Challenges and Opportunities In Crashworthiness Certification of Composite-Intensive Airframe Structures

AMTAS – University of Washington

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JAMS PM: Curt Davies

Presented by Rassaian at the Baltimore, MD JAMS Meeting in April 2012

JAMS RESEARCH BACKGROUND

Background

- *CMH-17 (former MIL-HDBK-17) Working Group supports the development of a self-contained section of the handbook on composite Crashworthiness and Energy Management.*
- *Aim is to generate and present for the first time in a concise and comprehensive fashion, recommended practices and guidelines for the experimental and numerical characterization of the crash behavior of composite-intensive airframes.*
- *Focus of the WG are regulatory agency requirements and industry methods of compliance for crashworthiness certification.*
- *The Crash WG activities have increased every year, drawing larger membership and attendance each meeting.*

Background

- *WG formed in March 2005 at the Charlotte meeting by PF*
- *Automotive and Aviation (Industry & Government) founding members*
- *From its inception, the key areas that were identified for investigation:*
  - *Test standard and experimental guidelines*
  - *Certification and compliance methodology guidelines*

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

Revision G Accomplishments

- *In 2005-2006 wrote an introductory section on Composite Crashworthiness, which was approved for publication in the Yellow Pages.*
- *This section now constitutes Chapter 14 in Vol. 3B of Rev. G*

MIL-HDBK-17-3F
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. Discussions are heavily reliant on experience gained in the rotorcraft and general aviation industry, since these represent the areas where composites and crash-oriented design philosophy have been most exploited. Wherever possible, reference is also made to the experience gained in the development of open-wheel racecar crashworthy structures, but accessibility to that information is often limited. On the other hand, a substantial portion of the results that will be presented in this chapter was developed during intensive automotive research and development work. As the associated composite technologies continue to evolve, additional applications and service history should lead to future updates with a more complete characterization of the dynamics of the impact event, and of the methodologies employed to achieve the desired crash performance.

Sections 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 efforts. 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 responses. Section 14.2 contains a general review of the methods employed in industry and academic institutions to determine the energy-absorbing characteristics of lab-size coupons for material characterization. Section 14.3 concentrates on the static and dynamic crushing response of thin-walled tubular structures, which represent typical current automotive-sized front rails. Section 14.4 focuses on the crashworthy characteristics of closed-cell structural elements, typical of aircraft subfloor elements.

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 will include the detailed design of a racecar energy-absorbing element, the design of a specific crashworthy subfloor for a prototype aircraft, the development process of a crashworthy primary structure for a production supercar, and the lessons learned in the development of a crashworthy front rail structure of a passenger car.

14.1.2 Principles of crashworthiness

The overall objective of designing for crashworthiness is to eliminate injuries and fatalities in relatively mild impacts, and to minimize them in all severe collisions. A crashworthy vehicle will also control the extent of crash impact damage. By minimizing personnel and material losses, crashworthiness conserves resources, improves effectiveness, and increases confidence of the end-users [14.1.1].

Many influencing parameters need to be considered before an optimum design for crashworthiness can be finalized. A complete systems approach should be employed to include all the parameters concerned with the design, manufacture, overall performance and economic constraints on the vehicle in meeting mission requirements. Trade-offs among these parameters must be made in order to arrive at a final design that closely meets the specifications.

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14.1.5 Existing research and development

In the area of aircraft crashworthiness, much of the research focus in the last decades has been directed to the development of composite primary crash structures [14.1.1, 14.1.5, 14.1.9-11]. Information concerning the inclusion of composite crashworthy features in military rotorcraft is available mainly through US Army-sponsored Research Programs. For example, the fuselage concepts developed during ACAP (Advanced Composite Aircraft Program) and SARAP (Survivable Affordable Repairable Aircraft Program) use a mix of frangible and crushable composite sandwich underfloor structures integral to the composite-intensive airframe (fig. 14.1.4). For fixed-wing aircraft, NASA and the FAA have been involved with an extensive research activity to characterize the advantages of retrofitting non-crashworthy designs of General Aviation (GA) aircraft with crashworthy features, as in the case of the Aviation Safety Program (ASP).

Since 1996, the European Union (EU) has funded three research projects (CRASURV-Commercial Aircraft Design for Crash Survivability, HICAS-High Velocity Impact of Composite Aircraft Structures, and CRAHVI-Crashworthiness of Aircraft for High Velocity Impact) concerned with the development and validation of Finite Element simulation tools to model the crash and impact response of composite energy-absorbing aircraft structures [14.1.12-13]. The focal point of the research effort in CRASURV was the development of crashworthy subfloor systems, which provide a high-strength structural platform to retain the seats and resist overturning, and a crushable zone to absorb energy and distribute dynamic loads evenly across the fuselage. One particular characteristic of composite aircraft structures that could be a concern to the designer is the intersection of longitudinal subfloor beams and lateral bulkheads. These hard points act as efficient load paths to transfer loads during a crash to the seat and the occupant, and often prevent the occurrence of desirable energy-absorbing failure modes [14.1.14]. The HICAS project focused on testing and modeling of composite materials at high strain rates, while CRAHVI dealt with local/global models for complete aircraft simulations as well as impact on different surfaces including water.

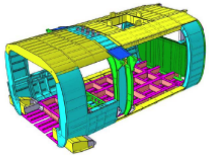


Fig. 14.1.4. Rotorcraft cabin and crashworthy subfloor concept for the Army Survivable Affordable Repairable Composite Airframe Program.

14-6

Analysis focus

- *Mostafa Rassaian of Boeing joins at Chicago meeting in July 2006*
- *Emphasis placed on numerical/ analytical needs*
- *Becomes co-chair and spearheads the creation of a Round Robin (RR) exercise to assess predictive capability of commercial FEA codes*
- *Various users with multiple codes and different modeling strategies join the effort*
- *RR begins January 2008 at Cocoa Beach meeting*

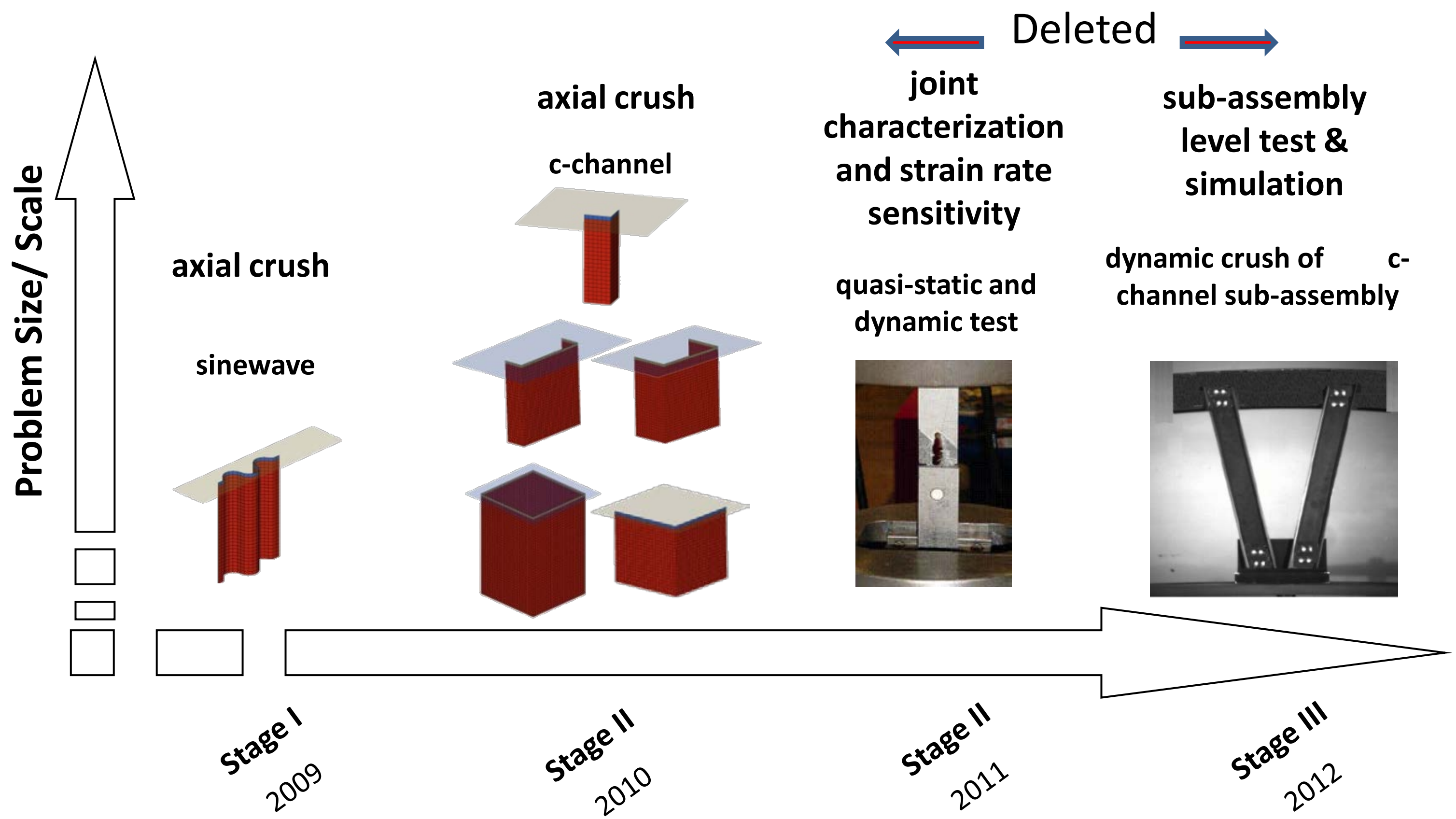
FEA Round Robin

- *The RR focuses on evaluating the capability of commercial FEA analysis tools and modeling strategies to simulate the crush energy absorption of composite structural elements.*
- *In 2011-2012 the Numerical Round Robin effort 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)*

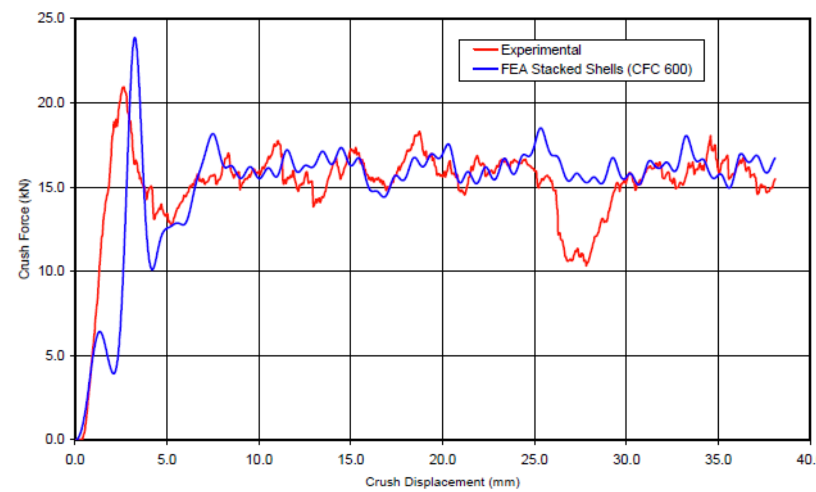
Abaqus VUMAT (Indermuhle) and PAMCRASH crushfront (Pickett) abandoned early on

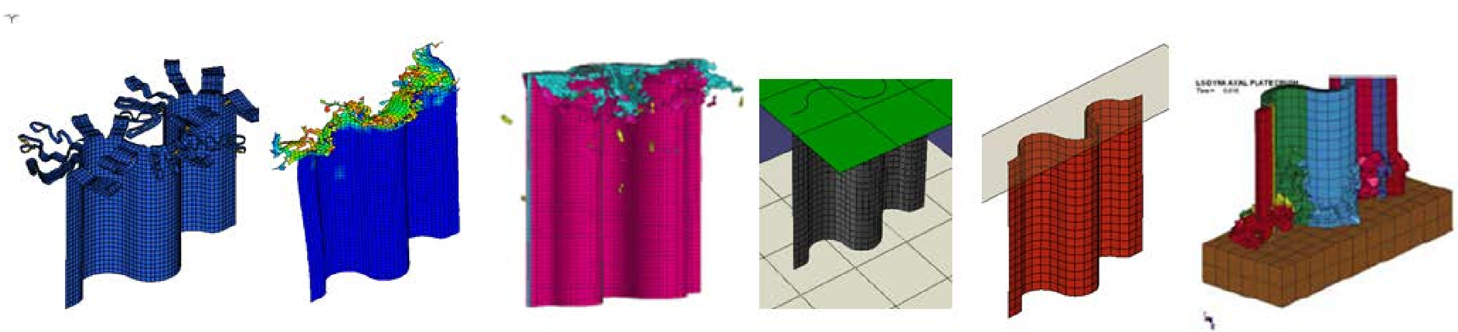
Roadmap for CMH-17 RR Crashworthiness



RR observations

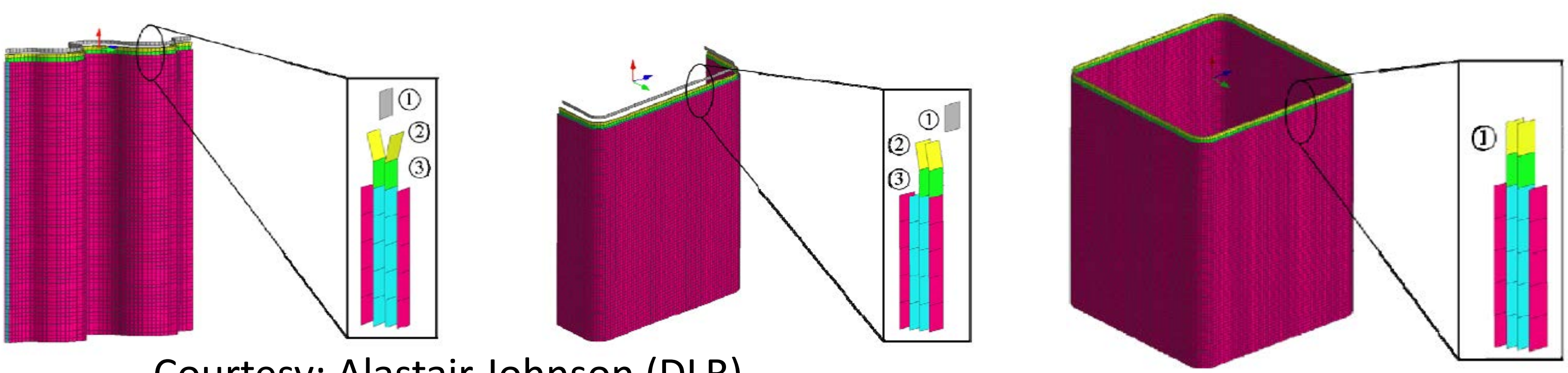
- *All approaches and codes can reproduce successfully the experimental results (with different accuracy)*





RR observations

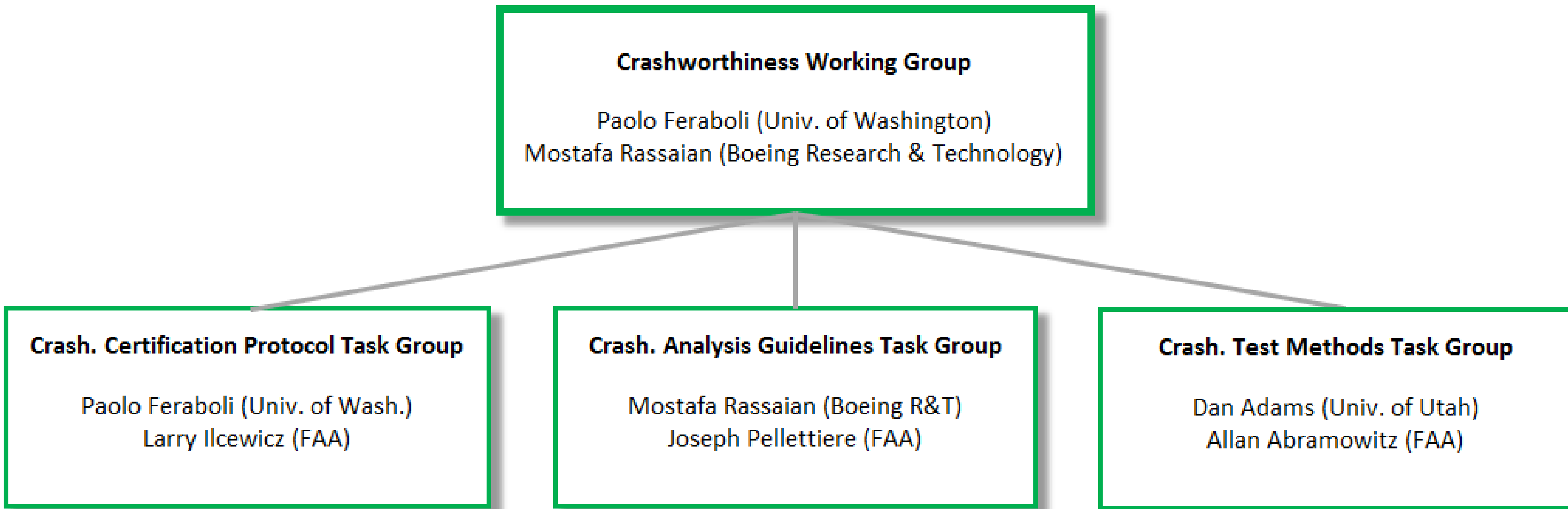
- *However, none of them are truly "predictive" but need to be used in the context of a Building Block Approach*
- *Example below shows how the PAMCRASH model by Alastair Johnson at DLR needs to be tweaked significantly to predict the right crush behavior for 3 different shapes*



Courtesy: Alastair Johnson (DLR)

Working Group Membership

- *The Working Group has recently been divided in three Task Groups, each focusing on a specific aspect of crashworthiness.*



- *Very active contributors have also been Karen Jackson (NASA Langley), Kevin Davis (Boeing BCA) and Michael Mahe (Airbus).*

JAMS RESEARCH CONTRIBUTIONS

JAMS Research Accomplishments to date

- *Experimental characterization (Feraboli, Wade)*
  - *100% complete*
  - *Several publications*
- *LS-DYNA MAT54 characterization (Wade, Deleo)*
  - *70% complete*
  - *1 FAA Tech Report delivered and in press*
- *LS-DYNA MAT54 CMH-17 RR entry (Wade)*
  - *100% Results and write-up*

Experimental focus: UW activity

- *UW initial activity focused on test methods*
- *Flat coupon derived from NASA proposed method*
  - "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)*
  - "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 (from flat to self-stabilizing)*
  - "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.

Experimental focus

- *Energy absorption (SEA) is NOT a material property*

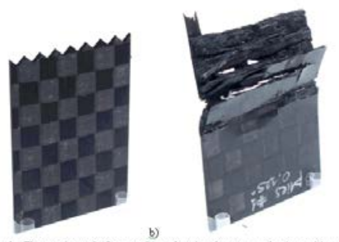


Figure 19 a, b. Flat specimen, before crushing showing the saw-tooth trigger (a), and after crushing (b) at 12.5 mm of unsupported height.

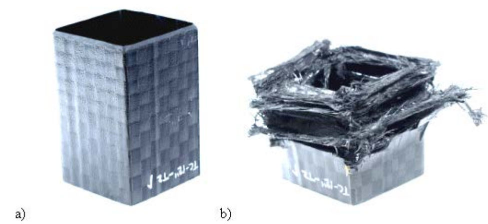


Figure 7 a, b. Square tube, specimen I, before and after crush testing

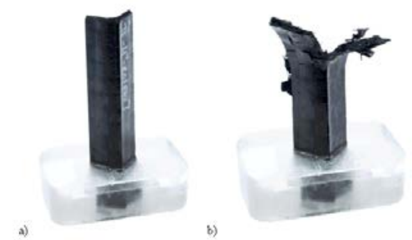
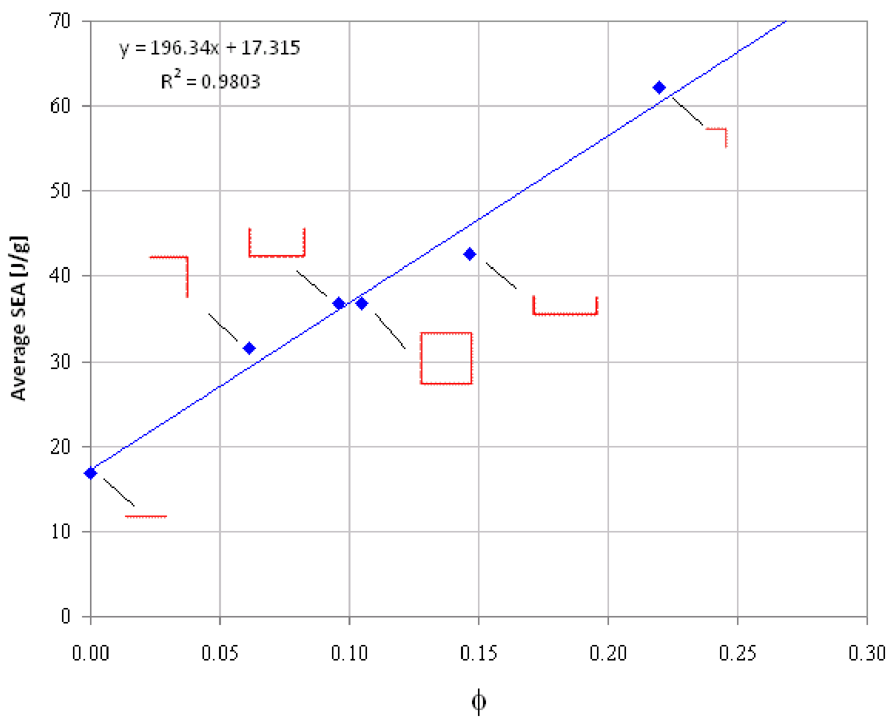
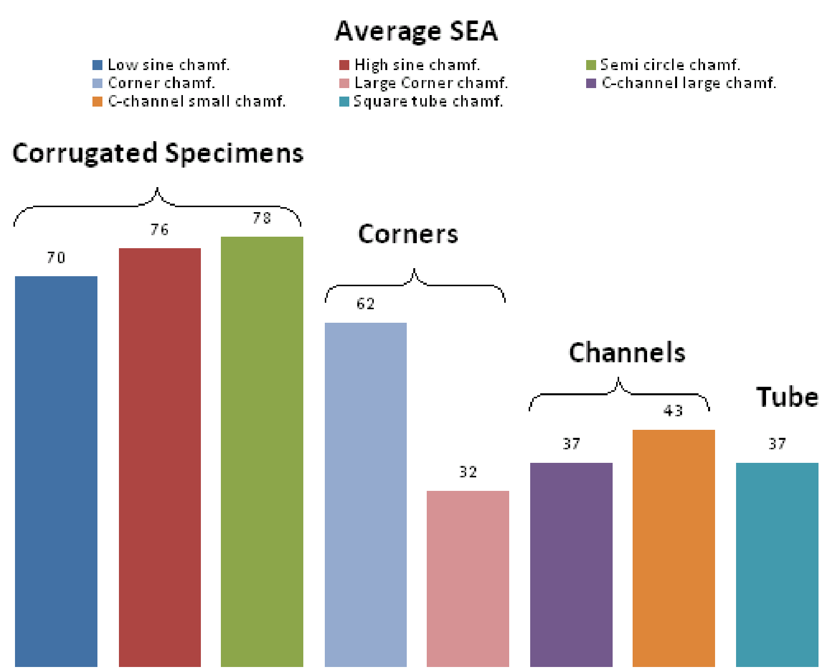


Figure 10 a, b. Small corner element, specimen IV, before and after crush testing



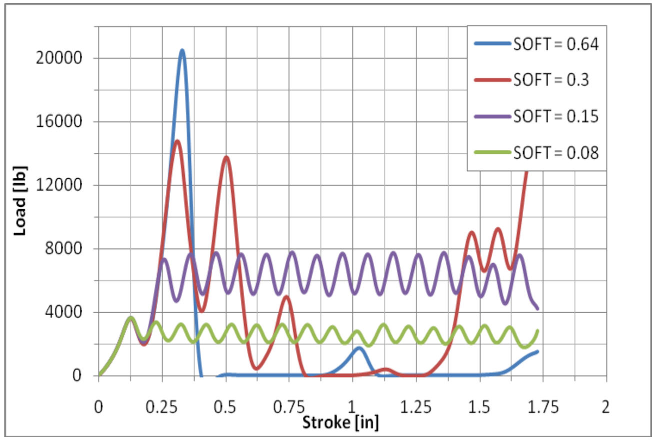


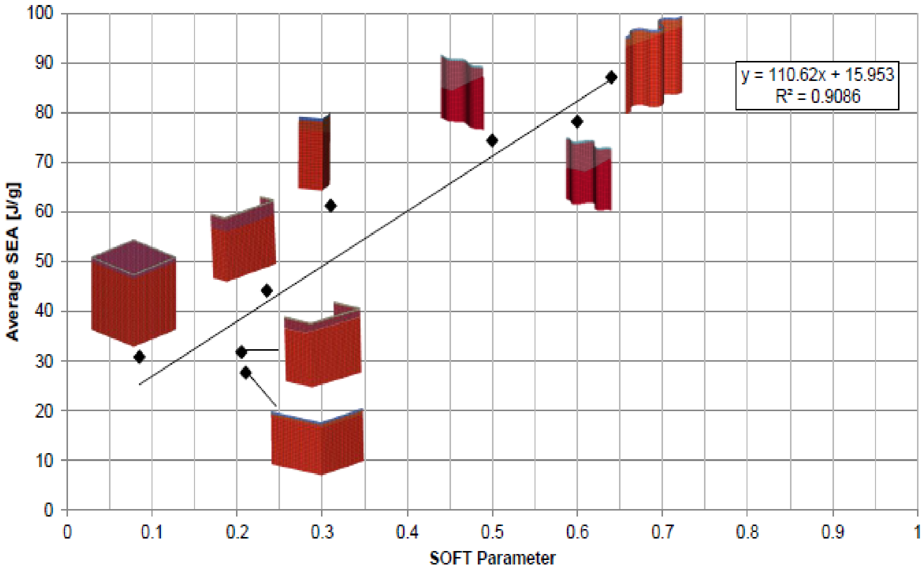
LS-DYNA MAT54

- *Began using LS-DYNA MAT54 after advice and based on guidance of Dr. Mostafa Rassaian*
- *No LS-DYNA Capability prior to that at UW ACSL*
- *Assessed robustness of MAT54 to modeling sinusoidal specimen*
  - P. Feraboli, B. Wade[2], F. Deleo[2], M. Rassaian[1], M. Higgins[1], A. Byar[1], "LS-DYNA MAT54 modeling of the axial crushing of a composite tape sinusoidal specimen", Composites (Part A), doi:10.1016/j.compositesa.2011.08.004
  - Detailed FAA Tech Report submitted and in press

Some key results

- Accurate matching of experimental results can be achieved
- MAT54 not purely predictive: MAT CARD needs to be tweaked to predict crushing of different shapes
- SOFT Crashfront parameter very influential





JAMS Research Ongoing activities

- *Educational Module* *(Feraboli)*
  - *80% complete*
  - *Lecture recorded and presentation ready*
- *LS-DYNA MAT54 characterization* *(Wade, Osborne)*
  - *Completing element level work*
  - *Completing single-element studies*
- *CMH-17 RR write-up* *(Wade)*
  - *Mostafa and Paolo with Bonnie to complete summary of RR effort*
- *Cert protocol/ guidelines document* *(Spetzler)*
  - *15% complete*

Educational Module

- *2 hr module within the 80 hr course*
- *Introduction to crashworthiness*

Crashworthiness Module

FAA Level II Course:
Composite Structural Engineering
Technology Safety Awareness

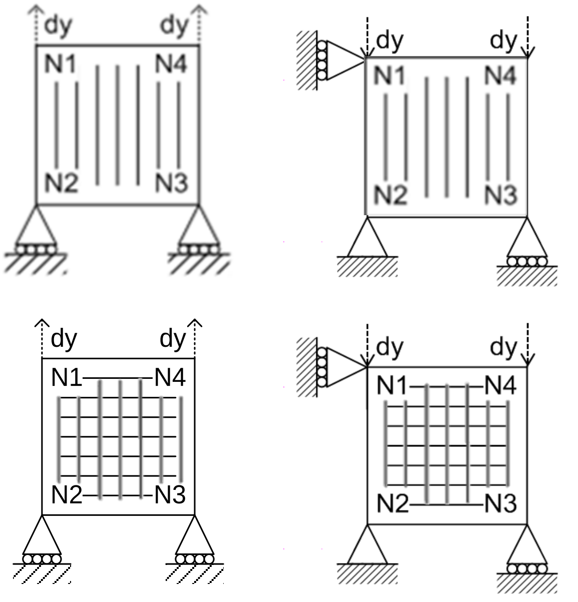
Paolo Feraboli, Ph.D.
Automobili Lamborghini ACSL
Aeronautics & Astronautics
University of Washington
Seattle, WA

March 2012

Outline

Single element study

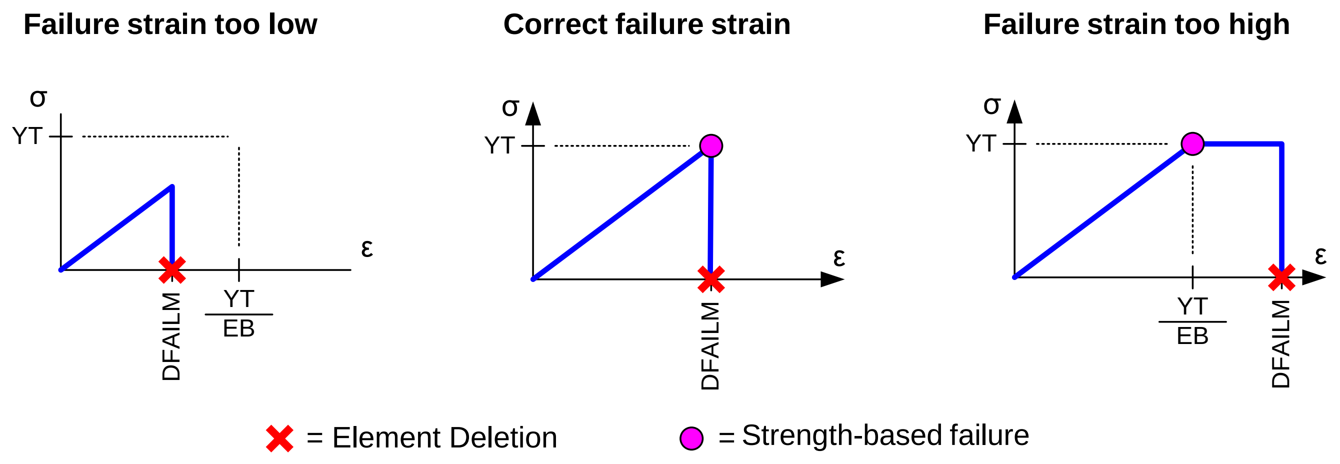
- *In-depth single element simulations study MAT54 input parameters using simple layups:*
  - *UD* $[0]_{12}$
  - *UD* $[90]_{12}$
  - *cross-ply UD* $[0/90]_{3s}$
  - *fabric* $[(0/90)]_8$



- *Goal is to determine critical parameters for ply failure and element deletion*

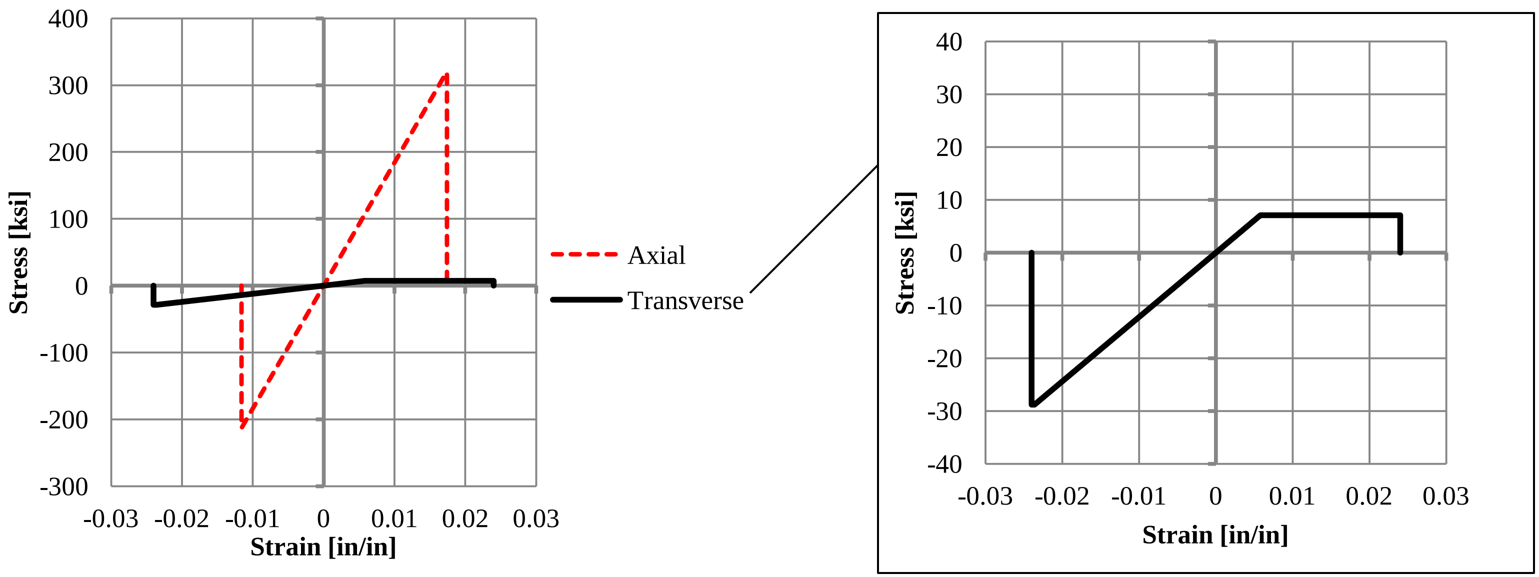
Single element study: UD

- *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*



Single element study

- *Although failure strains are the most significant MAT54 parameter, there is only one failure strain input for the matrix direction such that a large plastic region must exist in the 2-dir tensile stress-strain curve*

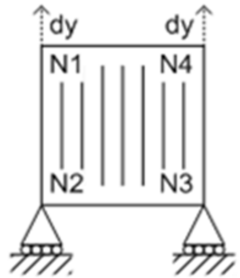


Single element study: fabric

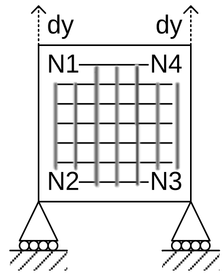
- *UD and fabric lamina properties are input for the $[0/90]_{3s}$ and $[(0/90)]_8$ laminates, respectively*

	F_{1t}^u	F_{1c}^u	F_{2t}^u	F_{2c}^u	ε_{1t}^u	ε_{1c}^u	ε_{2c}^u
UD	319000	213000	7090	28800	0.0174	-0.0116	0.024
FABRIC	132000	103000	112000	102000	0.0164	-0.013	0.014

- *In MAT54, the $[(0/90)]_8$ fabric is modeled as a $[0]_8$ laminate with fabric properties*

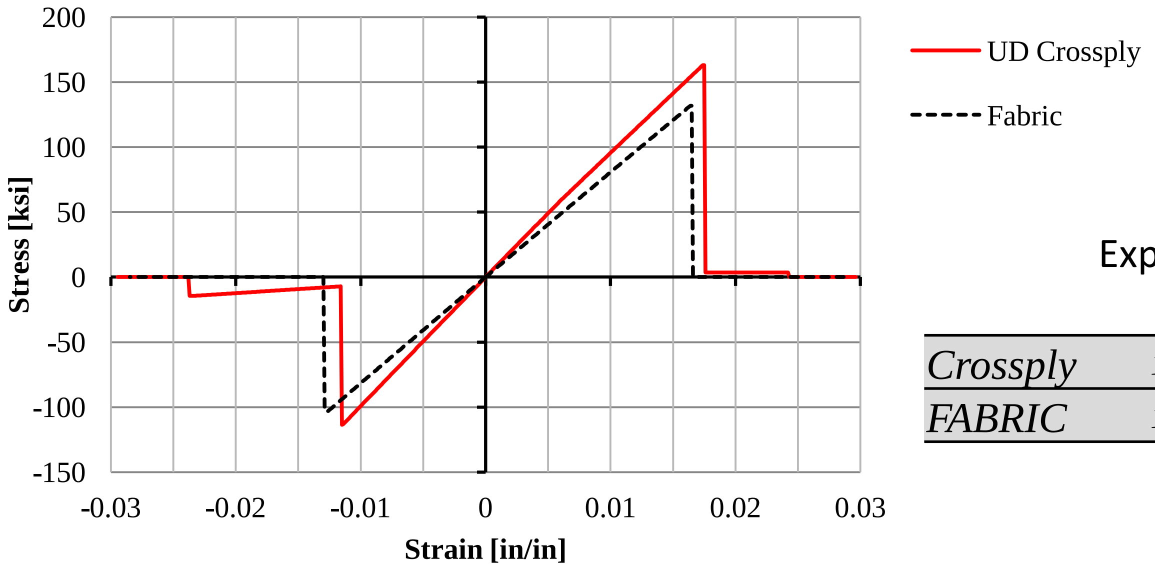


- *MAT54 uses the UD lamina properties and CLT to determine the behavior of the $[0/90]_{3s}$ laminate*



Single element study: fabric

- *The fabric element shows a linear-elastic brittle behavior*
- *The UD cross-ply results show low-energy plastic regions after the failure of the 0-degree plies, which terminate only after the 90-direction failure strain value (0.024 in/in) is achieved*

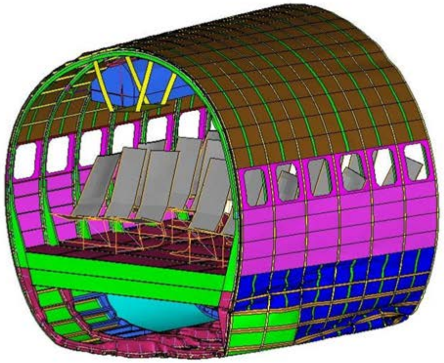


Expected laminate output:

	F_{1t}^u	F_{1c}^u	ε_{1t}^u	ε_{1c}^u
Crossply	*163000*	*120900*	*0.0174*	*-0.0116*
FABRIC	*132000*	*103000*	*0.0164*	*-0.013*

Cert protocol

- *Crashworthiness Certification protocol: Building Block Approach adapted to Crashworthiness*
- *Based on Analysis supported by test evidence*
- *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*



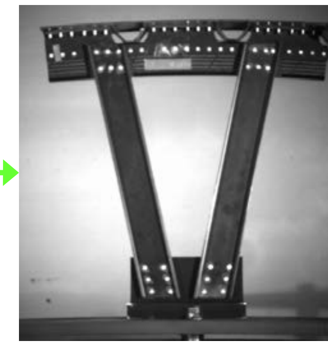
Courtesy: Boeing

Example of cert protocol for B787

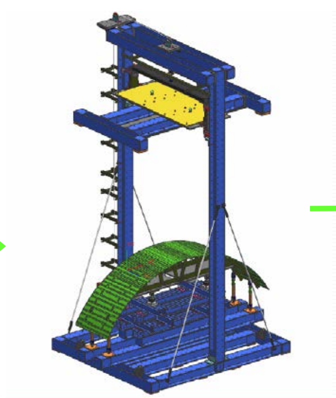
Courtesy: Boeing

Coupon

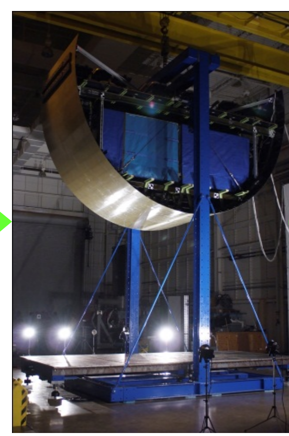
Element



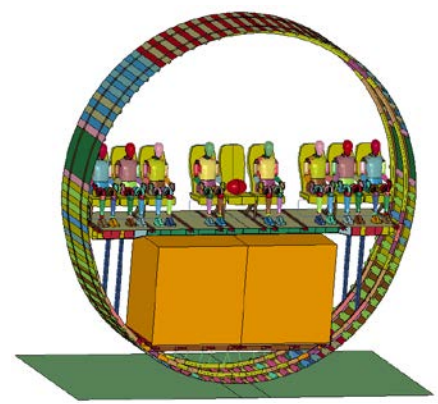
Subcomponent



Component



Large scale



Large scale

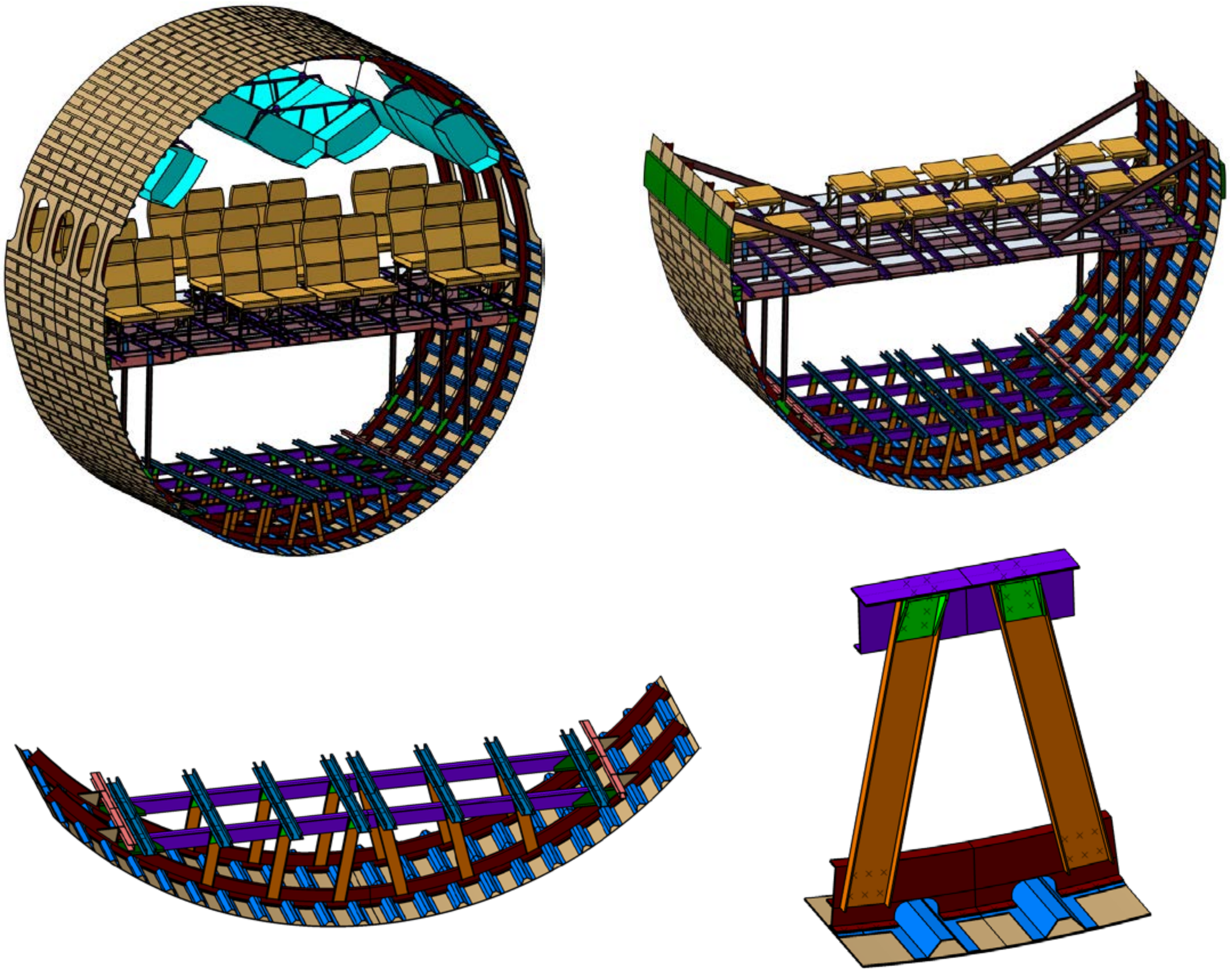
Cert protocol

- *Develop a guidance document that contains an example of a certification protocol for Part 25 aircraft based on a generic geometry*
- *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*

Cert protocol

- *Identify a suitable mock geometry, with all relevant structural features (floors, floor beams, floor supports, etc.)*
- *Synthetize 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*
- *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.*

General configuration Part 25 fuselage



Research to be continued

Completed by September 2012

- *All LS-DYNA MAt54 work (single element and higher level structures)*
- *Initial draft of test protocol for Mock Certification*
- *Transcribe lecture notes and complete educational module*
- *Complete CMH-17 RR writeup*

To be continued in 2013

- *Complete test protocol for Mock certification*
- *Complete analysis protocol for Mock certification*
- *Provide support material for guidance documents*