

The logo for the Joint Advanced Materials and Structures Center of Excellence (JAMS) features the letters 'JAMS' in a stylized, blue, 3D-rendered font. The letters are interconnected and have a textured, metallic appearance. Below the text are two curved, brush-stroke-like lines: a yellow one on top and a blue one on the bottom, both curving from left to right.

JAMS

Crashworthiness of composite structures: Experiment and Simulation

Paolo Feraboli (UoW)
AMTAS FALL MEETING 2012



The Joint Advanced Materials and Structures Center of Excellence

Motivation

- *Composite structure crashworthiness is a relatively new topic for FAA certification*

Benefits to Aviation

- *Streamline certification process*
- *Increase confidence and therefore level of safety*

Objective

- *Develop a guidance certification analysis & test protocol for composite fuselage crashworthiness certification*

Personnel Involved

- *Bonnie Wade, PhD student* *LS-DYNA Analysis lead*
- *Morgan Osborne, MSAA Student* *Single-element Analysis*
- *Max Spetzler, Pre-PhD student* *Cert protocol*
- *Bob Leibe, Visiting MS Student* *Test Article manufacturing*
- *Paolo Feraboli, Res Assoc Prof* *UW PI*
- *Dr. Mostafa Rassaian, Boeing BR&T* *Boeing PI, Advisor*
- *Kevin Davis, Boeing BCA* *Advisor*
- *Dr. Larry Ilcewicz, FAA* *Advisor*
- *Allan Abramowitz, FAA* *FAA PM*
- *Curt Davies* *FAA JAMS*

JAMS RESEARCH BACKGROUND

- *CMH-17 (former MIL-HDBK-17) Working Group supports the development of a section of the handbook on composite Crashworthiness and Energy Management. First section approved for publication: Chapter 14 in Vol. 3B of Rev. G*
- *Focus of the WG are regulatory agency requirements and industry methods of compliance for crashworthiness certification.*
- *WG formed in March 2005 at the Charlotte meeting by PF. Automotive and Aviation founding members. The Crash WG has drawn larger membership and attendance each meeting.*
- *From its inception, the key areas that were identified for investigation:*
 1. *Test standard and experimental guidelines*
 2. *Numerical/ analytical guidelines and best practices*
 3. *Certification and compliance methodology guideline*

Context: in March 2005 the Boeing 787 was just launched and the Special condition had not been issued

MIL-HDBK-17-2F
Volume 3, Chapter 14 – Crashworthiness and Energy Management
CHAPTER 14 CRASHWORTHINESS AND ENERGY MANAGEMENT

14.1 OVERVIEW AND GENERAL GUIDELINES

14.1.1 Section organization

This chapter of the handbook addresses the multitude of issues associated with the crash performance, energy-absorbing capability, and crashworthiness certification of composite materials and structures. Challenges are raised herein on important points in the research and general aviation industry, since these represent the areas where composite and structural design complexity has been most pronounced. Wherever possible, references are provided to the experimental and/or analytical data that are available to support the design and development work. As the associated composite technologies continue to evolve, additional applications and special design issues will be raised. Issues with a more complete characterization of the response of the impact event, and of the methodologies employed to address the related crash performance.

Section 14.2, 14.3, and 14.4, which comprise the bulk of this chapter, address the majority of material and structural responses, as well as design guidelines and analytical methods. Each section includes detailed discussions of: (a) the major factors that affect the crash response; (b) design-related issues and guidelines for meeting objectives and requirements; (c) testing methods and issues; (d) manufacturing considerations; and (e) analytical predictive methods, and their success in predicting observed response. Section 14.2 contains a general review of the methods employed in industry and academic institutions to quantify the energy-absorbing characteristics of device coupons for material characterization. Section 14.3 concentrates on the static and dynamic loading response of the actual fuselage structures, which represent typical current aluminum-cabin FFRS. Section 14.4 includes the crashworthy characteristics of composite structure elements, typical of aircraft author exams.

Section 14.5 includes several examples of successful crashworthy designs from a number of composite aircraft, automotive and rail applications. These examples illustrate how different aspects of crashworthiness come to the forefront as a function of application. They also include the detailed design of a typical energy-absorbing element, the design of a specific crashworthy structure for a prototype aircraft, the development process of a crashworthy primary structure for a production aircraft, and the rescue egress in the development of a crashworthy rear exit structure of a passenger car.

14.1.2 Synopsis of crashworthiness

The overall objective of designing for crashworthiness is to minimize injuries and fatalities in crashes and accidents, and to minimize repair or airframe damage. A crashworthy design will also control the extent of crash impact damage by minimizing personnel and material losses, crashworthiness sensitive resources, improve effectiveness, and increase confidence of the employees [14.1.1].

Many influencing parameters need to be considered before an optimum design for crashworthiness can be finalized. A systems approach should be employed to include all the parameters consistent with the design, manufacturability, weight performance and economic constraints on the vehicle in meeting regulatory requirements. Tradeoffs among these parameters must be made in order to arrive at a final design that closely meets the specifications.

MIL-HDBK-17-2F
Volume 3, Chapter 14 – Crashworthiness and Energy Management
14.1.3 Existing research and development

In the area of aircraft crashworthiness, much of the research focus in the last decade has been directed to the development of composite primary crash structures [14.1.1, 14.1.2, 14.1.3-14.1.11]. Information concerning the history of composite crashworthy structures is readily obtained & available mainly through US Army-sponsored Research Programs. For example, the Boeing composite aircraft research program (ACAP: Advanced Composite Aircraft Program) and DARPA (Defendable Affordable Resilient Aircraft Program) use a mix of bang-bang and composite composite aircraft research activities. In the composite aircraft research program (Fig. 14.1.4), the Boeing Aircraft, NASA, and the FAA have been involved with an extensive research activity to characterize the advantages of selecting nonconventional designs of General Aviation (GA) aircraft with crashworthy features, as in the case of the Avionics Safety Program (ASP).

Since 1999, the European Union (EU) has funded three research projects (CRASHPRO, Composite Aircraft Design for Crash Survivability, HSCA-High Velocity Impact of Composite Aircraft Structures, and CRASH-Crashworthiness of Aircraft for High Velocity Impacts) concerned with the development and validation of crashworthy composite structures to meet the crash and impact response of composite energy-absorbing aircraft structures [14.1.12-14.1.13]. The final part of the research effort in CRASHPRO was the development of crashworthy aircraft systems, which provide a high-strength structure platform to meet the static and load carrying, and a crashable zone to absorb energy and dissipate dynamic loads energy across the fuselage. One particular characteristic of composite aircraft structures that must be a concern to the designer is the interaction of longitudinal sparweb beams and cross members. These need joints, an efficient load path to transfer loads during a crash to the seat and the cockpit, and often require the presence of energy absorbing structures [14.1.14]. The typical aircraft structure of testing and modeling of composite materials at high strain rates, using CRASHPRO with composite models for composite aircraft simulations as well as impact on different surfaces including water.

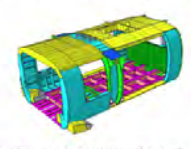


Fig. 14.1.4. Reinforced cabin and crashworthy aft fuselage for the Army Survivable Affordable Reconfigurable Composite Airframe Program.

FEA Round Robin

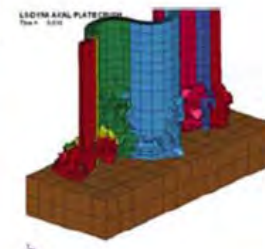
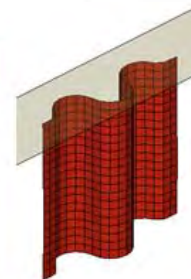
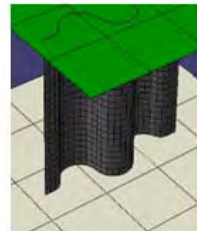
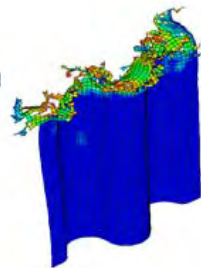
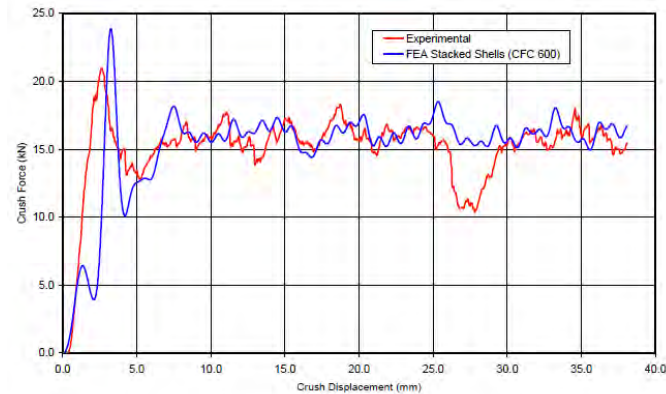
- *Mostafa Rassaian of Boeing joined at Chicago meeting in July 2006*
- *Emphasis placed on analytical needs. Becomes co-chair and spearheads the creation of a Round Robin (RR) exercise*
- *Assess predictive capability of commercial FEA codes. Various users with multiple codes and different modeling strategies to simulate the crush energy absorption of composite structural elements.*
- *RR begins January 2008 at Cocoa Beach meeting.*
- *In 2012-13 the RR will be completed, and a new section will be incorporated into the Handbook.*

- | | |
|-----------------------------|--------------------------------------|
| • LS-DYNA MAT58 | M. Rassaian (Boeing BR&T) |
| • LS-DYNA MAT58 | X. Xiao, V. Aihataraju (G.M.) |
| • LS-DYNA MAT54 | P. Feraboli (U. of Wash.) |
| • LS-DYNA MAT162 | R. Foedinger (MSC Corp.) |
| • PAMCRASH CDM | A. Johnson (DLR) |
| • RADIOSS Plasticity | JB Mouillet (Altair) |
| • RADIOSS Tsai-Wu | A. Caliskan (Ford) |
| • ABAQUS C-Zone | G. Barnes (Engenuity) |

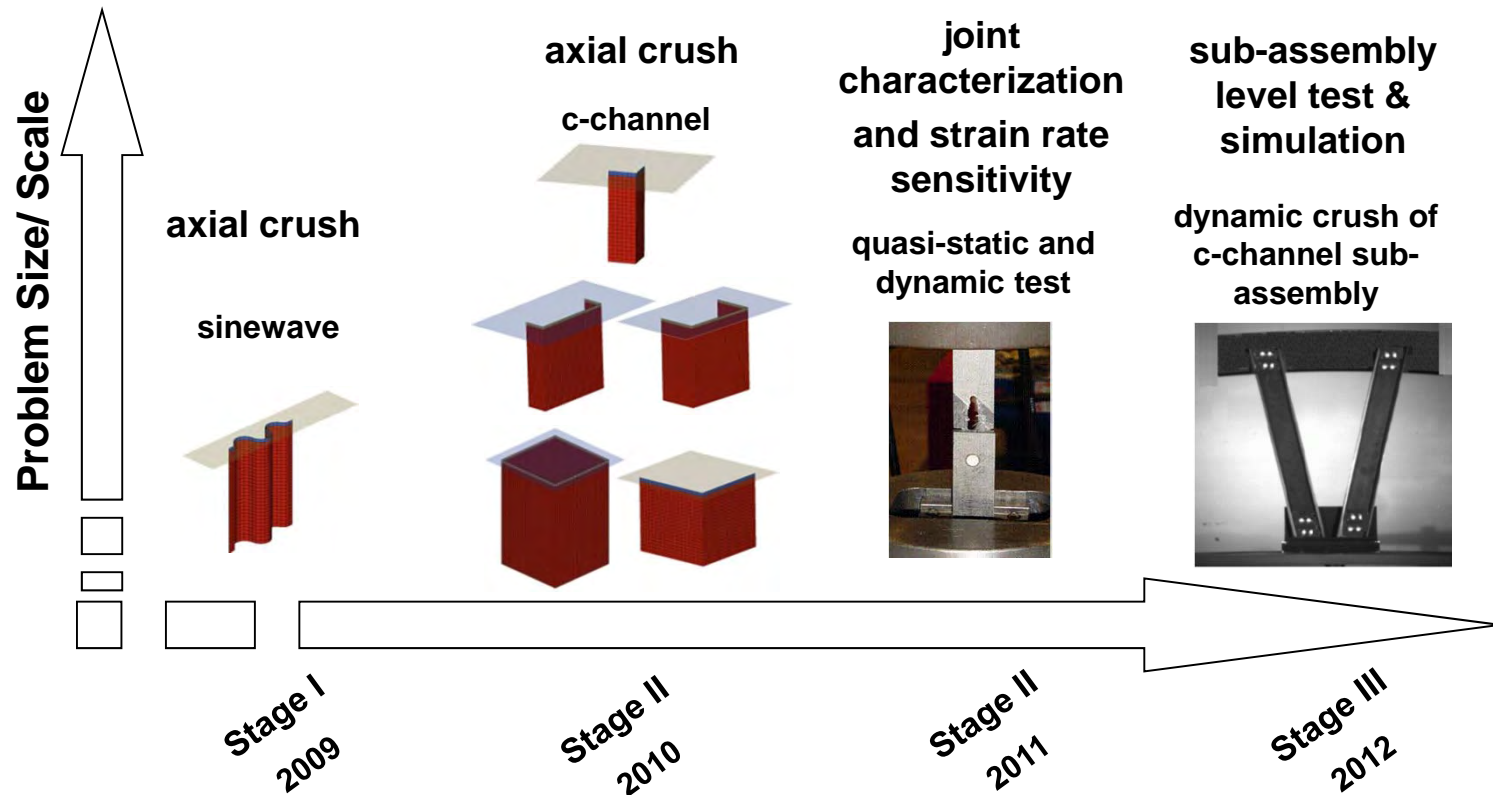
Abaqus VUMAT (Indermuhle) and PAMCRASH crushfront (Pickett) abandoned early on

Round Robin Observations

- *All approaches and codes can reproduce successfully the experimental results (with different accuracy)*
- *However, none of them are truly “predictive” but need to be used in the context of a Building Block Approach*



Roadmap for CMH-17 RR Crashworthiness



JAMS RESEARCH CONTRIBUTIONS



AMTAS (JAMS) Research Contributions



Testing

100% complete

- *Material property testing, quasi-static*
- *Crush testing of 9 element shapes, quasi-static.*
- *Several articles published.*

Analysis

80% Complete

- *LS-DYNA MAT54 CMH-17 RR entry and write-up* 100%
- *LS-DYNA MAT54 single-element characterization* 100%
- *LS-DYNA shapes simulations* 80%
- *MAT54 code/ model modifications & improvement* 0%
- *Complete summary report of RR effort for Crash WG* 5%
- *1 published, many in the works. 1 FAA Tech Report delivered*

Educational Module

100% complete

- *Presentation, lecture notes and video recorded*
- *1 FAA tech report to be developed*

Cert protocol/ guidelines

15% complete

- *Fuselage section design* 100%
- *Test Article(s) Design and manufacturing* 70%
- *Test/ Analysis correlation protocol* 0%
- *Quasi-static and Crash testing of test articles* 0%
- *Simulation of Test Article* 0%

Testing

-
- *UW initial activity focused on test methods shapes total 9*

 - *Flat coupon derived from NASA proposed method 1*
 - *“Development of a modified flat plate test and fixture specimen for composite materials crush energy absorption” – Feraboli P. – Journal of Composite Materials, published online July 2008.*

 - *Self-stabilizing coupon (corrugated/ sinusoidal) 3*
 - *“Development of a corrugated test specimen for composite materials energy absorption” – Feraboli P. – Journal of Composite Materials - 42/3, 2008, pp. 229-256*

 - *Effect of curvature (tube and channel sections) 5*
 - *“Crush energy absorption of composite channel section specimens” – Feraboli, P., Wade, B., Deleo, F., Rassaian, M. – Composites (Part A), 40/8, 2009, pp. 1248-1256.*

- Energy absorption (SEA) is NOT a material property



Figure 19 a, b Flat specimen, before crushing showing the saw-tooth trigger (a), and after crushing (b) at 12.5 mm of unsupported height

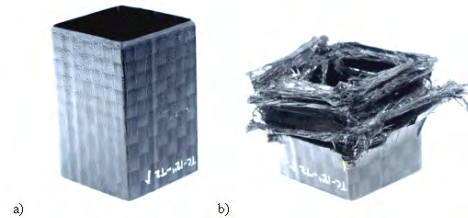
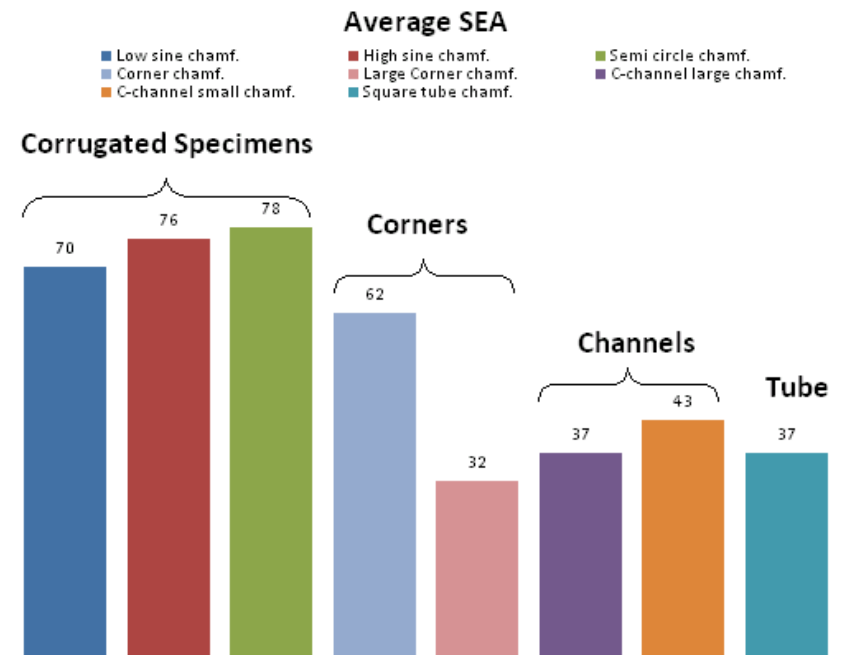
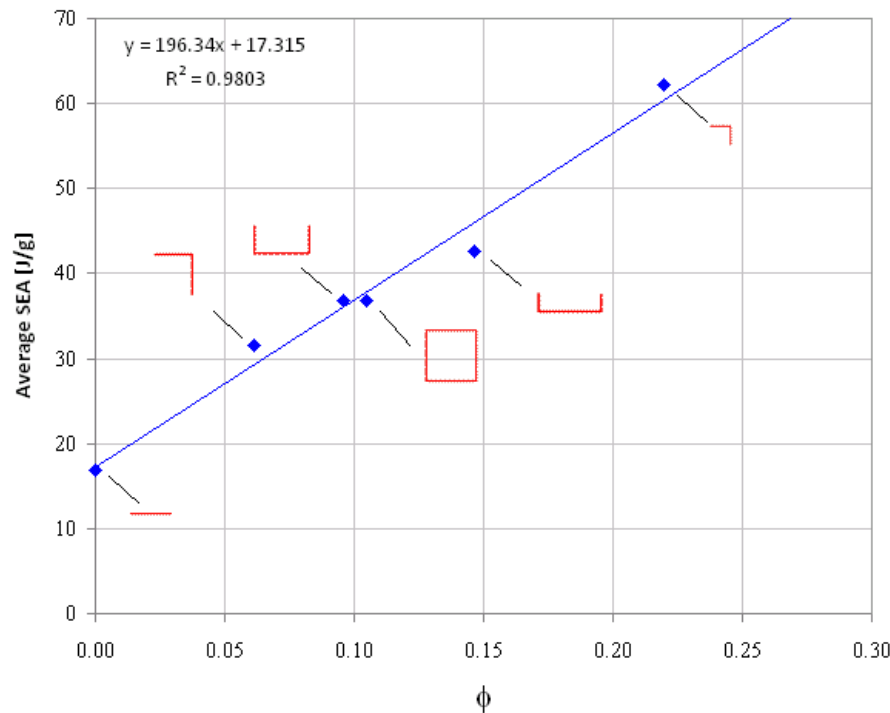


Figure 7 a, b. Square tube, specimen I, before and after crush testing



Figure 10 a, b. Small corner element, specimen IV, before and after crush testing



Analysis

Challenges in crashworthiness simulation

- *Composites are non homogeneous - damage can initiate and propagate in many ways*
- *Many failure mechanisms can occur (fiber breakage, delamination, cracking, etc.). Damage growth is not self-similar.*
- *Crash events involve exclusively damage initiation and propagation*
- *Importance of failure criterion and degradation scheme is paramount*
- *Time-dependent event requires explicit solvers (non-standard)*
- *Computationally very expensive, requires the use of shell elements (not solids)*
- *Current FEA technology cannot capture details of failure of individual fibers and matrix, but needs to make approximations. The key is to know how to make the right approximations.*
 - *Element failure treated macroscopically: cannot account for differences between failure mechanisms*
 - *Often it cannot account for delamination damage*

Numerical Standardization

- *Non-linear, dynamic simulation requires explicit FEA codes*
- *Common commercial codes used in this field are:*
 - *LS-DYNA (LSTC)*
 - *ABAQUS Explicit (SIMULIA)*
 - *PAM-CRASH (ESI)*
 - *RADIOSS (ALTAIR)*
- *Each code is unique for:*
 - *Material models*
 - *Failure criteria implementation*
 - *Strength and stiffness degradation strategies*
 - *Other code parameters*
 - *contact definition*
 - *damping, time steps, etc...*

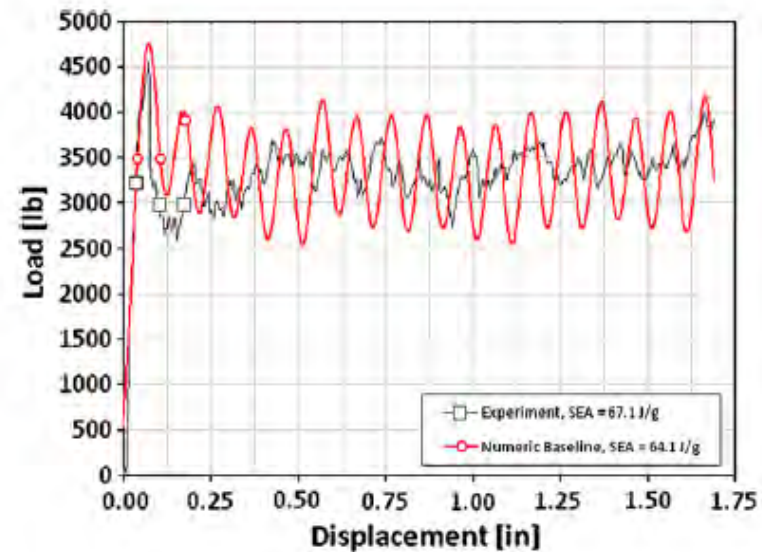
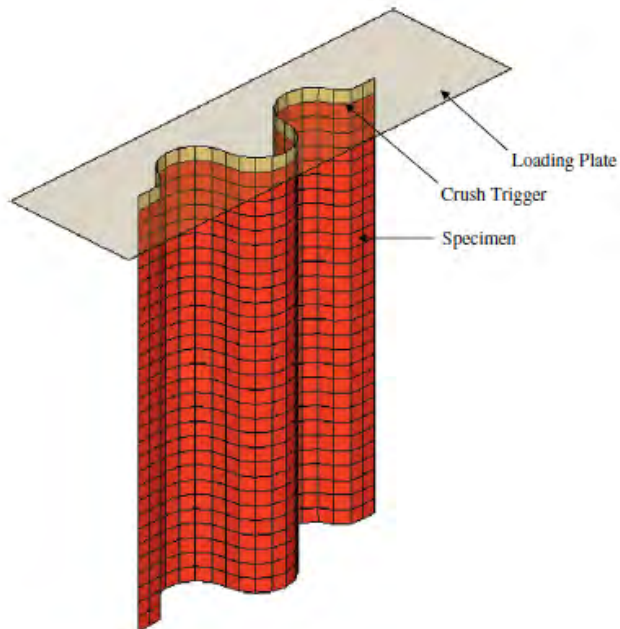
Modelling strategies with LS-DYNA

- *LS-DYNA considered benchmark for impact and crash analysis*
- *Composite constitutive models are continuum mechanics models - treat as orthotropic linear elastic materials within a failure surface*
- *Failure criterion varies*
- *Beyond failure, elastic properties follow degradation laws:*
 - *progressive failure models (PFM)*
 - *continuum damage mechanics (CDM) models.*

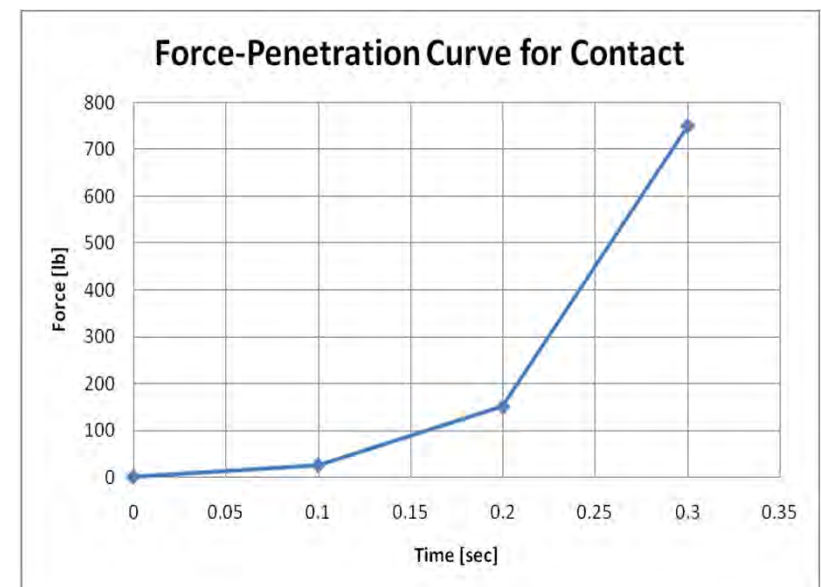
Table IV. Summary of composite material models available in the commercial explicit FE code LS-DYNA.

MAT	Title	Brick	Shell	T-shell	Degradation Law
22	Composite Damage	y	y	y	Progressive failure
54/55	Enhanced Composite damage		y		Progressive failure
58	Laminated Composite Fabric		y		Damage Mechanics
59	Composite Failure	y	y		Progressive failure
161	Composite MSC	y			Damage Mechanics

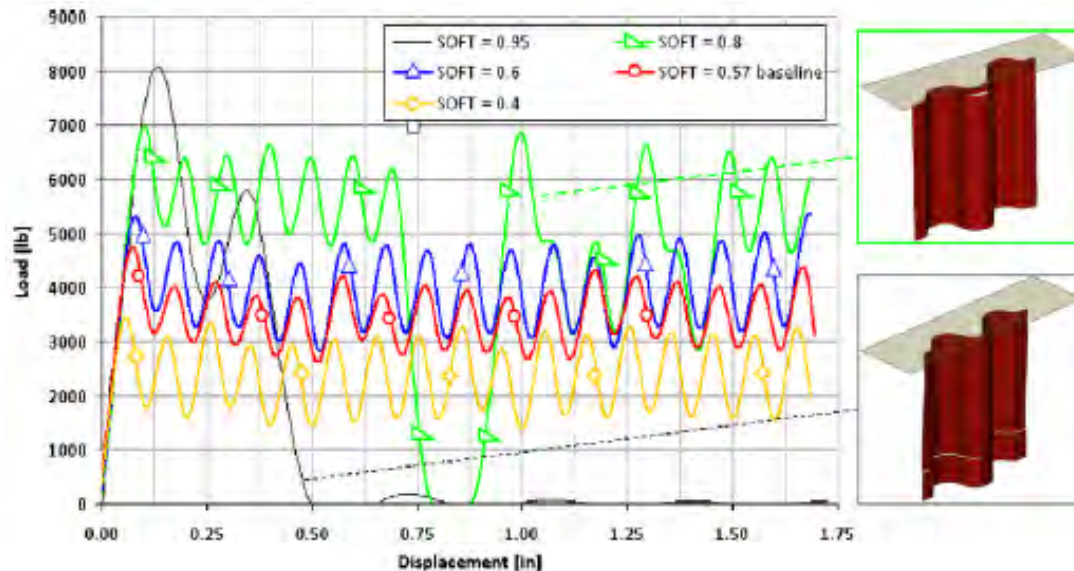
- *MAT54 is capable to model composite materials in crash simulations*
- *Questions have arisen about MAT54 which needed to be addressed*



- **SOFT.** Softening reduction factor. Used to reduce the strength of the row of elements immediately following that under crushing so that crushing occurs rather instability or other failures away from the crush front (varies between 0 and 1, default = 1.0).
- **Contact formulation:** different types of contact between entities
- **Force-penetration curve:** characteristic of the contact formulation
- These parameters cannot be measured by test or calculated mathematically
- They need to be calibrated using trial-and-error.

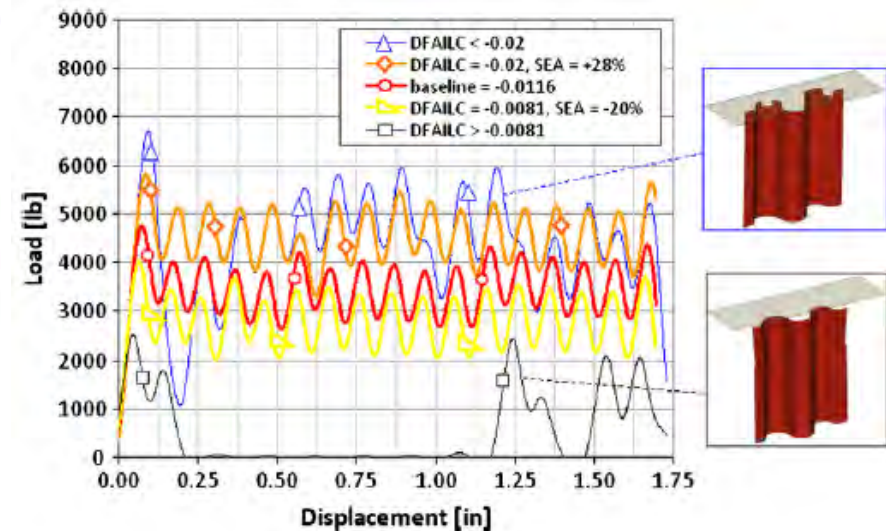
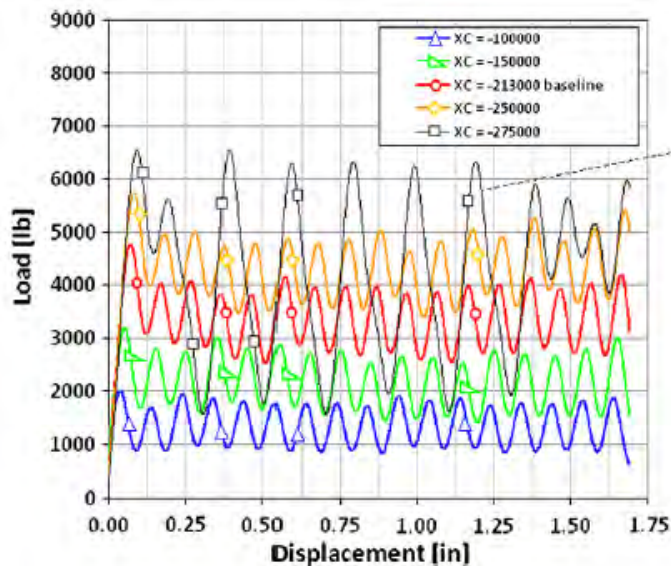


- *SOFT was found to be essential for crush simulation*
- *This parameter directly changes the average crush load value and the SEA*
- *SOFT can be interpreted as causing ‘virtual damage’ beyond the crush front, which simulates the damage zone caused by damage propagation*
- *The lower the SOFT, the greater the damage is beyond the crush front*



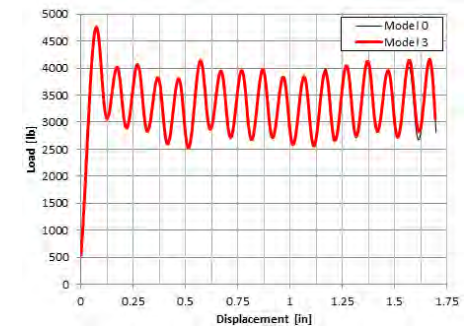
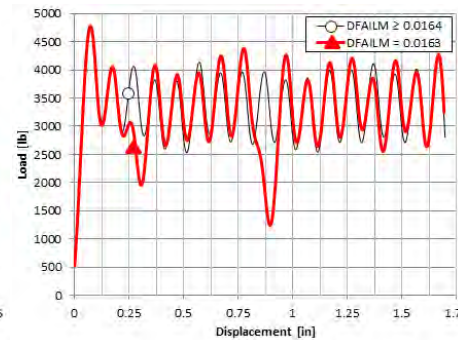
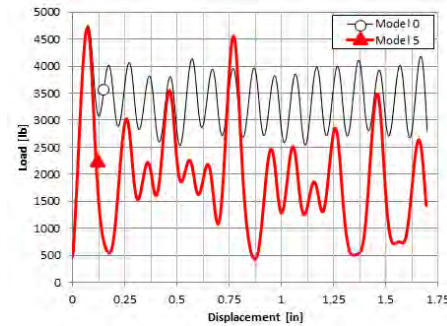
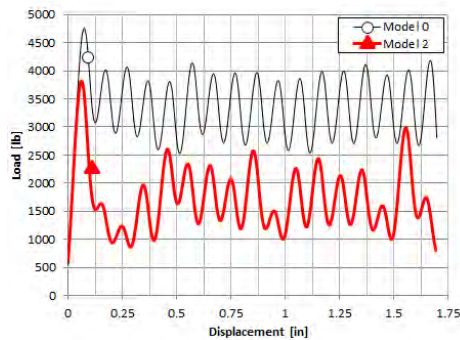
MAT54 not purely predictive: CARD needs to be tweaked to predict crushing of different shapes.

- All MAT54 parameters were varied in the UD sinusoid crush model to determine which parameters greatly influenced the crush model
- Some results were logical, like the effect of the **compressive strength and failure strain parameters, XC and DFAILC**

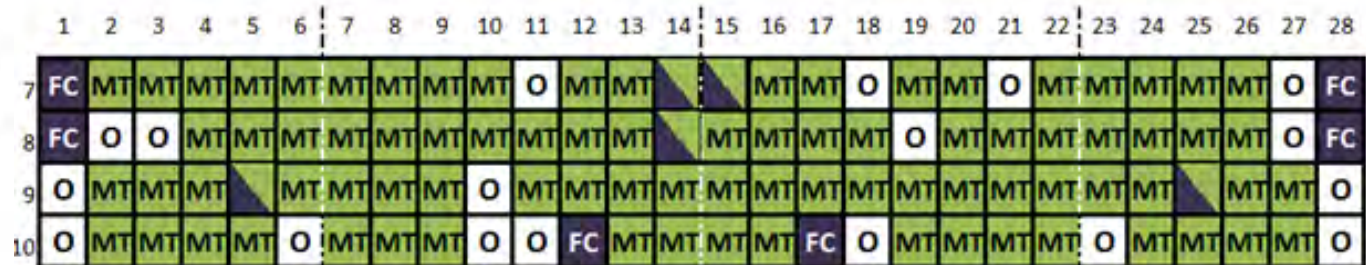
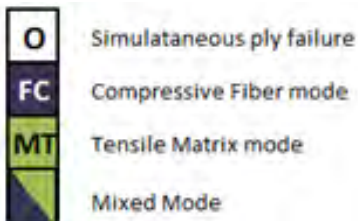
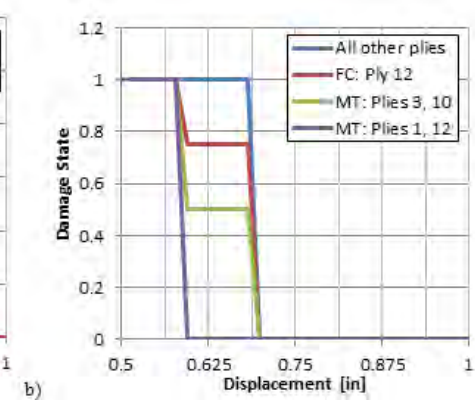
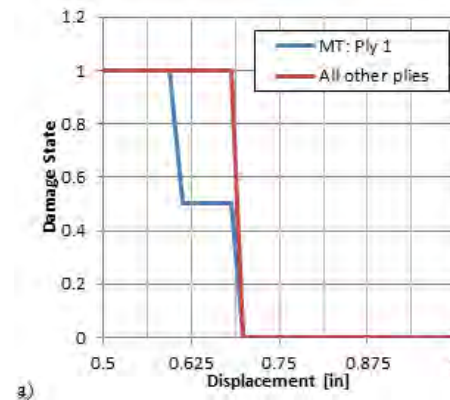
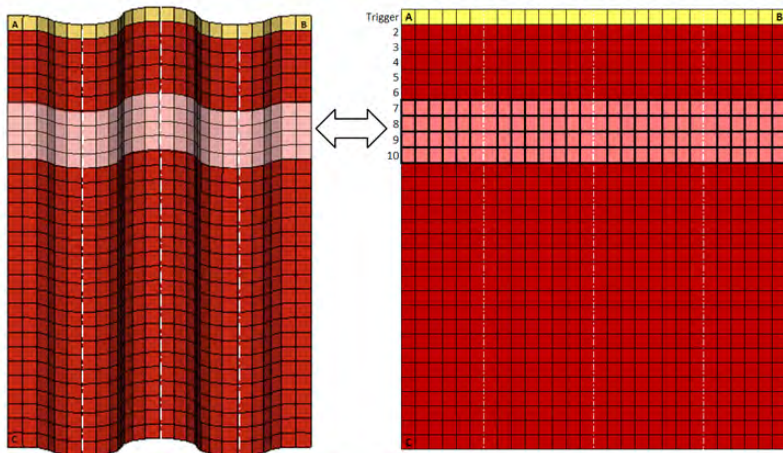


- Other results raised questions, such as the influence the transverse failure strain parameter, *DFAILM*, had on the stability of the crush model
- DFAILM* is the transverse failure strain for both tension and compression

Increasing *DFAILM*

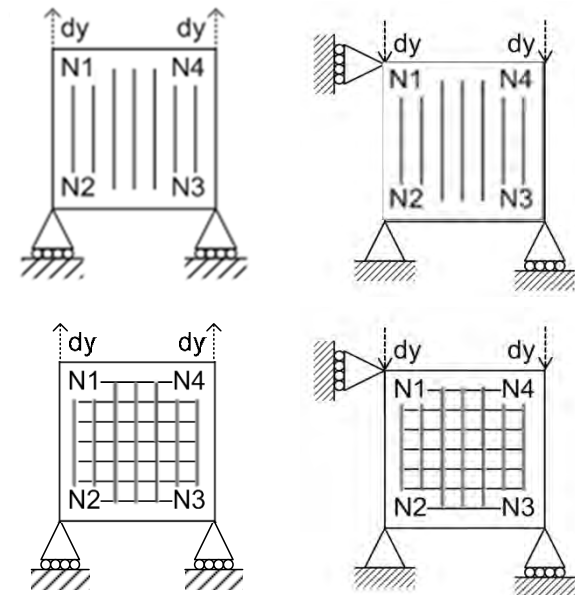


- History variables keep track of the strength-based failures in the plies
- Data from these variables showed that 'matrix tension' failure was dominant



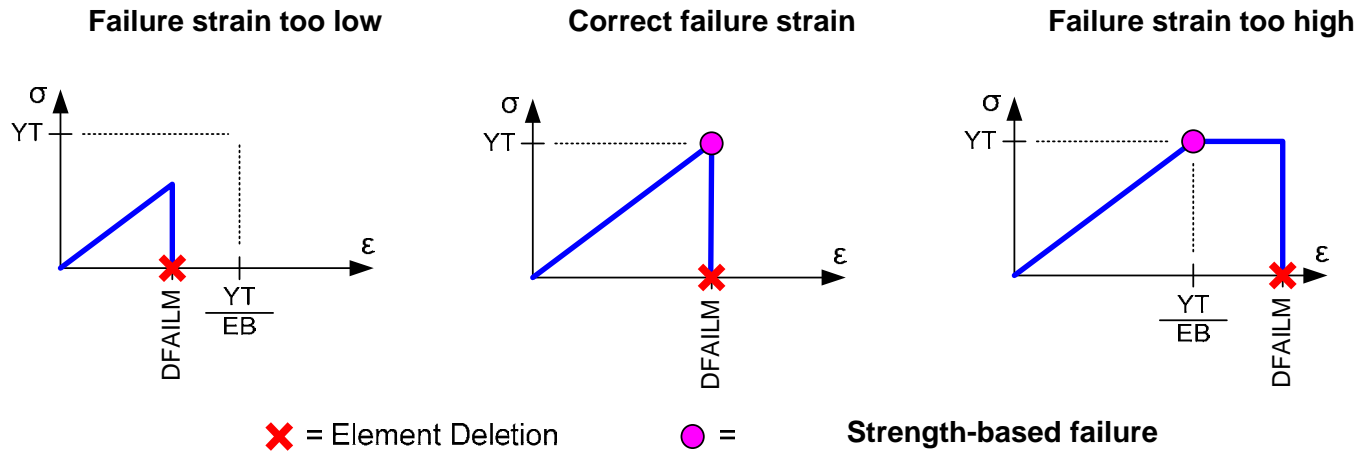
Single-element study

- To fully understand the MAT54 material model, single element simulations were constructed which tested the element in basic tensile and compressive loading conditions
- In-depth single element simulations study
- MAT54 input parameters using simple layups:
 - UD [0]12
 - UD [90]12
 - cross-ply UD [0/90]3s
 - fabric [(0/90)]8
- Goal is to determine critical parameters for ply failure and element deletion

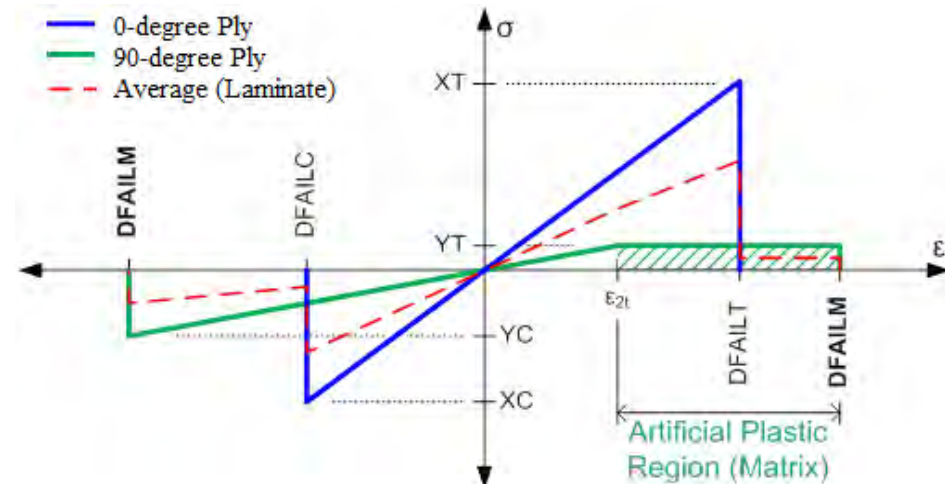
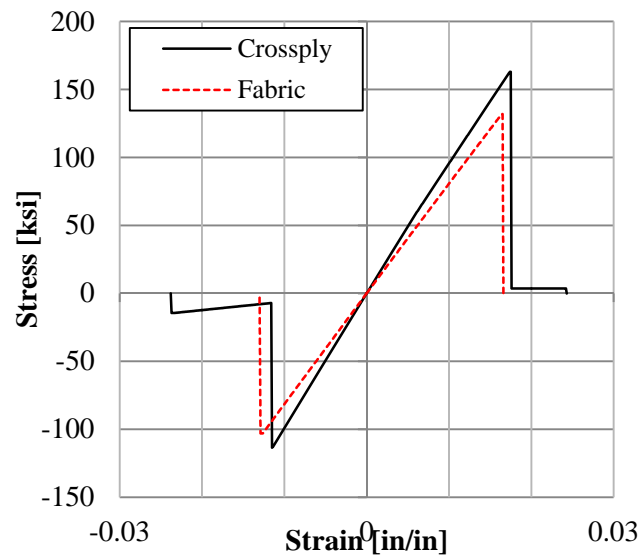


Single-element study UD

- Elastic properties are not zeroed after strength-based failure
- Failure strains determine element deletion, and can either prematurely delete an element or add a significant amount of energy to the element output



- The MAT54 simulations of the UD cross-ply and fabric single elements
- Progressive failure occurs only in the cross-ply element, and it requires continuous straining until the 90-degree plies have reached their failure strain, DFAILM





Educational

Composite Structural Crashworthiness Educational Module

- *Aid the FAA in the development of guidance material for crashworthiness certification for the transport industry, and in the preparation of educational/training material for new engineers.*
- *2-hr course within 80-hr class*
- *Introduction to crashworthiness*
- *Lecture notes, video-recorded segments, PPT presentation*

Crashworthiness Module

**FAA Level II Course:
Composite Structural Engineering
Technology Safety Awareness**

Paolo Feraboli, Ph.D.
Automobili Lamborghini ACSL
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University of Washington
Seattle, WA

March 2012



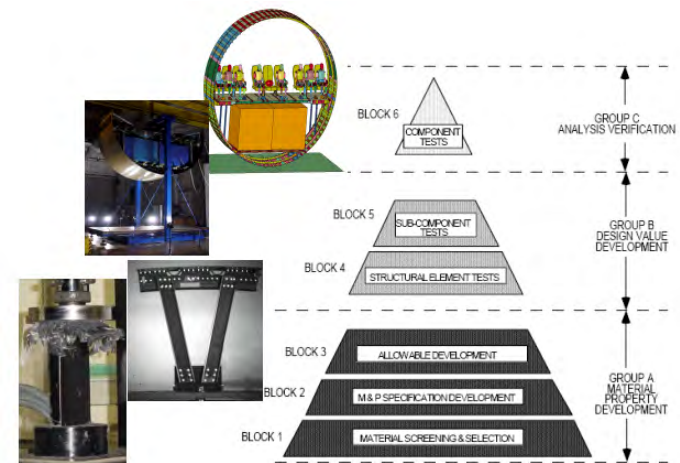
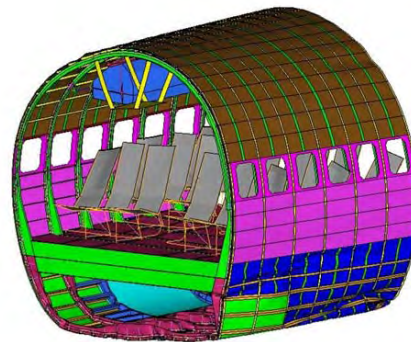
Outline

1. Introduction	p. 2-10
2. FAA Requirements	p. 11-31
3. Elements of Structural crashworthiness	p. 32-41
4. Composites energy absorption	p. 42-54
5. Hardware/ Design considerations	p. 55-70
6. Methods of Compliance	p. 71-82
7. Challenges	p. 83-103
a) Definition of test protocol	
b) High strain rate testing	
c) Large-scale test expectations	
d) Progressive failure and damage analysis	
8. Conclusions and Acknowledgments	p. 104-106

Certification Protocol

Crashworthiness Certification protocol

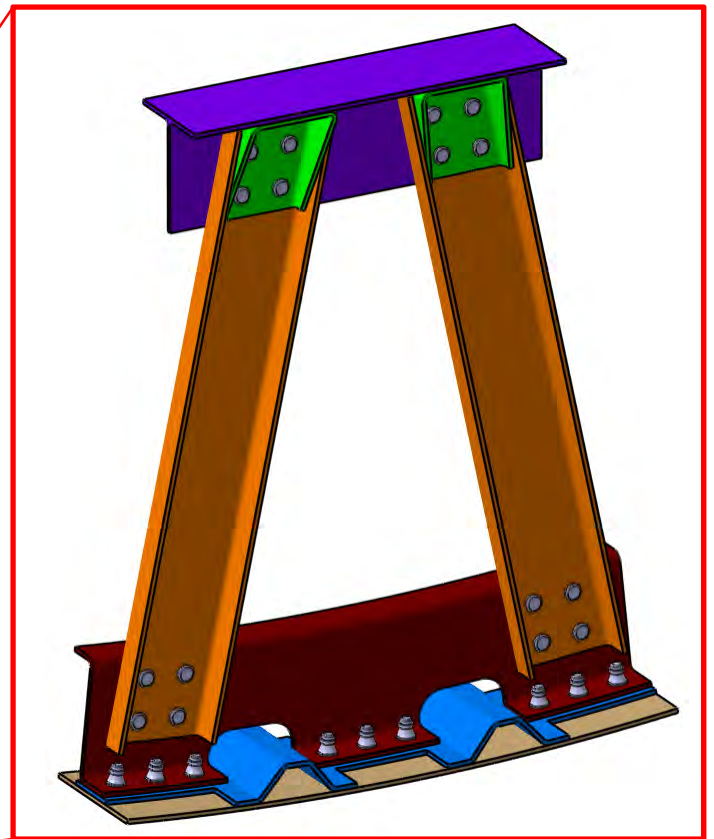
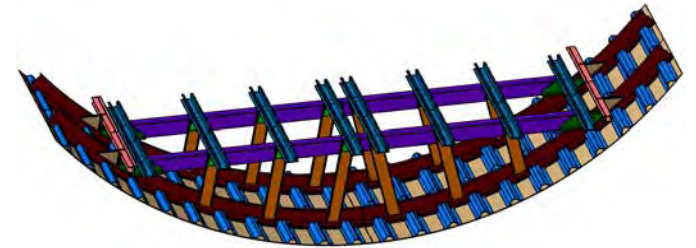
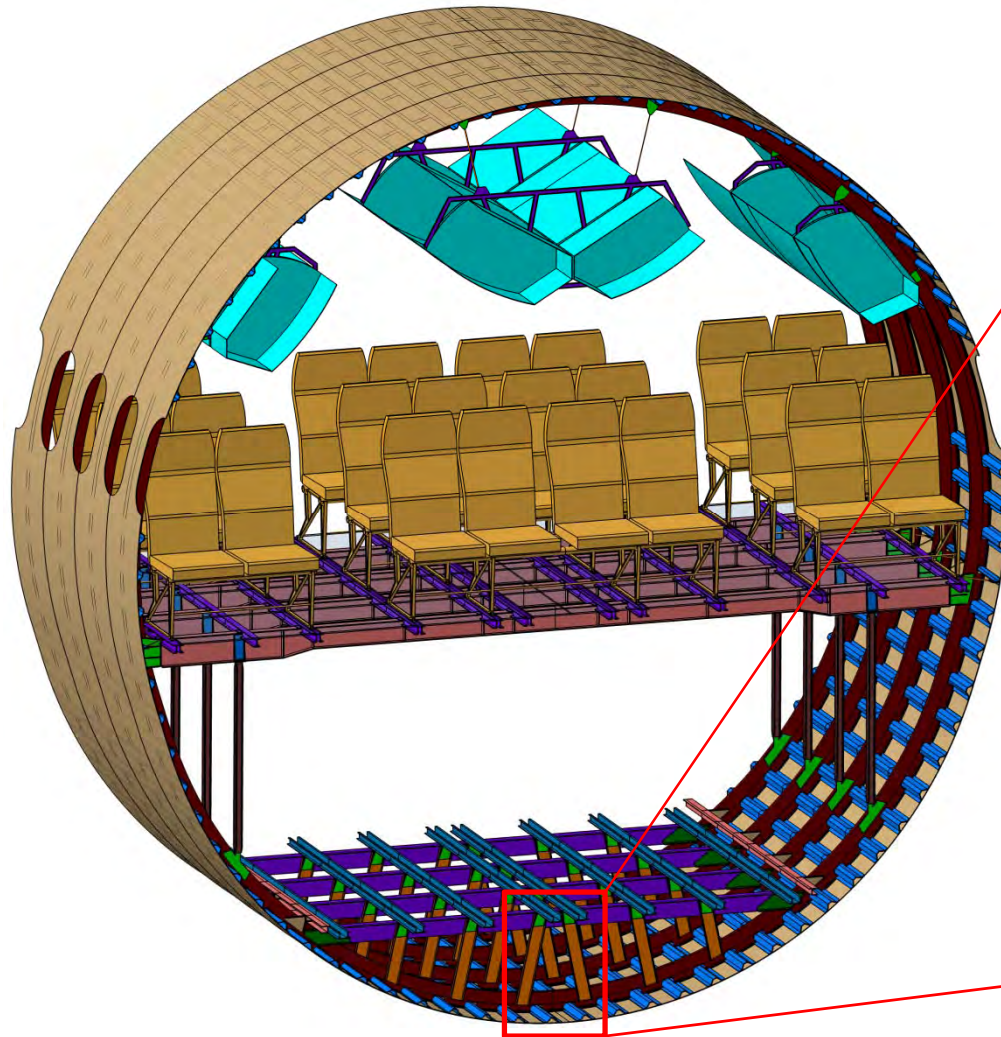
- *Building Block Approach adapted to Crashworthiness*
- *Based on Analysis supported by test evidence*
- *First CFRP fuselage certified: only 1/2 section of barrel segment drop tested*
- *Successfully adopted by Boeing for 787 to meet Special Condition*
- *Cert by test not likely to be an option for Part 25 but may be considered for Part 23*



Courtesy: Boeing

- *Goal is to develop a guidance document that contains an example of a certification protocol for Part 25 aircraft based on a generic geometry*
- *Identify a suitable mock geometry, with all relevant structural features (floors, floor beams, floor supports, etc.)*
- *Synthesize the wording of a mock Special Condition into a series of requirements*
- *Define a series of methods of compliance with such requirements*
- *Lay-out the details of the certification protocol for such mock configuration*
- *Indicate a path toward certification of a virtual aircraft for crashworthiness:*
 - *Certification strategy*
 - *List of Allowables tests*
 - *Definition of Element level tests*
 - *Definition of component and subassembly tests*
 - *Definition of analyses and analysis-correlation procedures*
 - *Validation and large-scale test expectations*

BBA sub-component level



TEST AND ANALYSIS CORRELATION

- *Incorporates knowledge gained at coupon- and element-level*
- *All laminates are modeled with shell elements MAT54*
- *Bolted joints are modeled as calibrated spot welds*
- *Tied contact between co-cured skin and stringers*

