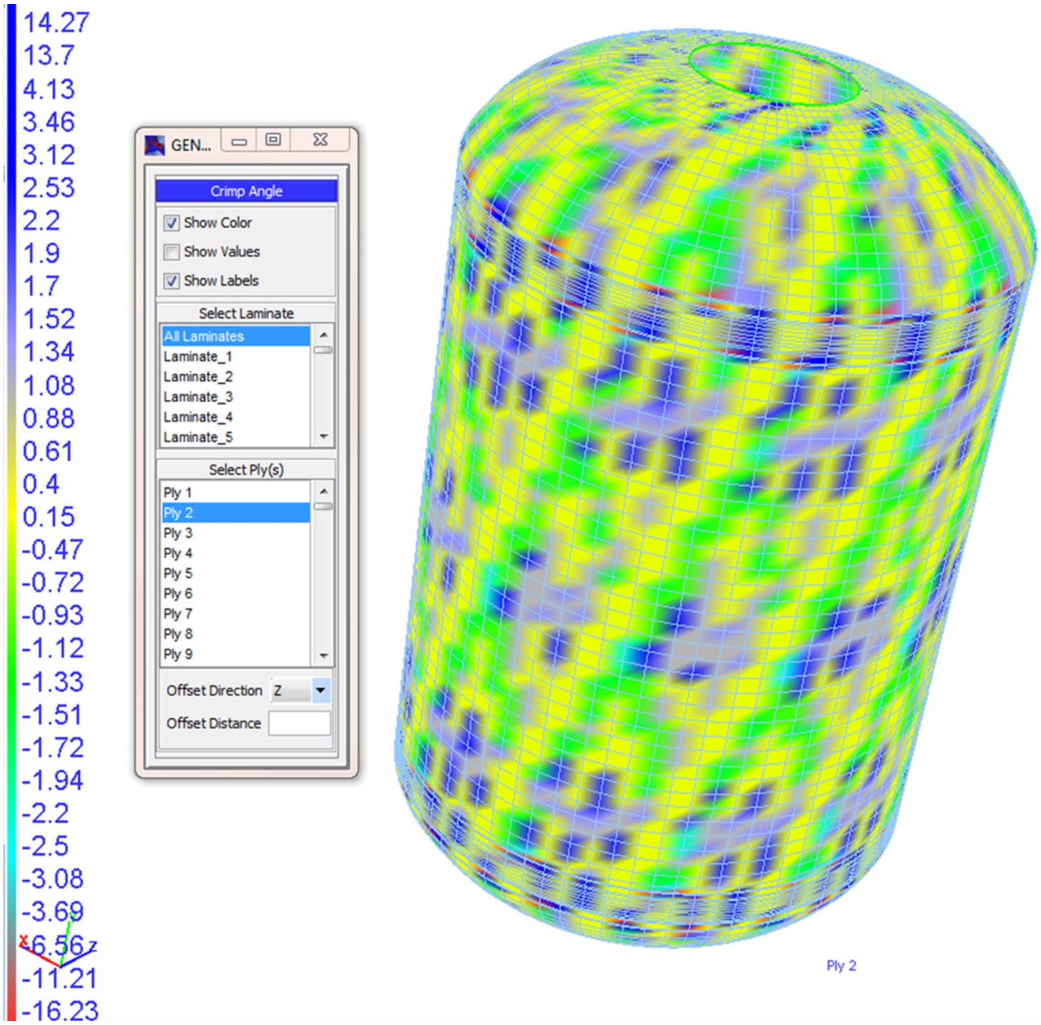
(2b). Buckling mode shape with two delaminations for panel under shear loading with knockdown factor (KDF) in buckling load (bottom).

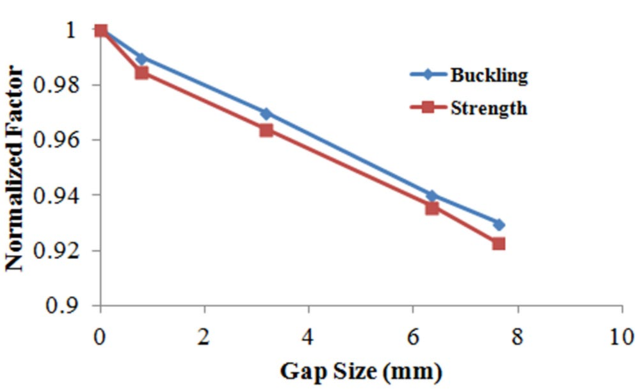
**Figure 3.** Structural damage in stiffened panel subject to axial compression loading.



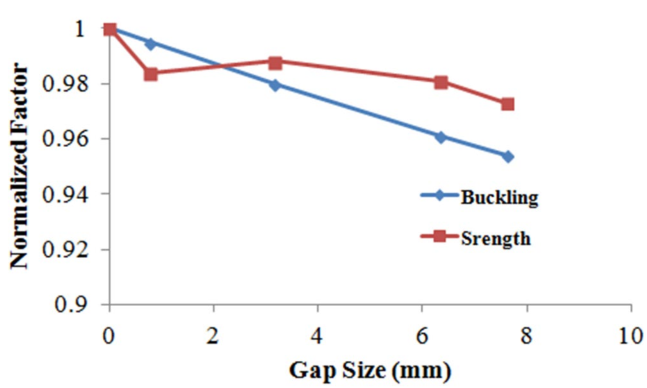

(3a). Damage evolution and % contribution.

**Figure 4.** Determination of Fuselage Structure Tape Layup resulted Crimp and crack formation.




(3b). Predicted knockdown as function of gap size in strength and stability in stiffened composite panel subjected to axial compression loading.




(3c). Predicted knockdown in strength and stability as function of gap size in stiffened composite panel subjected to shear loading.

# 09 AEROSPACE SOLUTION OPTIMIZATION THROUGH FRONT LOADING TECHNIQUES

**Martijn van Rij[1,2],** martijn.vanrij@fokker.com; Tobie van den Berg[1], tobie.vandenBerg@fokker.com; Ton van der Laan[1], ton.vanderlaan@fokker.com
[1]Fokker Aerostructures BV, Papendrecht, Netherlands
[2]Design Engineering Manager

## ABSTRACT

As a tier 1 supplier, Fokker Aerostructures needs to be able to quickly respond to market demands from aircraft integrators. To distinguish itself in the current competitive market environment, Fokker needs to be able to rapidly respond to new product opportunities and apply innovative technologies in the offered solutions. To achieve this, front loading techniques are being developed to perform detail design studies before the actual requests for proposal comes from a potential customer. These studies form the basis for a multi-disciplinary design optimization process that allows Fokker to quickly respond to RFPs and also gives Fokker a head start in the design process. Fokker currently investigates these techniques in the “Rudder in a Month project”. This project will be used to validate Fokker’s vision on using front loading. However many obstacles need to be overcome. These mainly consist of obtaining better, more mature software tools and better and more transparent storage of the knowledge used in these software tools. Finally social change is required to make the current generation of Aerostructures engineers accept radical changes to the design process.

**Keywords:** Front loading, design automation, structures design

## 1 INTRODUCTION

Fokker Aerostructures is a Tier 1 supplier of aircraft structures for many of the major aircraft integrators. Fokker usually operates on the design and build principle, meaning that the company is responsible for both the design of a structural component and its manufacturing. Fokker has designed and manufactures the empennages for the Gulfstream G550 and G650 and the Dassault F5X, as well as the outboard flap of Airbus A350. Fokker Aerostructures is part of Fokker Technologies which also consists of companies involved in aircraft wiring and aircraft maintenance.

Fokker’s main areas of expertise are Fiber Metal Laminates (FML), metal bonding, thermoplastic and thermoset composite. Fiber metal laminates are found in the fuselage construction of the Airbus A380 and consist of alternating thin layers of aluminum sheet and unidirectional glass fiber layers embedded in an adhesive system. Thermoplastic composites consist of glass or carbon fibers in a matrix consisting of thermoplastics resin, for example PPS. Thermoplastic composites allow other manufacturing techniques compared to thermoset composites, like induction welding and co-consolidation. In recent years Fokker has developed the control surfaces (rudder and elevators) of both the Gulfstream G650 (winner JEC innovation award 2010) and the Dassault F5X, and developed the Augusta Westland AW169 horizontal tail plane (winner JEC innovation award 2013) using this carbon/PPS material.

Because Fokker is responsible for both the development and manufacture of aircraft components it deals directly with aircraft integrators. The latter are increasingly asking for more affordable, meaning cheaper, components developed in a shorter lead time. Besides product excellence (e.g. by using innovative materials and manufacturing processes), design process excellence is needed that addresses the market needs of today. It is increasingly difficult to meet these requirement using the standard development process. Therefore Fokker proposes a design process in which automation and optimization are incorporated as much as possible, and engineering actions are performed as soon as possible in the development process. In this paper the vision of Fokker for its future front loaded design process is described.

## 2 PROBLEM DESCRIPTION AND FOKKER VISION

In the aircraft industry today the focus is on incremental growth and disruptive growth (**Figure 1**). This means that technical progress on the aircraft level is not high but that improvements are found by providing customers with more value through technology improvements on a lower level.

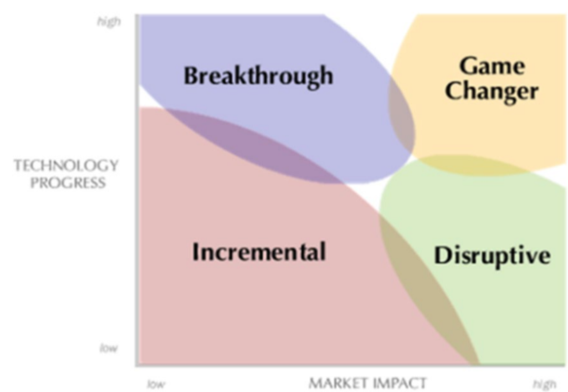
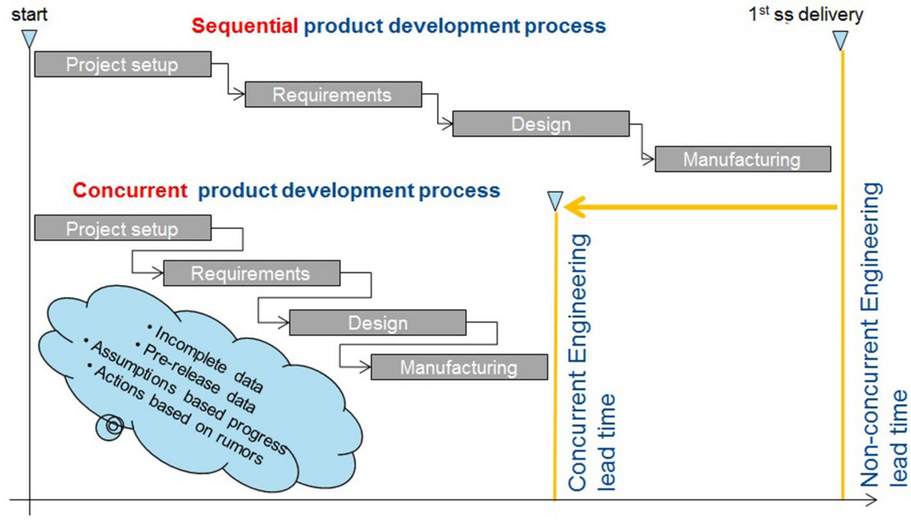



**Figure 1. Development areas of the aerospace market.**

Incremental improvements are only viable with low cost and short time to market. The reason for this is that the value for the customer is limited so the price this customer is willing to pay is also limited. Furthermore incremental improvements must have a short time to market to ensure the value advantage with respect to the competitor can be realized.

For Fokker the tendency towards incremental growth provides both opportunities and challenges. First of all aircraft integrators are constantly looking for opportunities to improve their existing designs. There is therefore ample opportunity for Fokker to apply its unique technologies on existing aircraft types. The challenges are that Fokker competitors are also aware of these opportunities and can therefore try to replace Fokker components on existing aircraft with improved designs. To overcome this there is an continuing pressure to improve existing components either by increasing performance (e.g. weight reduction, improved aerodynamics) and/or by reducing their cost.

**Figure 2.** Concurrent development process currently used at Fokker Aerostructures (right).




New aircraft component designs and design concepts need to be affordable. Therefore the non-recurring cost of a new aircraft component must be kept low to reduce the influence of sale price by amortization. There are several aspects of non-recurring cost, but the most significant one is the development cost. Therefore it is essential to keep this development cost low.

The current practice for the development process within Fokker is to apply a so-called concurrent engineering process (**Figure 2**). This means that development phases are run concurrently. This results in a shorter development lead time than the traditional sequential process. However by having the different phases run concurrently inefficiencies are introduced. For example assumptions need to be made because certain requirements are not clear when a design is made. When those assumptions prove to be wrong, a re-design is required, which incurs extra cost.

To ensure Fokker Aerostructures can remain competitive and offer competitive non-recurring cost figures a radical rethink of the design process is required. Fokker proposes a design process where front loading and virtual prototyping play an important part. Front loading was described by Thomke and Fujimoto [7] as *"a strategy that seeks to increase development performance by shifting the identification and solving of design problems to earlier phases of a product development process."*

Shifting problem identification and problem solving to earlier phases of the development process has already become common place in aircraft development processes. Fit an interference problems can be identified earlier by using (wooden) mock-ups and (as is the case nowadays) CAD Digital Mock-Ups. Virtual simulation using computer models offer faster and less costly results than physical testing. Production simulation and verification tools are used to detect errors and optimize the manufacturing process.

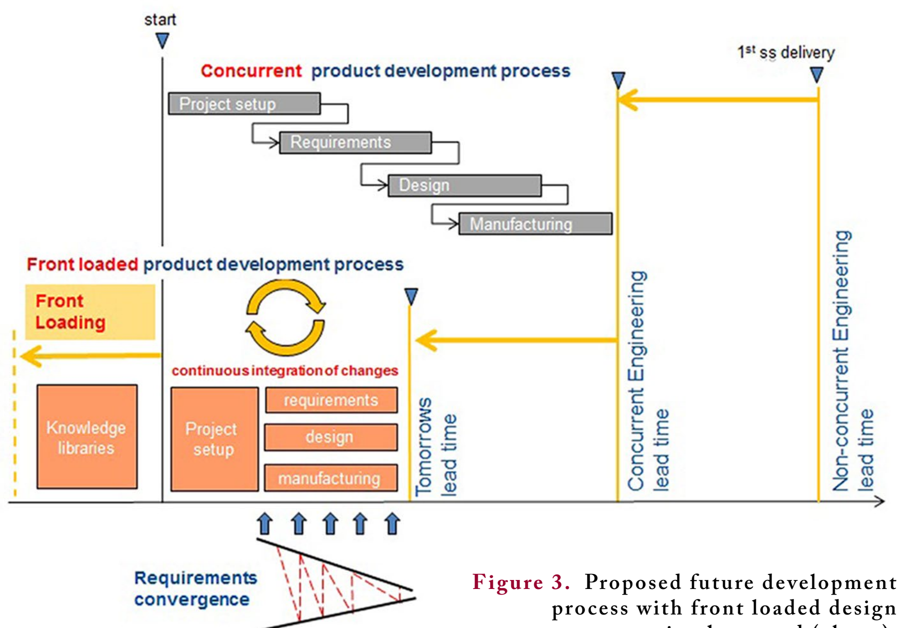



**Figure 3.** Proposed future development process with front loaded design implemented (above).

Fokker proposes to take the problem identification and problem solving even further forward by using front loading, meaning developing engineering knowledge before the earliest phases, i.e. before the actual design process starts (**Figure 3**). This is achieved by capturing product knowledge from earlier projects, and re-use and standardize this engineering knowledge and design process to rapidly evaluate many design variants covering different requirements sets. With the front loading principle, improved overall maturity, compliancy, change integration and controllability is achieved.

During the actual design process this evaluation of design concepts is continued. In the process the goal is to achieve full maturity of each of the design concepts evaluated and enabling continuous integration of changes, while new concepts, knowledge and methodology generation is done in the front loading phase. This ensures that no time-consuming changes are required once a design concept has been chosen. Multiple options can be kept open during the design definition phase, which provides the flexibility to switch to alternative concepts as the design input requirements from the customer becomes more mature.

For new Design-Build programs, the development pace will follow the airplane level phases (**Figure 4**), but problems can be identified and solved more quickly and earlier in the design process, and changes can be absorbed more quickly. For incremental changes on existing aircraft platform, the front loading process will allow a short time-to-market, because maturity is achieved more quickly.

The front loaded design process can only work when the design concepts can be evaluated quickly and completely using a computer, at a time when the ability to influence changes in design is relatively high and the cost to make those changes is relatively low. In the proposed development process each design concept is fully developed and analyzed, however it will not be manufactured in a physical sense. Therefore this practice is called virtual prototyping.

There may no longer a clear distinction between the Conceptual Design Phase and the Full Scale Development Phase. The customer input may mature, change and expand during the development process, but all output generated has always the same (or better) completeness and maturity (**Figure 5**).

In order for virtual prototyping to work the analysis of a design concept needs to be as complete as possible. For this analysis we can use well-known engineering techniques such as KBE (Knowledge Based Engineering) and MDO (Multidisciplinary Design Optimization). While these techniques have been used for several years now and have provided satisfactory results both in industry **[1-3]** and in academia **[5-6]**, application in a front loading scenario requires them to handle the complexity and uncertainty of the aircraft component design process.

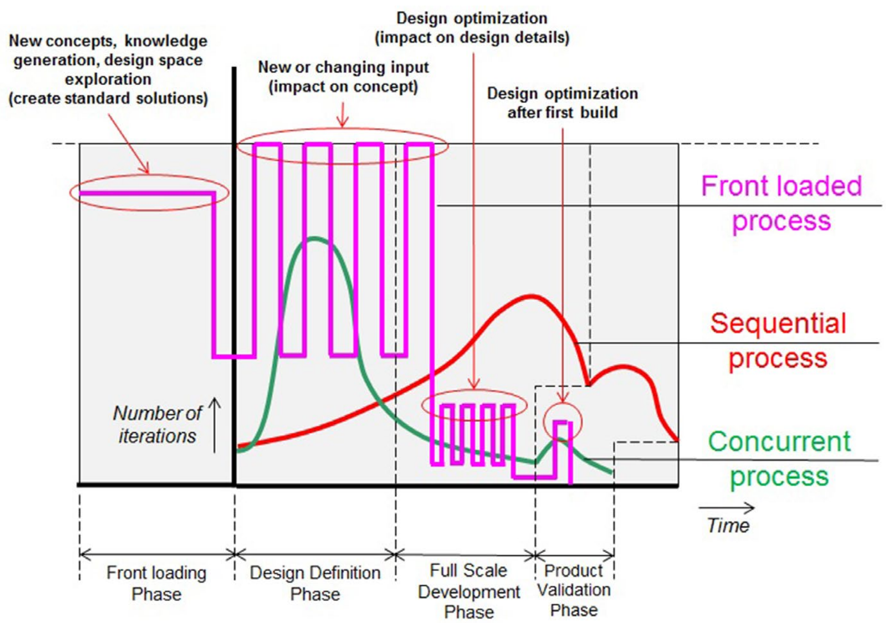



**Figure 4.** **Iterations sequential, concurrent and front loaded development process for new design-build.**

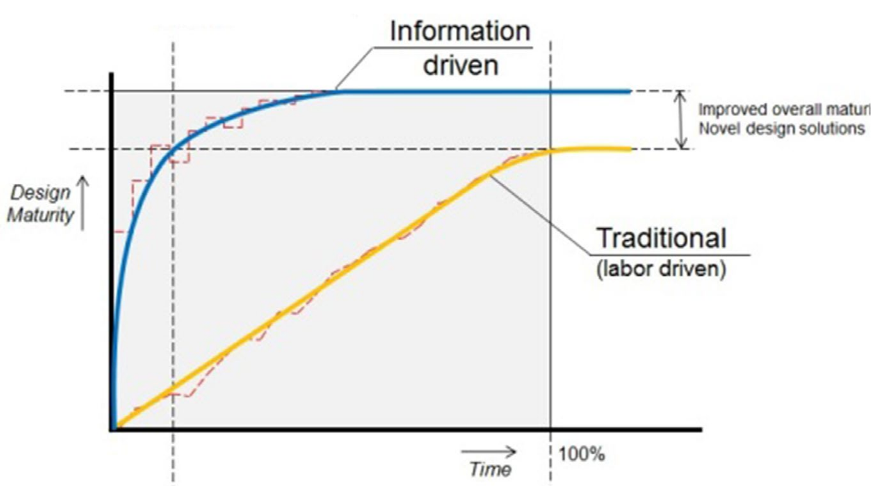



**Figure 5.** **Design maturity achieved in the front loaded design process using virtual prototyping.**

Because the design concepts are completely analyzed in the front loading scenario (including sensitivity and robustness analysis by design space exploration), a high maturity is achieved quickly. This ensures that development setbacks can be identified quickly and earlier in the design process, and allows a better response to changing requirements. Because the influence of changes at a higher level on the design of an aircraft component can be quickly analyzed it allows a Tier 1 supplier like Fokker to provide active feedback to the development cycle of the aircraft integrator.

In order for the front loaded development system to work using virtual prototyping, automation elements are required:

1. **KBE systems:** KBE systems provide the possibility to automatically create product models including geometry and associated engineering data based on formalized engineering rules. Because many of the engineering problems are geometry based, KBE systems are essential to find possible solutions.

2. **Workflow managers:** In order to automate the engineering process many smaller processes need to be linked and the information needs to be transported between the tools used in these processes. This requires a workflow manager. This workflow manager must be able to monitor the status of the information in the system and must also allow for human interaction where required. Different workflow management may be required for different process levels such as business process management and simulation process management.

3. **Multidisciplinary Design Optimization (MDO) tools:** To achieve the best possible solution the solution needs to be optimized. This has to be done in an intelligent manner because of the total complexity of the problems, it is impossible to evaluate all possible solutions. Multidisciplinary Design Optimization tools providing design of experiments and numerical optimization techniques should be used for this.

4. **Tools for robust design:** During a design process, some to many requirements and design inputs are (first) unknown, uncertain, incomplete or not frozen. In order to be well-prepared for a development request the sensitivities to requirement deviations need to be known. Tools are required in the front-loading process that can evaluate the robustness of a design solution linked to variations in the requirements set. Subsequently tools are needed in the design process that are able to predict and complete missing data accounting for the associated uncertainties.

5. **Data management:** Product data and standards must be controlled and made available in machine and human readable standardized formats, without the need for duplication according to the single source of truth philosophy. Various systems such as Product Data Management (PDM) and Simulation Process Data Management (SPDM) systems may provide solutions for this.

With the automation elements described above, the front-loaded development process can be executed. However for the system to be a success another change is also required. This is the change in the engineers attitude and behavior in the development process. In the current development system engineers are classified into different categories such as design, stress or manufacturing. In the new system engineers must be able to think multidisciplinary and be able to judge the results that come from the various multi-disciplinary system analyses. Furthermore engineers will need to accept that the computer will take a lot of their work out of their hands. New and additional capabilities and disciplines like IT & software specialists (architects, programmers) and Knowledge engineers will be needed besides the current engineers / users. Of all the changes required the social change required to implement the described vision might well be the most difficult to achieve.

To achieve the required social change and to ensure trust in the developed design tools, it is imperative that the rules used in the tools and its results are transparent. This means that the rules applied must be made accessible. Furthermore intermediate results must be viewable by the engineer. This ensures the engineer can assess the quality of the intermediate results and compare them with the results expected based on his experience.

## 3 RUDDER-IN-A-MONTH PROGRAM

The front loaded development system has not been implemented in commercial projects within Fokker. Aspects of this vision have been addressed in pilot projects (e.g. TAPAS2 **[3]**, Rudder-in-a-Month).

Rudder in a Month is an internal Fokker process improvement program aiming at discovering and developing techniques to realize the vision of the Front Loaded development process and show feasibility of an integrated, complete, automated workflow. The main objective is to develop an aircraft movable (rudder, elevator, aileron flap), within the timespan of a single month to a level that corresponds to the normal results of the full-scale development (FSD) phase up to the critical design review (CDR) and Industrialization. Such a development process would take about two to three years using current methods.

The ultimate goal is lead time reduction and operational excellence in the non-recurring development phase using standardized design process, design process innovation (including knowledge management and IT infrastructure), formalizing and re-use of knowledge and best practices, and automation of business processes and tasks, in order to:

- Accelerate the execution of tasks on the critical path.
- Reduce non-recurring cost of the total program.
- React quicker to customer requests and changes.
- Improve and expand available knowledge by front loading process (e.g. sensitivity analysis, design space exploration, driving design parameters) and virtual rapid prototyping, in order to aid and intensify the creative process.
- Improve quality of the product and process by having a predictable design process, performing more iterations and having automated requirements compliance checks.

### 3.1 Development approach

To obtain solutions for the many aspects of the front loaded development process for a rudder, an agile development approach is applied in which both the product scope and the technology scope

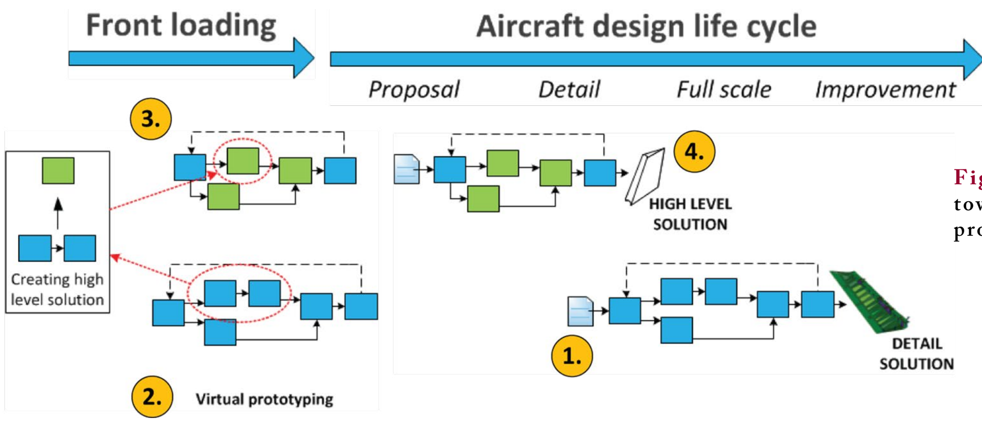
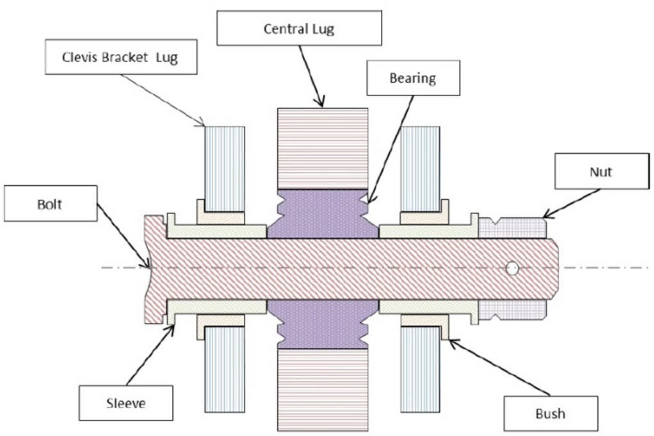
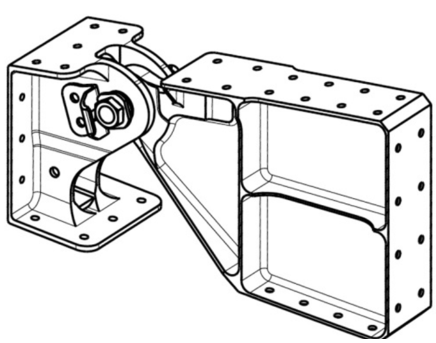



**Figure 6.** Development approach towards a front-loaded engineering process.

**Figure 7.** Schematic illustrations.




(7a). Sliding hinge



(7b). 3D representation of a sliding hinge.

are increased iteratively. With respect to the front loaded process, the anticipated development sequence is indicated in **Figure 6**. Development will start with obtaining the means to automate the development process during the detail design phase and demonstrating it (1). The detail design tools will be applied to perform virtual prototyping, explore relevant design spaces, improve design and analysis methods and standards (2). Potential design simplification opportunities are identified to define higher level solutions to enable MDO (3). The tools and standard libraries are then used in an actual development program in order demonstrate the achieved reduction in lead time (4).

### 3.2 Phase I – hinge design

As the overall scope of the Rudder in a Month program is vast, the first phase was aimed at a somewhat narrowed product and process scope. As the interface elements of a rudder are often driving the (initial) design, the design of a hinge was taken as product scope. The engineering process scope was set to the evaluation of a detailed design to its requirements, the generation of CAD models and requirements compliancy reports (for stress, weight and cost). The toolset for the RiaM first phase was required to be at the detail design level. This corresponds to the features required in the lower-right corner of **Figure 6.**

The hinge system of a rudder typically consists of a set of hinges that can be clamped or sliding, fail-safe or not fail-safe. **Figure 7** shows a schematic illustration of a sliding hinge consisting of a bolt, nut, bearing, bushes and lugs. Given the part identification or dimensions of each of these components, the objective is to determine whether the hinge complies to requirements and by what margin. The main constraints are the rudder OML and the loads applied to the hinge, taking the desired margin of safety into consideration. The results are reported in the form of certification document style Excel and Word files.

In order to integrate the steps required for the process the engineering BPM system KE-chain by KE-works was used. Both manual and automated tasks were modelled in the system. The workflow execution enables the automated tasks to automatically trigger tools via a tool server (KE-node by KE-works). For this purpose generic interfaces were made to automatically call Excel and CATIA VBA based tools. KE-chain also provides a product data model which was used to manage the input and output data for each task.

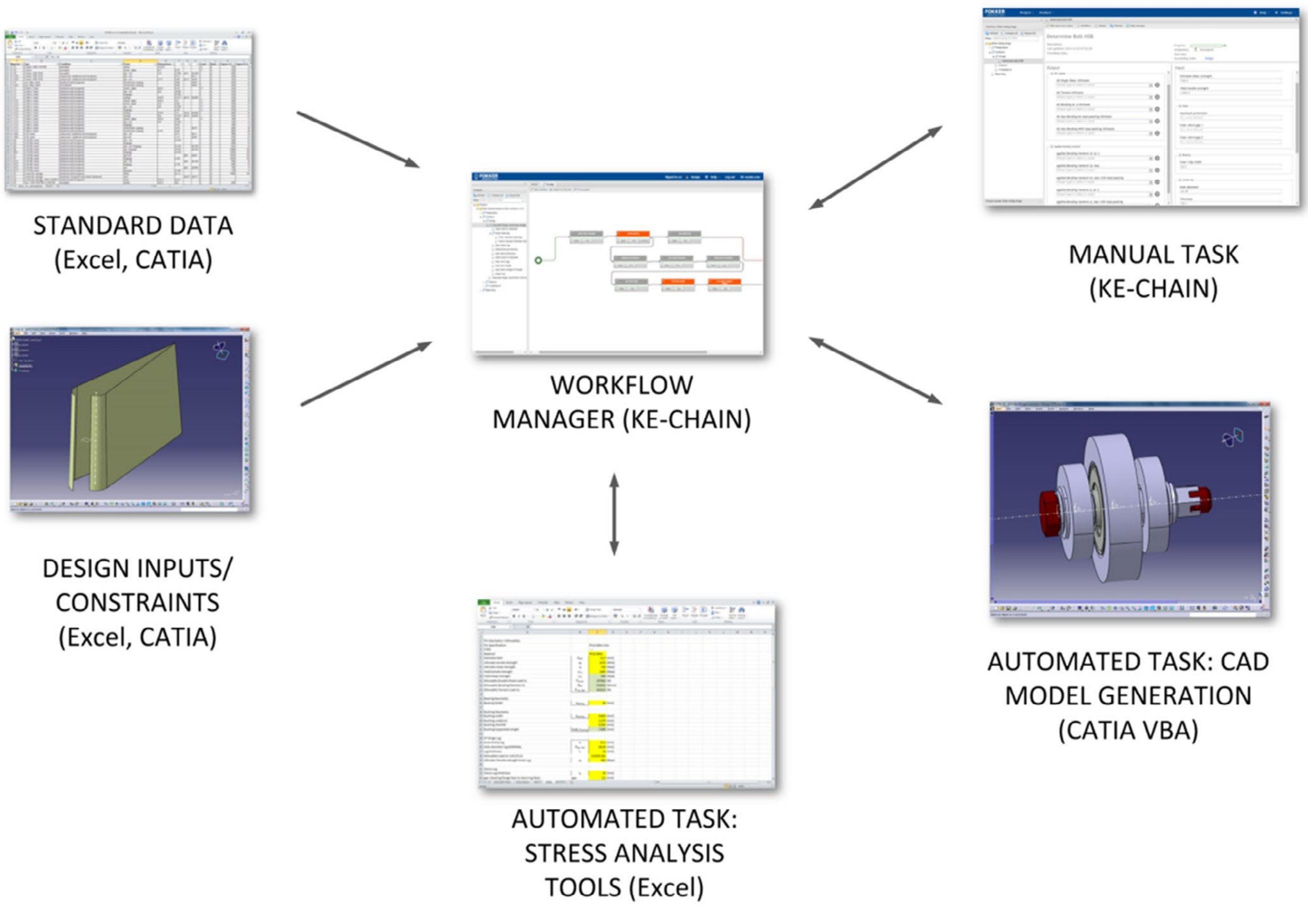



**Figure 8.** **The Rudder-in-a-Month phase 1 main framework components, where the workflow manager orchestrates all data exchange and (automated) task execution.**

For all geometry related activities, CATIA VBA tools were created, in particular: an import tool to interactively select the relevant geometric components from a native CATIA V5 file; a hinge generator tool to create, size and assemble all hinge components and several geometry analysis tools (e.g. volume measuring, OML intersection constraint checking). Starting CATIA and subsequently running each of these tools with the framework requires no user interaction.

All load sorting and stress analysis activities were implemented in standardized Excel tools. For each standard component a tool was provided capable of computing all relevant margins of safety. Report generation tools were implemented in Python, both generic (excel report based on selected attributes from KE-chain product model) and specific (word stress report). Fokker has defined many standard parts and materials, but these are often not available in standardized, computer-readable data formats. Therefore standard parts and material data was digitalized into databases that could be imported by KE-chain. Standard CATIA parts (e.g. bolts) were available, but often needed to be modified to match with the orientation convention.

The complete toolset (**Figure 8**) was deployed on the Virtual Laboratory (VLAB) at Fokker, an environment separated from the operational IT environment for R&D purposes. The VLAB LAN consists of a server on which KE-chain and the Python-based tools were deployed and a workstation with a browser (to access KE-chain), CATIA V5 and MS Office applications. The framework was demonstrated using input data based on a hinge Fokker recently designed.

### 3.3 Phase I evaluation

The first phase showed that a product, which was on first inspection considered to be comparatively simple, actually features more complexity than anticipated. This can be characterized by the large number of parameters in the product model (800 parameters) and tools/scripts created (50 tools). The large number of parameters led to narrowing down the product evaluation scope (e.g. by ignoring tolerance analyses), which means that the case did not cover the detail development process to the desired extent.

The objective of achieving a high level of modularity lead to a large number of small modules, for which interfaces had to be managed.

The integration of all modules was done at one level, which, combined with the large number of parameters, increased the complexity of the solution. For the solution to be scalable, some of the integration should be applied in submodules instead of the main product model definition.

Developing the tools for phase I and demonstrating them to Fokker experts provided feedback on the methodologies used in order to obtain a correct procedure. This in fact is an aspect of front loading: formalizing an engineering procedure for automation will trigger questions and can lead to new insights.

### 3.4 Next phases

This first phase mainly focused on a framework suitable for the analysis of a defined product. Next phases will address cases that include implementing design engineering logic as well and will require the incorporation of search or optimization tools in order to automated iterative design processes. The product scope will be expanded to the torsion box of the control surface.
The torsion box product scope will show feasibility of an integrated, standardized, automated design process / workflow with integrated design logic, linking Master Geometry (definition of structural interfaces and design concept), FEM analysis (automatic generation of FE model by CAD-FEM integration), stress sizing (integrated stress toolbox with workflow, including loads extraction and sizing loops with FE model), detailed CAD models (3D solid production definition models of detail parts and assemblies), compliance reporting (e.g. stress, weight and cost reporting) and design of tooling (assembly jigs and detail part lay-up tooling).

Initial development will focus on enabling execution of trade studies on the torsion box of a thermoplastic, post buckled movable (multi-rib and multi-spar). This requires knowledge acquisition of recent designs of thermoplastic, post-buckled, welded torsion box, and development of the framework and tools to support executing the trade studies (based on weight, cost, manufacturability, etc.), to enable more mature, robust, lower risk (preliminary) design to generate better competitive offers to customers proposals, and reduction in hours per trade study and/or perform more trade studies in the same total time.

## 4 DISCUSSION OF REQUIRED ELEMENTS FOR IMPLEMENTATION OF THE FOKKER VISION

As was shown in the Rudder-in-a-Month case study, there are several technologies that are required to apply the Fokker vision of the future development process. The required elements and their impact on the development process will be discussed.

### 4.1 Standards (simulation) data management

A lot of data is created in the process of finding the best solution. In order to achieve the required process transparency the simulation, and other data, generated in the development process, must be managed in a structured way.

### 4.2 Knowledge management system

Knowledge is used extensively, for example in the form of rules used in sizing tools. To be able to manage the knowledge used a well-structured knowledge management system is required.

### 4.3 Design rationale tracking/traceability

Like the knowledge rules discuses in the previous paragraph the design rationale or design logic applied in the development process must be stored and traceable. This makes the automated design process more transparent.

### 4.4 Virtual laboratory

When automating the development process new software and other tools will be introduced regularly. It is impossible to test all this software and tools in an environment that also supports the normal operation of an aerostructure manufacturer. Therefore a separate environment is required where software and tools can be tested rapidly without the danger of disturbing day to day operations of the company. This environment is called the virtual laboratory.

### 4.5 Bridge between structures engineering and software engineering

In the development of tools that fit in the envisaged design system two problems are encountered. Tools developed by structural design engineers often are not robust enough or, in other words, do not meet common software development standards. On the other hand tools developed by software engineers, whilst robust and stable, do not meet the required functionality standards. In order to overcome this the strengths of both sides need to be combined.

### 4.6 Mature KBE system

In the design process geometric manipulations are often required. When used in an optimization loop common CAD systems are often too slow. Instead KBE systems can be used for geometry generation. These are faster and therefore better fit in an optimization loop. However to Fokker's experience the KBE systems currently marketed are not mature enough. Main issue is the lack of critical mass and the lack of a support base for outsourcing tool development.

### 4.7 Framework integrating processes and tools that fit within a professional environment

The design process consists of many tools with a lot of data exchange between them. To run this process, framework management tools are required. However to use these tools in a professional setting, security and intellectual property issues need to be addressed.

### 4.8 Mature MDO software and strategies

Optimization is required to find the correct design solution. To be able to do this, MDO tools are required that provide the optimization algorithms and fit in a multi tool design environment. Besides tools, optimization strategies are also required to achieve an optimal optimization process.

### 4.9 Culture change of aircraft component engineers

The most important element of change required for Fokker 's vision to become reality is cultural change. Companies and engineers involved in the design process of aircraft components must realize that design process and required skills will fundamentally change in years to come. If they do not adapt to this new reality they will be overtaken by other companies and engineers that are able to do a better job for less money.

## 5 CONCLUSION

In this paper the vision of Fokker on a new implementation of the aircraft component design process are presented, using the front loading principle. This vision is ambitious, but is essential to remain competitive in the aircraft component development business, by capturing, improving and expanding knowledge; reduce lead time; reduce hour volume; reduce / mitigate risks; and improve robustness and quality. Realizing this vision will be a challenge that Fokker will not be able to address on its own. In order to achieve the level of automation required partners in the area of software development must be found.

There is still a lot of work to be done to achieve full maturity of the design process automation envisaged. Besides development on the methods and software tools side, this will also require a change in the attitude of engineers with respect to design automation. We at Fokker look forward to meeting the challenges ahead and defining the future with a new aircraft component design process.

## 6 REFERENCES

[1] Berg, T. van den, La Rocca, G. & Tooren, M. van., "Automatic Flattening of Three-Dimensional Wiring Harnesses For Manufacturing", 28th International Congress of the Aeronautical Sciences, Brisbane 2012
[2] Laan, T. van der, Dalen, F. van & Vermeulen, B., "Design support for metallic machined ribs using Knowledge Based Engineering techniques", Aeronautical Journal, November 2010, Volume 114 Number 1161, pp 681-688
[3] Laan, T. van der, Berg, T. van den, Hootsmans, L., "Integrated multidisciplinary engineering solutions at Fokker Aerostructures", CEAS 2015 paper no. 115, Delft, The Netherlands, 2015
[4] Laan, T. van der, Vermeulen, B. & Dalen, F., "Automating the development process of thermoplastic composite sheet ribs using knowledge based engineering techniques", 26th International Congress of the Aeronautical Sciences, Anchorage, 14-19 September 2008.
[5] La Rocca, G., Langen, T.H.M. & Brouwers, Y.H.A., "The design and engineering engine. Towards a modular system for collaborative aircraft design", 28th International Congress of the Aeronautical Sciences, Brisbane 2012
[6] La Rocca, G., Tooren, M. van, "A Knowledge Based Engineering Approach to Support Automatic Generation of FE Models in Aircraft Design", 45th AIAA Aerospace Sciences Meeting and Exhibit, AIAA-2007-0967, Reno, NV, USA, 2007.
[7] Thomke S. & Fujimoto, T., "The effect of "Front-Loading" Problem solving on product development performance", J PROD INNOV MANAG 2000; 17:128-142.

THURSDAY AUGUST 27, 2015

# SESSION III: LAKE CITY

## 10 AUTOMATION IN COMPOSITES: EXPECTATIONS, REALITY AND FUTURE

**Michael Muser**[1,2]
[1]Nngersoll Machine Tools, Inc., Rockford, IL, United States
[2]Composites Business Manager

### ABSTRACT

The manufacturing chain of composites is far more intricate and complex than traditional metal manufacturing. Multiple trades are unconventional and specific to composites such as in-line quality, bagging, curing, etc. Obviously, this does not include the multiple design constraints that exponentially complicate the design task. All of this leads to high aspirations for automation of composites and hopes to reduce the complexity of manufacturing composite structures. Automation application is somewhat different in between the multiple markets. While automotive is way ahead of aerospace, we can see that the wind sector trails behind. Today, we have multiple production generations from the very starting point of hand lay-up leading to the 4th generation in automated fiber placement machines that support the automation of composites manufacturing. For future tendencies and challenges, we note the current trends of using wider materials as well as the research on alternative solutions using dry fiber technologies. It will be also be highly beneficial to automate non-machine related trades such as the complicated design task.

## 11 INVESTIGATION OF DAMAGE GROWTH IN SANDWICH STRUCTURES UNDER GROUND-AIR-GROUND CYCLES

**Waruna Seneviratne**[1,2]**,** waruna@niar.wichita.edu; John Tomblin[1], Caleb Saathoff[1], Shawn Denning[1]
[1]National Institute for Aviation Research, Wichita State University, Wichita, KS, United States
[2]Technical Director

### ABSTRACT

Fluid-ingression phenomenon in composite structures is a concern for sandwich structural details. Inadequate design details and/or poor material selections can result in microcracks during ground-air-ground (GAG) cycling that consequently coalesce to form

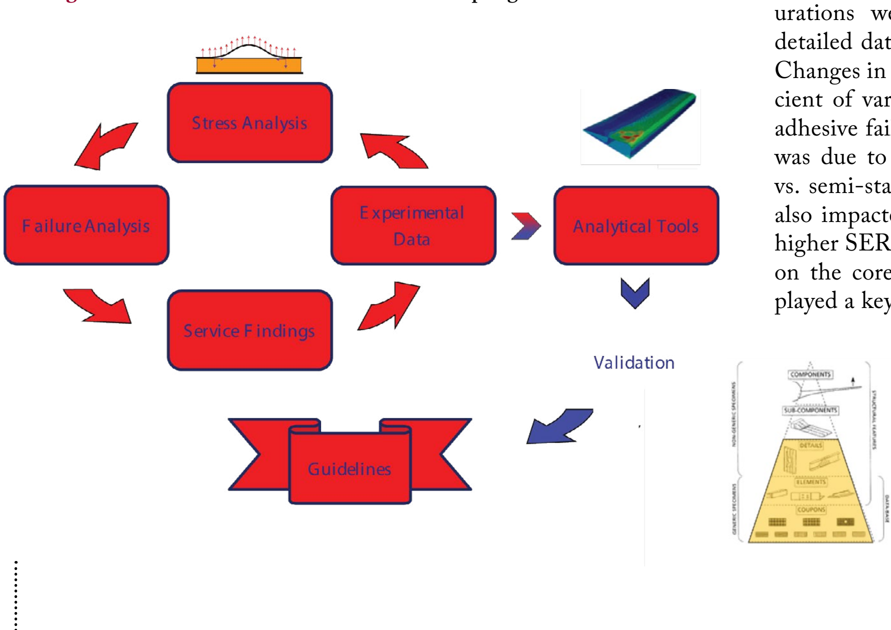
transverse matrix cracks that lead to moisture ingression into the subsequent composite and adhesive layers and finally into the core. Impact damages on sandwich structures exacerbate the fluid-ingression phenomenon as a result of localized transverse cracks, delaminations, disbonds, and core damages. Thermo-mechanical loads during GAG cycling could cause the local buckling on compression side of a sandwich structure that result in localized mode I stresses that may result in further delamination/disbond growth creating more passageways for fluid migration. Additionally, the trapped water in sandwich cells translate into vapor during high temperatures and increase the internal pressure and cause core disbond and/or fracture. In some cases, the damage growth due to the above-mentioned two mechanisms is stable and occurs over a period of several flights, but may not be readily detected on the ground, when the thermo-mechanical and internal vapor pressure loads are released. Although the damage size continues to grow in such cases, the structure continues to carry loads until it reaches a critical damage threshold (CDT), where the unstable damage growth triggers the catastrophic failure. Unless such damage is detected and repaired prior to reaching CDT, GAG effects will further the damage size and threaten the structural integrity and safety of the aircraft. This research investigated the effects different core configurations on the damage growth of sandwich structures. Furthermore, the effects on GAG cycling on damage growth rate was investigated.

**Keywords:** Sandwich structures, damage growth, fluid ingression, ground-air-ground cycling, testing

## 1 RESEARCH OVERVIEW

Current research tasks are designed to investigate the fluid ingression phenomenon in sandwich structures and resulting progressive damage growth due to ground-air-ground cycling. Inadequate design details and/or poor material selections as well as operational damages can cause fluid ingression into core. Impact damages on sandwich structures exacerbate the fluid-ingression phenomenon as a result of localized transverse cracks, delaminations, disbonds, and core damages. Thermo-mechanical loads during GAG cycling could cause the local buckling on compression side of a sandwich structure that result in localized mode I stresses that may result in further delamination/disbond growth creating more passageways for fluid migration. Additionally, the trapped water in sandwich cells changes phase to vapor during high temperatures and increase the internal pressure and cause core disbond and/or fracture. In some cases, the damage growth due to the above-mentioned two mechanisms is stable and occurs over a period of several flights, but may not be readily detected on the ground, when the thermo-mechanical and internal vapor pressure loads are released. Although the damage size continues to grow in such cases, the structure continues to carry loads until it reaches a critical damage threshold (CDT), where the unstable damage growth triggers the catastrophic failure. Unless such damage is detected and repaired prior to the reaching CDT, GAG effects will further the damage size and threaten the structural integrity and safety of the aircraft. The primary objective of the current research program is to provide guidance for demonstrating durability and damage tolerance of sandwich composite structures against fluid ingression and GAG cycle effects as shown in **Figure 1**. During initial phases of this research, the influence of sandwich parameters such as core size, density, and facesheet/core stiffness ratio on the onset and damage growth rate of sandwich composites was investigated using single-cantilever beam (SCB) static and fatigue testing for Mode I fracture toughness of core-facesheet disbond.

**Figure 1.** Overview of current research program.




Current phase of the research focus on investigating the effects of ground-air-ground cycling on damage growth behavior of sandwich structures with synchronized temperature, pressure and mechanical loads; investigate the conditions for onset of damage growth and damage growth rates. Also, a standardize procedure and test apparatus for GAG testing for simulate damage growth due to mixed-mode stress state caused by pressure differential at high altitude coupled with in-plane mechanical loads is developed. Furthermore, predictive capabilities of onset of damage growth and progressive failure mechanisms using virtual crack closure technique and cohesive zone modeling couple with multi-scale material models were evaluated. The information gathered through this research will be instrumental in developing analytical methods and validating finite element analysis procedures to further investigate the damage growth mechanics of sandwich composite structures.

## 2 CONCLUSION

Strain energy release rates (SERR) for different specimen configurations were coupled across different variables and required detailed data analysis for determining the impact of each variable. Changes in failure mode substantially impacted data scatter (coefficient of variation). Core failure resulted in the least scatter, then adhesive failure. Pullout failure resulted in the highest scatter. This was due to the mechanisms behind the failure, i.e., stable (core) vs. semi-stable (pullout) crack growth. Changes in failure mode also impacted fracture toughness, with pullout failure resulting in higher SERR than adhesive failure. However, core failure depended on the core type, cell size and cell density (paper thickness also played a key role).

Theoretically, facesheet thickness indicates no influence on the fracture toughness. However, large deflection, material non-linearity, and changing failure modes (and changing paper thickness) result in facesheet thickness playing a predominant role in SERR amongst various sandwich configurations. Typically, the thicker the facesheet larger the fracture toughness, regardless of core type, cell size or cell density considering the critical values or the crack propagation curves.

When examining the entire resistance curve, it was found that hexagonal core was somewhat more fracture resistant than over-expanded core. Additionally, the failure modes between the two core types varied significantly. Cell size played a predominant role in determining fracture toughness. However, cell fillets and paper thickness may have also contributed to how cell size influenced fracture toughness. The 1/8 core resulted in primarily core and adhesive failure, while 3/16 core resulted in primarily adhesive and pullout failure. 3/8 core resulted primarily in pullout failure. Cell size also affected the load displacement curves, i.e., larger load drops (and crack arrest) as the cell size is increased. Core density had a smaller impact as compared to the above-mentioned factors. This is due to the fillets and how they artificially thicken the cell walls and potentially the paper thickness. Failure mode was influenced by core density moving from core to pullout failure as density increased. Core density also affected the load displacement curves, i.e., larger load drops (and crack arrest) as the core density is increased.

The prescibed crack length played a predominant role in determining fracture toughness. Large prescibed crack lengths led to significantly larger displacements and non-linear behavior in thin facesheet specimens. Once the correction factors for large displacements had been applied, it was observed that the shortened (1-inch) specimens had significantly higher fracture toughness than the (2.5-inch) specimens regardless of core type, cell size or core density. Additionally, both the resistance curves and the load displacement curves (superimposed) appeared to be continuous for any given sandwich configuration.
Fluid ingression using an acidic Skydrol/water mixture had a significant impact on both the bond line (acid degradation) and the core (moisture absorption), which resulted in altering the fracture toughness. Crack tip softening due to moisture absorption and the weakened adhesive played a key role in damage growth, especially at the initial region of the resistance curve. When considering the entire resistance curve, it can be observed that the resistance curves typically converged amongst the various environmental conditions.

Element level GAG testing indicated that the damage growth rate under mechanical loading is considerably accelerated with pressure differential during GAG cycling.

## 12 DISCRETE DAMAGE MODELING IN COMPOSITE LAMINATES UNDER STATIC AND FATIGUE LOADING

**Endel Iarve[1],** endel.iarve@udri.udayton.edu; Kevin Hoos[1], kevin.hoos@udri.udayton.edu; David Mollenhauer[2], david.mollenhauer us.af.mil
[1]University of Dayton Research Institute, Dayton, OH, United States
[2]Air Force Research Laboratory, Wright-Patterson Air Force Base, Ohio

### ABSTRACT

The present paper addresses the issue of direct simulation of complex local failure patterns in laminated composites including matrix cracking, delamination, and fiber failure. The analytical technique uses the Regularized Xtended Finite Element Method (Rx-FEM) for the simulation of matrix crack initiation and propagation at initially unknown locations; cohesive interface models for delamination as well as continuum damage mechanics model for fiber failure. The essence of this technique is the insertion of true displacement discontinuities independent of mesh orientation to simulate matrix cracking. Multiple cracking in each ply is allowed. All plies are tied together by using cohesive interfaces, which are allowed to delaminate. An important feature of the technique is that it uses independently measured standard ply-level mechanical properties of the unidirectional composites for static and fatigue prediction of unnotched and notched laminates. A $[60/0/-60]_{3s}$ IM7/977-3 laminate under static and fatigue loading was modeled and compared with experimental data. Post fatigue residual strength trends as well as matrix cracking and delamination patterns were in agreement with experimental data.

**Keywords:** Aerospace Structures, Materials, Simulation, Cracking, Delamination, Fracture

### 1 INTRODUCTION

Strength prediction even under uniform in-plane loading has presented formidable problems as reflected by the World Wide Exercise **[1]**. The complexity of the problem lays in the interaction of various modes of damage such as matrix cracking, delamination and fiber failure, which cooperatively lead to the loss of the load carrying capacity and/or loss of integrity.

The progressive damage modeling methodology potentially addresses the damage evolution and interaction phenomena. To assess the state of the art of progressive damage methodology a round robin exercise was recently launched by the Air Force Research Laboratory (AFRL) for prediction of tensile and compressive strength of several carbon fiber reinforced composite laminates. The exercise consisted of two parts, the first part was devoted to static loading **[2]** and the second part was devoted to fatigue loading and will be reported below.

The Discrete Damage Modeling (DDM) method, which was utilized for analysis, is based on direct simulation of displacement

**Figure 1.** Residual tensile and compression strength prediction after 200,000 cycle fatigue (1a) tension (top) and (1b) compression (bottom).

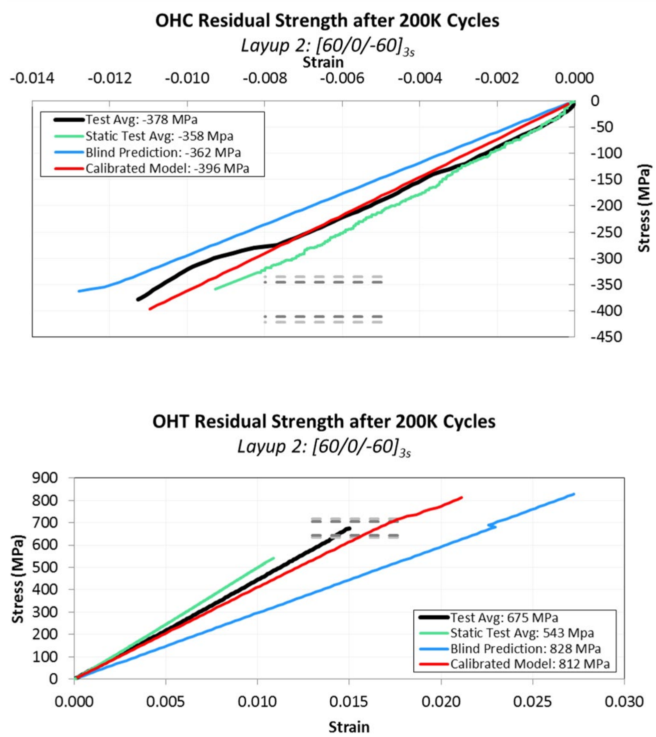
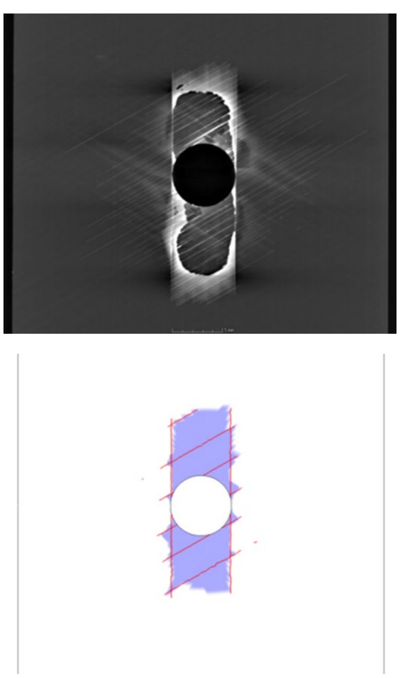



**Figure 2.** (2a) Delamination extent on outer 0/-60 interface after 200,000 cycles (top). (2b) Matrix cracks in red, delamination in blue (bottom).



discontinuities associated with individual instances of matrix cracking occurring inside the composite plies, and delaminations at the interfaces between the plies. The DDM utilized Regularized eXtended Finite Element Methodology (Rx-FEM)[**3**].

## 2 DISCRETE DAMAGE MODELING METHODOLOGY

The matrix cracks are modeled by using the regularized formulation [**3**], termed Rx-FEM. The regularized formulation deals with continuous enrichment functions, and replaces the Heaviside step function with continuous function changing from 0 to 1 over a narrow volume of the so called gradient zone. The simulation begins without any initial matrix cracks, which then are inserted based on a failure criterion during the simulation. In the case of static loading the LaRC04 failure criterion is used. In the case of fatigue loading a material history variable in each integration point is introduced and updated after each loading increment, corresponding to certain load amplitude and number of cycles. The Palmgren-Miner rule is used for material history variable evolution. The propagation of each MIC in static regime is performed by using the cohesive zone formulation. In the case of fatigue loading a new formulation of the cohesive zone model was proposed and implemented. It uses strength based S-N strategy for damage initiation and Paris law cycle integration strategy for damage propagation [**4**]. Fiber direction failure was considered unaffected by fatigue loading and same methods as in static analysis [**2**] were applied.

## 3 RESULTS AND DISCUSSION

A $[60/0/-60]_{3s}$ IM7/977-3 composite laminate with a 6.35mm central open hole will be considered below. The DDM methodology uses standard ply level stiffness and strength properties measured by using ASTM standard methods. Those include stiffness, ply level strength, Mode I and II fracture toughness for static simulation and S-N curves for transverse strength and in-plane shear properties as well as delamination grows Paris law data for fatigue. Static tensile and compressive strength was predicted in pristine laminates as well as after 200,000 cycles of fatigue loading at 80% static failure load. The respective stress strain curves are shown on **Figure 1.**

Two predictions are shown on each figure; one was performed before the experimental data was known and one after. The blind prediction results exhibited significantly more damage than was seen on the experiment. A review of the methodology revealed an algorithmic error, which was corrected and new results, designated as calibrated model were obtained. The curves designated as static test represent pristine laminate testing and test curves represent residual strength testing after fatigue loading. Both in the case of tensile and compressive residual strength prediction the analysis correctly captured the trends. It showed relatively low sensitivity in the case of compressive loading and increase of residual strength for tensile loading. This increase is explained by massive delamination caused by fatigue loading, which in combination with splitting in the 00 plies causes significant stress relief in fiber direction. The damage pattern at one such interface is shown on **Figure 2**.

Large delamination patterns were observed and predicted on other interfaces as well. In all cases unmistakable resemblance between predicted and experimentally observed delamination and matrix cracking patterns was seen.

## 4 CONCLUSIONS

DDM methodology has been extended to fatigue loading. The cohesive zone based fatigue algorithm has been proposed, which eliminates any ambiguity or need for initial damage size or presence of any cracks or delaminations in the structure. Correct trends for residual tension and compressive strength as well as damage patterns for the $[60/0/-60]_{3s}$ laminate after 200,000 cycles of fatigue loading at 80% static strength were predicted.

## 5 REFERENCES


[1] Hinton, M. J. and Soden, P. D., (1998) "Predicting Failure in Composite Laminates: the Background to the Exercise," *Composites Science and Technology*, Vol. 58, No.7, pp 1001–1010

[2] Iarve E, Hoos K, Braginsky M, Zhou E (2015) Tensile and Compressive Strength Prediction in Laminated Composites by Using Discrete Damage Modeling, Proceedings 56th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Kissimmee FL, Jan 5-9, 2015

[3] Iarve, E.V., Gurvich, M.R., Mollenhauer, D.H., Rose, A.C. and Davila, C.G. (2011) Mesh-independent matrix cracking and delamination modeling in laminated composites, Int. J. Numerical Methods in Engineering, 88(8), pp. 749-773, 2011

[4] E. V. Iarve, K. H. Hoos and D. H. Mollenhauer, (2014) "Damage Initiation and Propagation Modeling in Laminated Composites under Fatigue Loading," Proceedings of the American Society for Composites: Twenty-Ninth Technical Conference, La Jolla, California, September 8-10, 2014, American Society for Composites, CD-ROM –Paper 664, 18pp.


# 13 ROADMAPPING FOR COMPOSITE JOINING AND REPAIR


**Chuck Zhang[1],** chuck.zhang@gatech.edu; Ben Wang[1], ben.wang@gatech.edu; Les Kramer[2], advmatlpro@gmail.com; Richard Liang[3], zliang@fsu.edu; Charles Browning[4], cbrowning1@udayton.edu; Barbara Jeol-Pieters[1], barbara.jeol@gatech.edu

[1]Georgia Institute of Technology, Atlanta, GA, United States

[2]Advanced Materials Professional Services, Orlando, FL, United States

[3]Florida State University, Tallahassee, FL, United States

[4]University of Dayton, Dayton, OH, United States


## ABSTRACT


The National Institute of Standards and Technology (NIST) Advanced Manufacturing Technology Consortia (AMTech) Program established the Consortium for Accelerated Innovation and Insertion of Advanced Composites (CAIIAC) consisting of Georgia Institute of Technology, Advanced Materials Professional Services, Florida State University, the University of Dayton, and over 40 companies and organizations. This technical effort will generate a roadmap to address transitioning composites technologies from development and demonstration to product launch. The overall vision of CAIIAC is to create an innovative domestic manufacturing ecosystem that significantly shortens the manufacturing development cycle while providing "right-the-first-time material yields" for composite processing. Information obtained during CAIIAC workshops/meetings helped to guide the CAIIAC team toward a prioritization of six "Grand Challenges." This effort was conducted in conjunction with an industry led "Meta-Roadmapping" process. We not only were able to identify major technical gaps while being able to understand challenges for broader composites market acceptance, but also found that Composite Joining and Repair (CJAR) was an under-served market segment in the composites industry. The recent surge in heavy usage of composites for aero-structures, automotive and wind energy applications will result in unprecedented demand for reliable repair and joining technologies, which became the focus of CAIIAC roadmapping foci. The CAIIAC roadmapping effort is further enhanced by the team's recent work on technology, manufacturing, business case and ecosystem readiness assessment models. This presentation will provide recent progress, workshops outcomes, and a future plan of CAIIAC.


**Keywords:** Composites, Joining, Repair, Roadmapping

## 1 INTRODUCTION

NIST ran a competition for planning awards to support industry-driven consortia in developing research plans and charting collaborative actions to solve high-priority technology challenges and accelerate the growth of advanced manufacturing in the United States. This NIST AMTech Program aims to spur consortium-planned, industry-led R&D on long-term, pre-competitive industrial research needs. Major objectives also include eliminating barriers to advanced manufacturing and promoting domestic development of an underpinning technology infrastructure. CAIIAC is one of the 19 first round AMTech awards announced in May 2014.

CAIIAC is a consortium concept for advanced composites being validated and planned that will result from a technology roadmap exercise to be presented to NIST. Over 40 companies and organizations in the field of composites have been participating in CAIIAC. They cover the entire value chain of composites in various sectors, ranging from small- and medium-sized enterprises such as Acellent Technologies and MADE to large OEMs like ATK and Spirit AeroSystems, as well as organizations such as Georgia MEP and Oak Ridge National Lab.

The objectives of CAIIAC are (1) to develop an objective, verifiable and consistent roadmap to identify and validate emerging cross-cutting composite technologies, and (2) to help identify/create a domestic innovation manufacturing ecosystem to accelerate advanced composite products into the market. The CAIIAC mission includes (1) accelerate innovation and assist rapid insertion of advanced composites, (2) develop broad-based applications for advanced composites, and (3) encourage "invent here, build here" in the United States to improve U.S. competitiveness and sell advanced composite products globally.

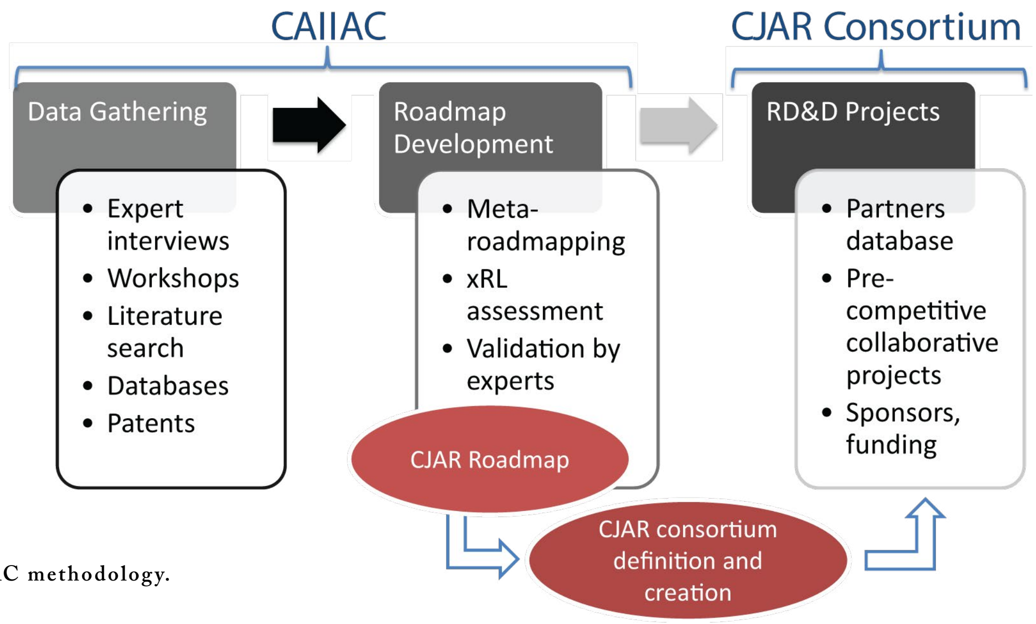



**Figure 1.** CAIIAC methodology.

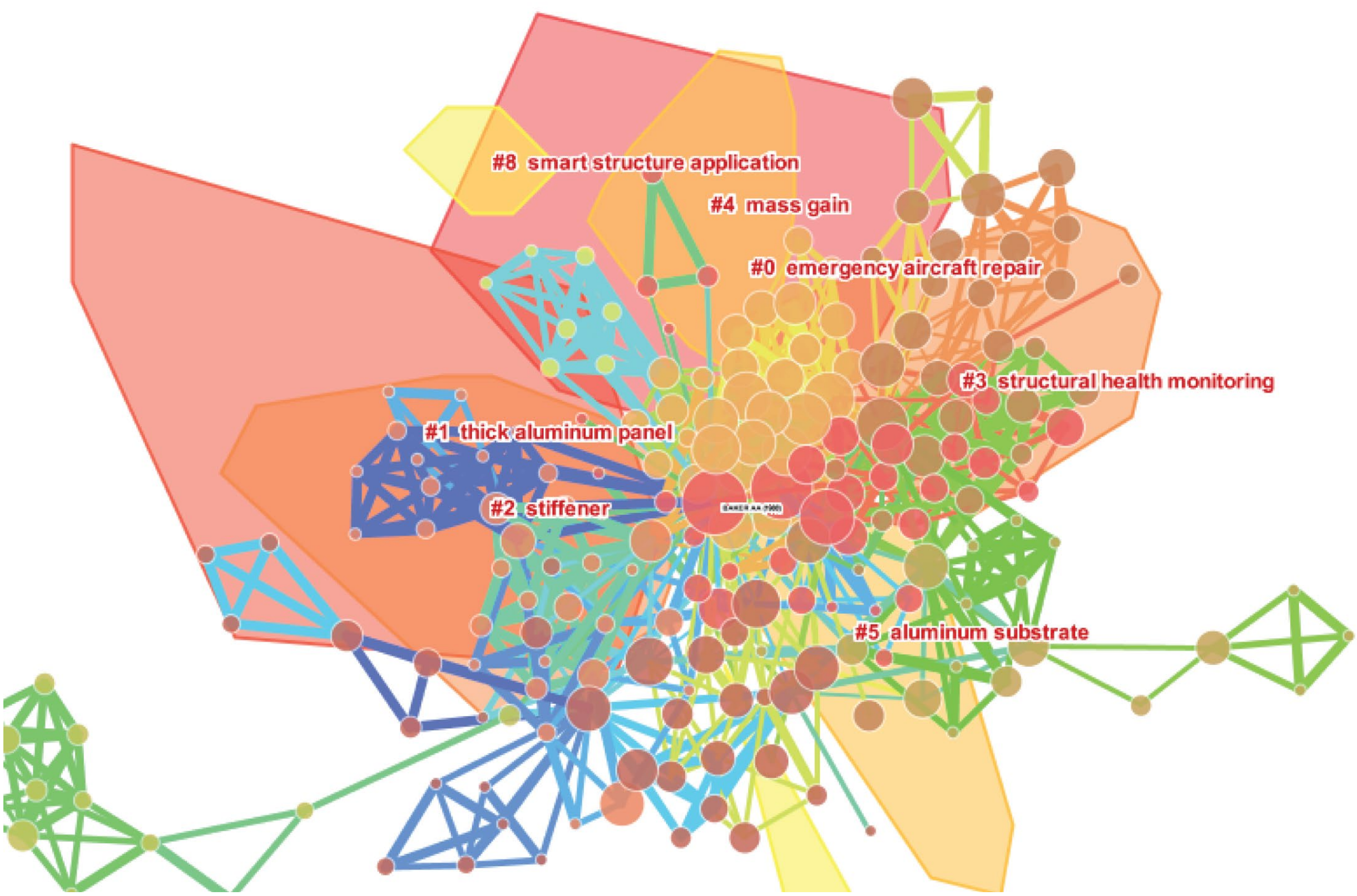



**Figure 2.** Co-citation network generated by CiteSpace© for keywords of "Aircraft" + "Composite" + "Repair."

Despite this growth over the past 30 years, broad-based commercial adoption of lightweight composites has been slower than expected. Industry has yet to be convinced of the superior system-level performance and life-cycle cost benefits. The following "Grand Challenges" for advanced composites are identified by the CAIIAC planning committee and industry partners: 1) scalable and reproducible out-of-autoclave processes and affordable tooling, 2) structural health monitoring of life cycle performance, 3) inclusion of nanomaterials for improved performance, 4) quick and reliable joining and repairs, 5) standardized composite design and testing for faster and more affordable certifications, 6) recycling and reuse of composites. Information obtained during CAIIAC workshops/meetings helped to guide the CAIIAC team toward a prioritization of theses six major challenges. This effort was conducted in conjunction with an industry led "Meta-Roadmapping" process. We not only were able to identify major technical gaps while being able to understand challenges for broader composites market acceptance, but also found that Composite Joining and Repair (CJAR) was an under-served market segment in the composites industry. The recent surge in heavy usage of composites for aero-structures, automotive and wind energy applications will result in unprecedented demand for reliable repair and joining technologies, which became the focus of CAIIAC roadmapping foci.

## 2 TECHNICAL APPROACH

The CAIIAC approach is unique in three distinct ways: 1) assessing technology maturation – evaluating concurrent maturation of TRL, MRL, business cases and an ecosystem to accelerate innovation and insertion as well as to ensure that the new technology is "invent here, build here in the U.S.;" 2) full value chain engagement – involving small- and medium-sized enterprises that support composites OEMs in a wide range of sectors including aerospace, automotive, alternative energy and medical devices; and 3) scientific meta-roadmapping method – searching and analyzing scientific publications, patents and existing technology roadmap/reports, as well as experts assessment to develop the roadmap. **Figure 1** shows the methodology for developing CAIIAC roadmap and consortium.

Through the feedback from industry partners and experts in this area, we identified the following key areas for improving CJAR:

- Design for CJAR
- New materials for CJAR
- Innovative NDE/NDI techniques
- Process automation
- Standardization and qualification

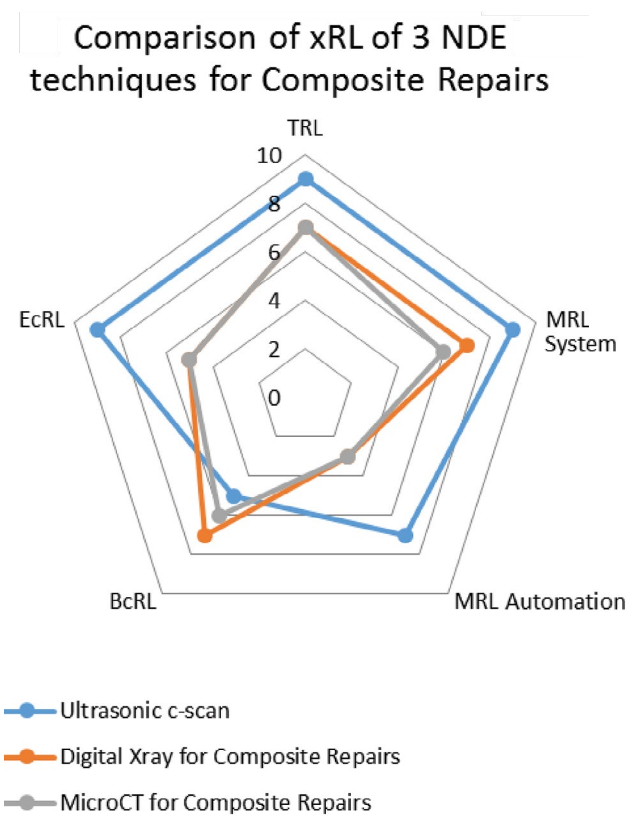
Using the technology mining method, the CAIIAC team is identifying core technologies related to the above key areas for CJAR. **Figure 2** shows a sample result of identification of technologies from the scientific literature search on keywords of "Aircraft", "Composite" and "Repair."

Similar search processes will be conducted for patents and existing technology roadmaps/reports search to identify core technologies for CJAR. Then, the data from searches of relevant publications, patents and roadmaps will be analyzed together with feedback/opinion from industry experts (meta-roadmapping) to create the final CAIIAC CJAR roadmap. In addition, for the identified technologies, the CAIIAC team will assess their technology, manufacturing, business case and ecosystem readiness using the assessment models developed by the authors. **Figure 3** shows a sample result of comparison of xRLs of three NDE techniques for CJAR.

## 3 CONCLUSIONS

This presentation will provide recent progress and workshops outcomes of CAIIAC. Specifically, technical approaches/methods for the CAIIAC CJAR roadmap development will be presented with examples/cases. Finally, the future plan of CAIIAC will be discussed.

**Figure 3.** xRL assessment for NDE techniques for CJAR.



ACE '15 TECHNICAL SYMPOSIUM

# ABSTRACT CITATIONS

## SESSION I: CHALLENGER

**Mondo, J. (2015).** Thermoplastic composite materials: Past, Present and Future. In R. Harik, M. van Tooren, & Z. Gürdal (Eds.), ACE'15 Technical Symposium. Paper presented at The South Carolina Aerospace Industry Conference and Expo 2015, Columbia, South Carolina, USA, 26-27 August (pp. 02) ISBN:978-0-692-49924-5

**Yancey, R., & Zhou, M., & Wollschlager, J., & Dias, W. (2015).** Beyond Black Aluminum – Optimization of Composite Structures. In R. Harik, M. van Tooren, & Z. Gürdal (Eds.), ACE'15 Technical Symposium. Paper presented at The South Carolina Aerospace Industry Conference and Expo 2015, Columbia, South Carolina, USA, 26-27 August (pp. 02-04) ISBN:978-0-692-49924-5

**Luzinov, I., & Demir, T., & van Tooren, M. (2015).** Towards Nanoscale Engineering of Thermoplastic-Epoxy Composite Interfaces. In R. Harik, M. van Tooren, & Z. Gürdal (Eds.), ACE'15 Technical Symposium. Paper presented at The South Carolina Aerospace Industry Conference and Expo 2015, Columbia, South Carolina, USA, 26-27 August (pp. 04-05) ISBN:978-0-692-49924-5

**van Tooren, M., & Elham, A. (2015).** Wing Aerostructural Optimization Using Simultaneous Analysis and Design Strategy. In R. Harik, M. van Tooren, & Z. Gürdal (Eds.), ACE'15 Technical Symposium. Paper presented at The South Carolina Aerospace Industry Conference and Expo 2015, Columbia, South Carolina, USA, 26-27 August (pp. 06-07) ISBN:978-0-692-49924-5

## SESSION II: MCNAIR

**Rubin A. (2015).** Thermoplastic Composites for Aerospace Applications. In R. Harik, M. van Tooren, & Z. Gürdal (Eds.), ACE'15 Technical Symposium. Paper presented at The South Carolina Aerospace Industry Conference and Expo 2015, Columbia, South Carolina, USA, 26-27 August (pp. 08-09) ISBN:978-0-692-49924-5

**Hauber, D., & Langone, R. (2015).** Additive Manufacturing of Advanced Composites Structures. In R. Harik, M. van Tooren, & Z. Gürdal (Eds.), ACE'15 Technical Symposium. Paper presented at The South Carolina Aerospace Industry Conference and Expo 2015, Columbia, South Carolina, USA, 26-27 August (pp. 10-11) ISBN:978-0-692-49924-5

**Le Duigou, J., & Danjou, C., & Durupt, A., & Eynard, B. (2015).** Automated Dynamics Features Recognition for Manufacturing Knowledge Management. In R. Harik, M. van Tooren, & Z. Gürdal (Eds.), ACE'15 Technical Symposium. Paper presented at The South Carolina Aerospace Industry Conference and Expo 2015, Columbia, South Carolina, USA, 26-27 August (pp. 11-13) ISBN:978-0-692-49924-5

**Abdi, F., & Talagani, M., & Gürdal, Z. (2015).** Effect of Defect on Structural Integrity by Tape Layup Manufacturing Processes. In R. Harik, M. van Tooren, & Z. Gürdal (Eds.), ACE'15 Technical Symposium. Paper presented at The South Carolina Aerospace Industry Conference and Expo 2015, Columbia, South Carolina, USA, 26-27 August (pp. 13-15) ISBN:978-0-692-49924-5

**van Rij, M., & van den Berg, T., & van der Laan, T. (2015).** Aerospace Solution Optimization through Front Loading Techniques. In R. Harik, M. van Tooren, & Z. Gürdal (Eds.), ACE'15 Technical Symposium. Paper presented at The South Carolina Aerospace Industry Conference and Expo 2015, Columbia, South Carolina, USA, 26-27 August (pp. 16-23) ISBN:978-0-692-49924-5

## SESSION III: LAKE CITY

**Muser, M. (2015).** Automation in Composites: Expectations, Reality and Future. In R. Harik, M. van Tooren, & Z. Gürdal (Eds.), ACE'15 Technical Symposium. Paper presented at The South Carolina Aerospace Industry Conference and Expo 2015, Columbia, South Carolina, USA, 26-27 August (pp. 23) ISBN:978-0-692-49924-5

**Seneviratne, W., & Tomblin, J., & Saathoff, C., & Denning, S. (2015).** Investigation of Damage Growth in Sandwich Structures under Ground-Air-Ground Cycles. In R. Harik, M. van Tooren, & Z. Gürdal (Eds.), ACE'15 Technical Symposium. Paper presented at The South Carolina Aerospace Industry Conference and Expo 2015, Columbia, South Carolina, USA, 26-27 August (pp. 23-25) ISBN:978-0-692-49924-5

**Iarve, E., & Hoos, K.,& Mollenhauer, D. (2015).** Discrete Damage Modeling in Composite Laminates under Static and Fatigue Loading. In R. Harik, M. van Tooren, & Z. Gürdal (Eds.), ACE'15 Technical Symposium. Paper presented at The South Carolina Aerospace Industry Conference and Expo 2015, Columbia, South Carolina, USA, 26-27 August (pp. 25-27) ISBN:978-0-692-49924-5

**Zhang, Z., & Wang, B., & Kramer, L., & Liang, R., & Browning, C., & Jeol-Pieters, B. (2015).** Roadmapping for Composite Joining and Repair. In R. Harik, M. van Tooren, & Z. Gürdal (Eds.), ACE'15 Technical Symposium. Paper presented at The South Carolina Aerospace Industry Conference and Expo 2015, Columbia, South Carolina, USA, 26-27 August (pp. 27-29) ISBN:978-0-692-49924-5

JOIN US FOR THE

# SC AEROSPACE CONFERENCE AND EXPO 2016

AUGUST 24 -25, 2016
COLUMBIA METROPOLITAN CONVENTION CENTER