JAMS

Crashworthiness of composite structures: Experiment and Simulation

Paolo Feraboli (UoW)

AMTAS FALL MEETING 2012

A Center of Excellence
AMTAS
Advanced Materials in
Transport Aircraft Structures

CECAM
center of excellence for
composites and advanced materials

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

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

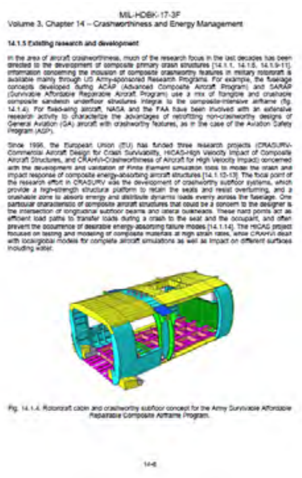
MIL-HDBK-17-3F
Volume 3, Chapter 14 – Crashworthiness and Energy Management

CHAPTER 14 CRASHWORTHINESS AND ENERGY MANAGEMENT

14.1 OVERVIEW AND GENERAL GUIDELINES

14.1.1 Section organization

14.1.2 Principles of crashworthiness



MIL-HDBK-17-3F
Volume 3, Chapter 14 – Crashworthiness and Energy Management

14.1.5 Existing research and development

Background

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.*

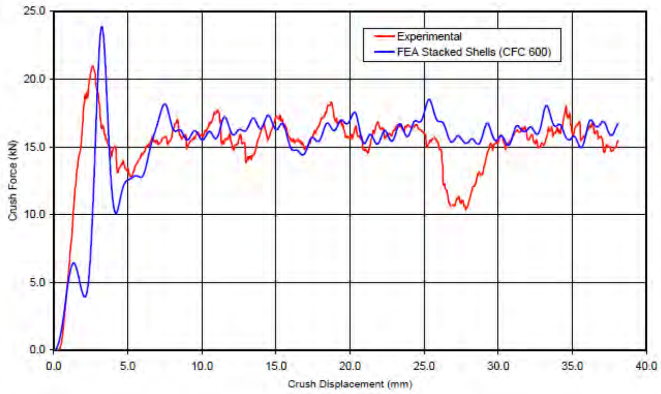
LS-DYNA MAT58	***M. Rassaian (Boeing BR&T)***
LS-DYNA MAT58	***X. Xiao, V. Aihataraju (G.M.)***
LS-DYNA MAT54	***P. Feraboli (U. of Wash.)***
LS-DYNA MAT162	***R. Foedinger (MSC Corp.)***
PAMCRASH CDM	***A. Johnson (DLR)***
RADIOSS Plasticity	***JB Mouillet (Altair)***
RADIOSS Tsai-Wu	***A. Caliskan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

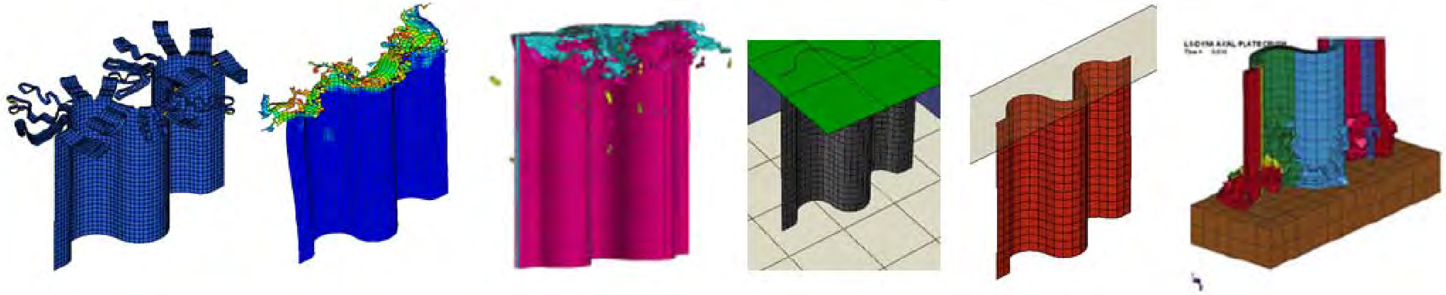
Abaqus VUMAT (Indermuhle) and PAMCRASH crushfront (Pickett) abandoned early on

Background

Round Robin Observations

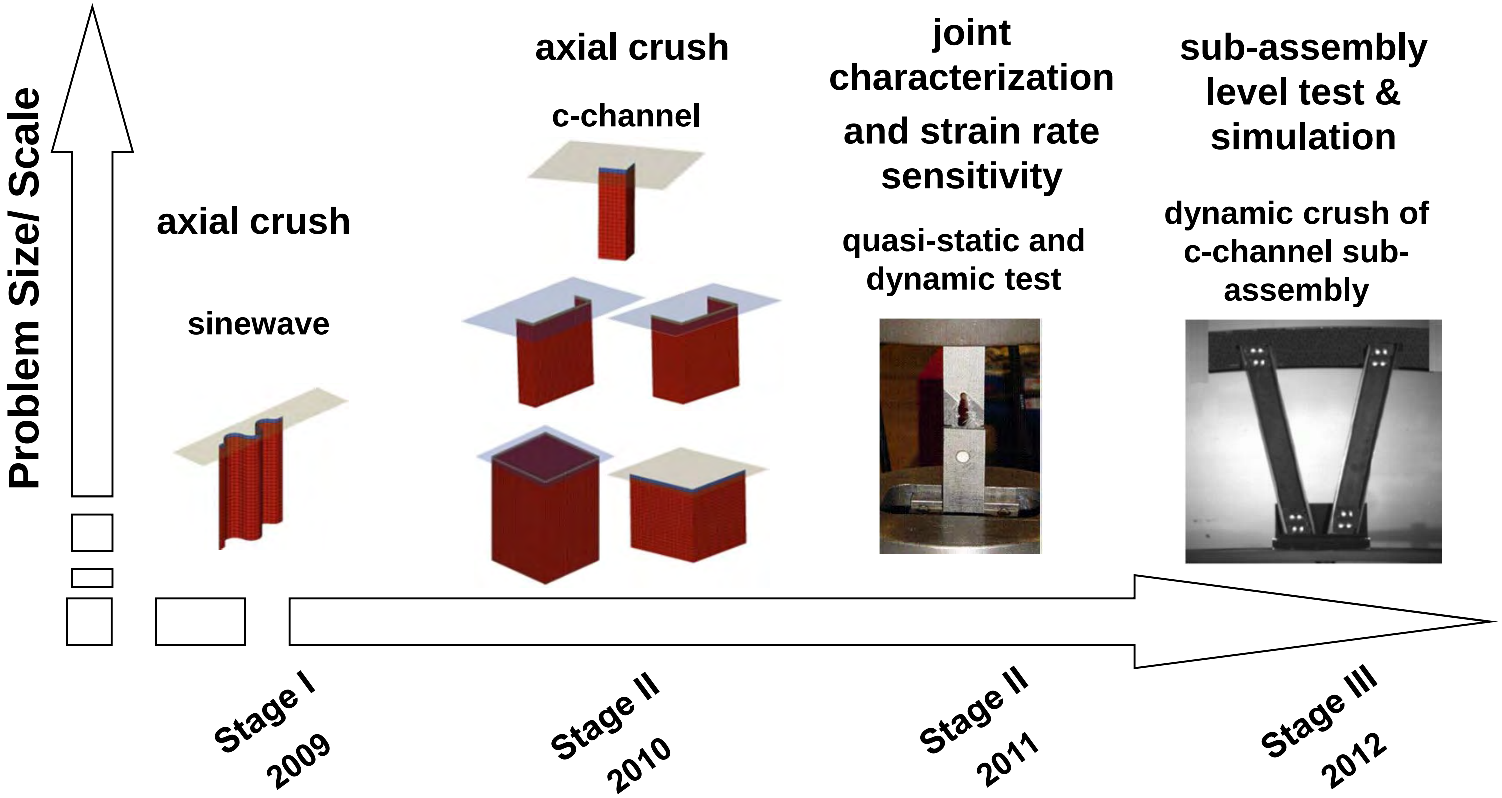
- *All approaches and codes can reproduce successfully the experimental results (with different accuracy)*
- *However, none of them are truly "predictive" but need to be used in the context of a Building Block Approach*





Background

Roadmap for CMH-17 RR Crashworthiness



Problem Size/ Scale

axial crush

sinewave

Stage I
2009

axial crush

c-channel

Stage II
2010

joint characterization and strain rate sensitivity

quasi-static and dynamic test

Stage II
2011

sub-assembly level test & simulation

dynamic crush of c-channel sub-assembly

Stage III
2012

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.*

Experimental focus

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

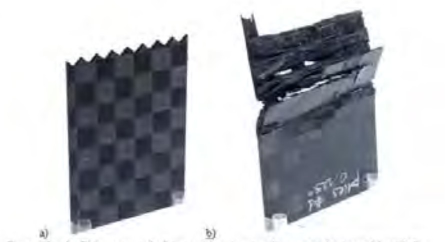


Figure 19 a, b. Flat specimen, before crushing showing the saw-tooth trigger (a), and after crushing (b) at 12.5 mm of unsupported height

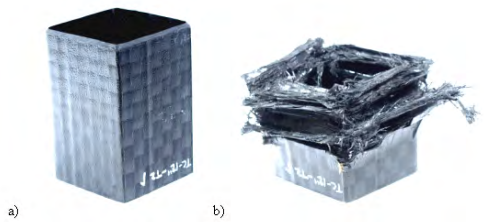
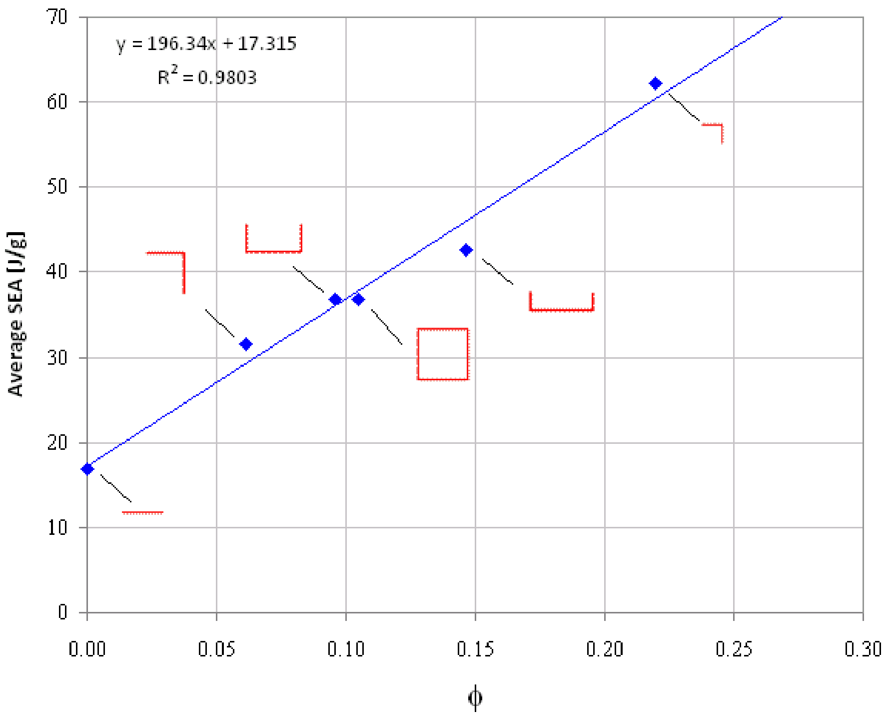
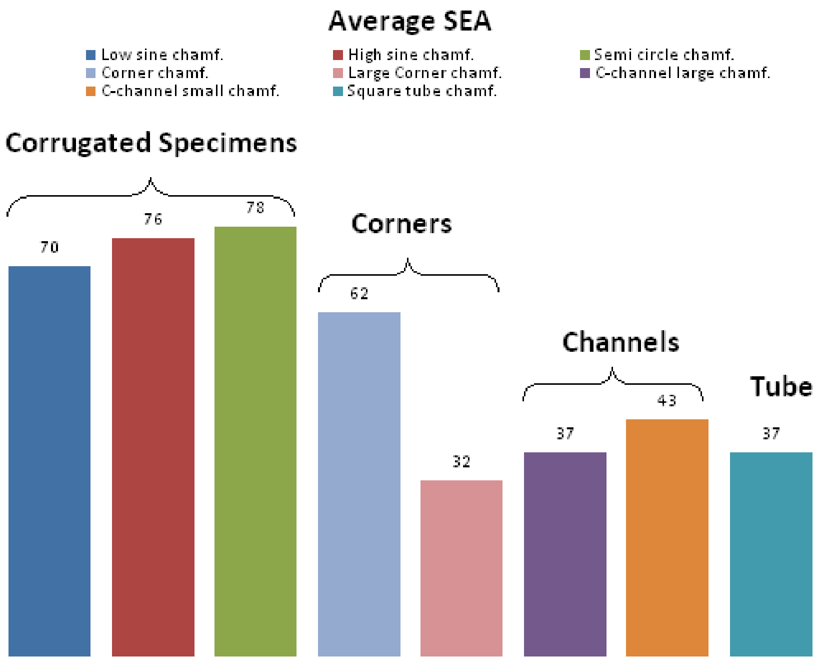


Figure 7 a, b. Square tube, specimen I, before and after crush testing

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





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.*

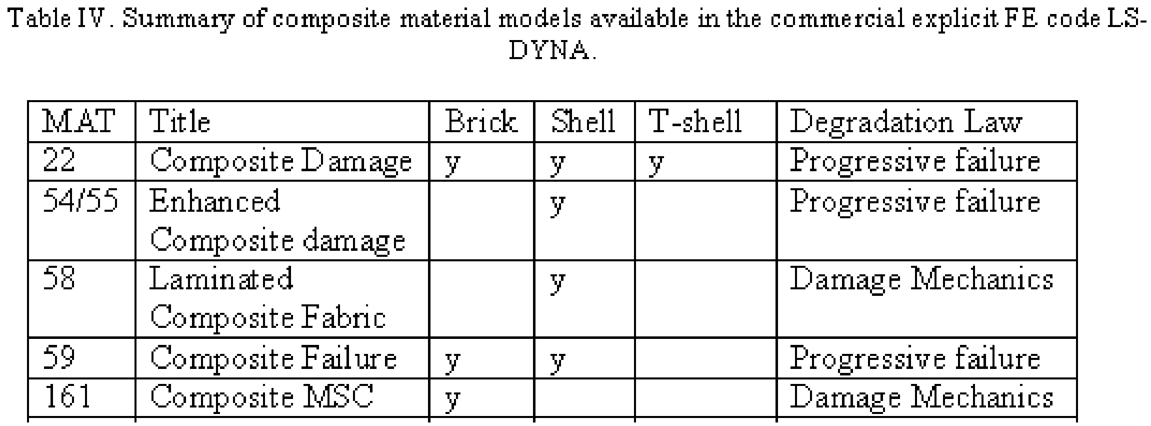
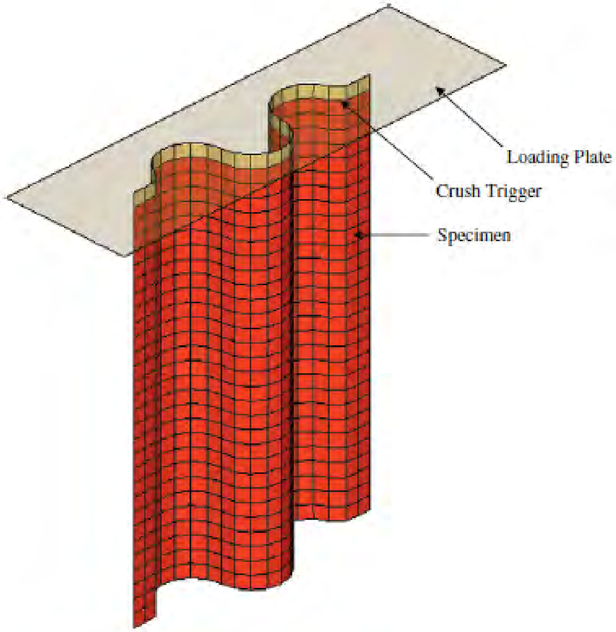
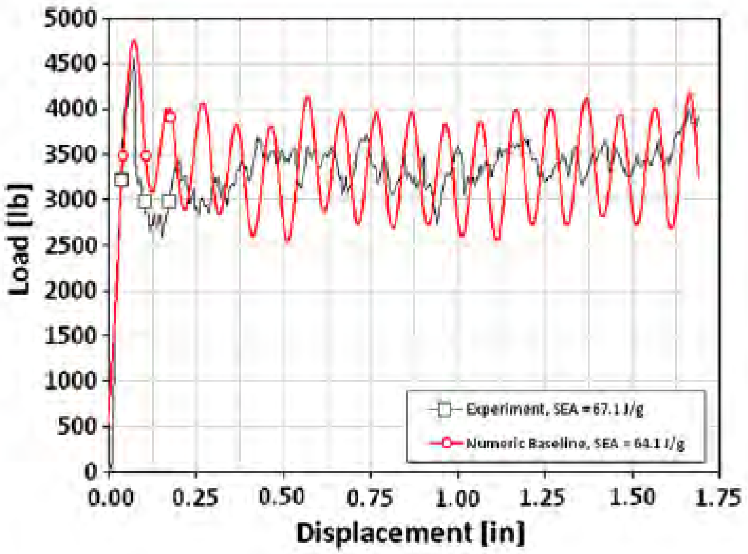


Table IV. Summary of composite material models available in the commercial explicit FE code LS-DYNA.

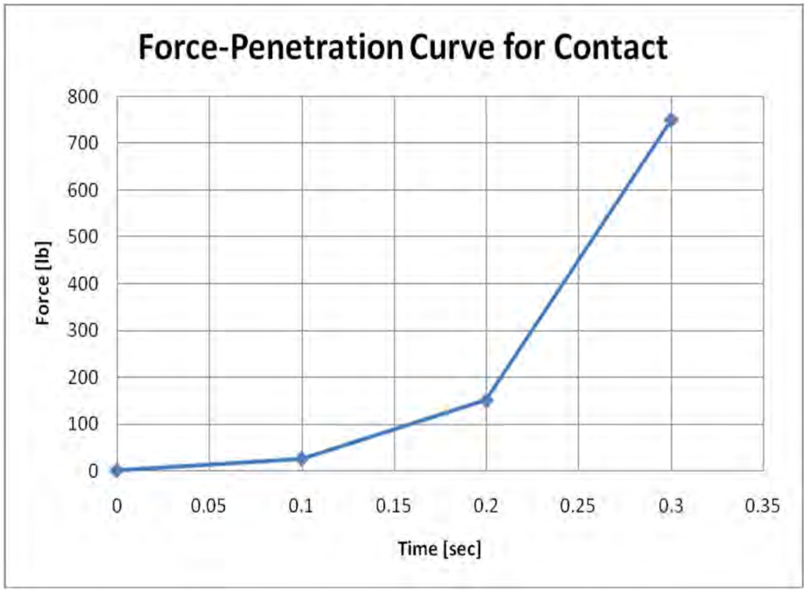
MAT	Title	Brick	Shell	T-shell	Degradation Law
22	Composite Damage	y	y	y	Progressive failure
54/55	Enhanced Composite damage		y		Progressive failure
58	Laminated Composite Fabric		y		Damage Mechanics
59	Composite Failure	y	y		Progressive failure
161	Composite MSC	y			Damage Mechanics

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

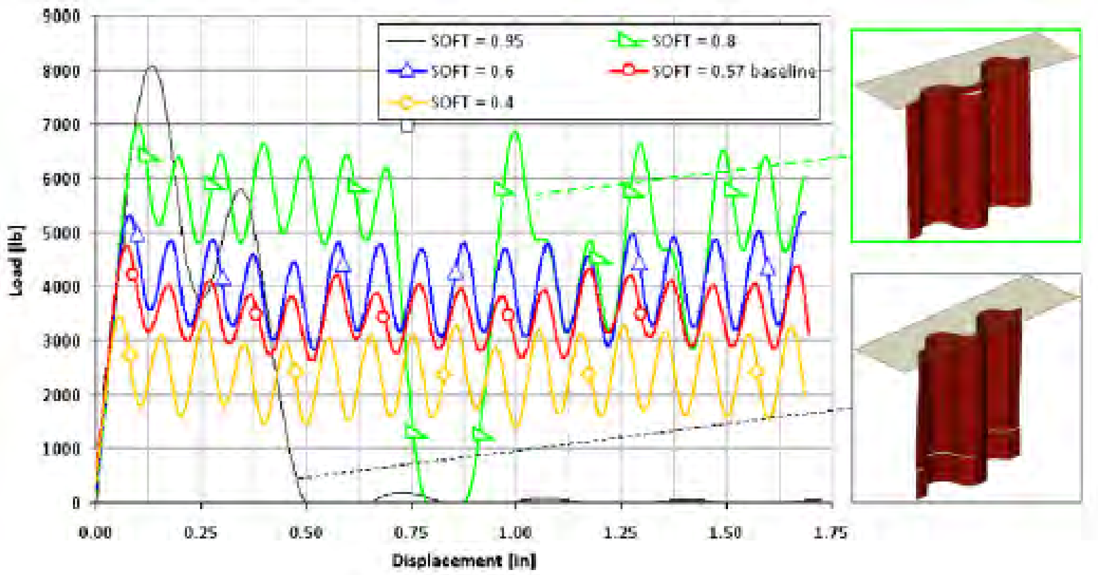




- ***SOFT****. Softening reduction factor. Used to reduce the strength of the row of elements immediately following that under crushing so that crushing occurs rather instability or other failures away from the crush front (varies between 0 and 1, default = 1.0).*
- ***Contact formulation****: different 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.*

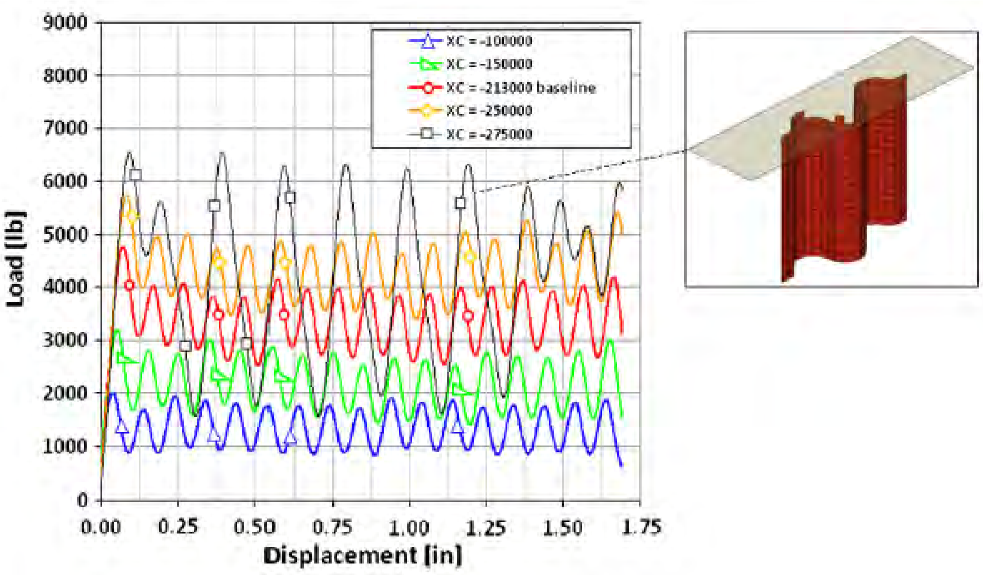


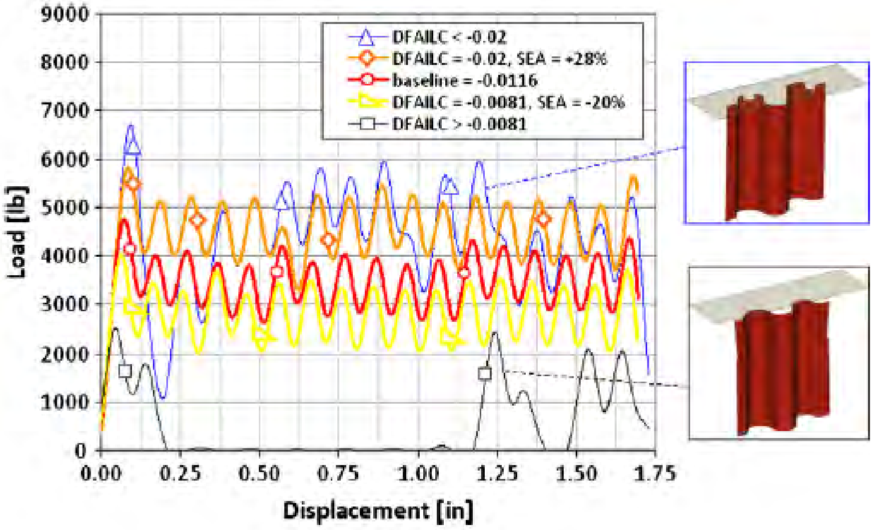
- *SOFT was found to be essential for crush simulation*
- *This parameter directly changes the average crush load value and the SEA*
- *SOFT can be interpreted as causing 'virtual damage' beyond the crush front, which simulates the damage zone caused by damage propagation*
- *The lower the SOFT, the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



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

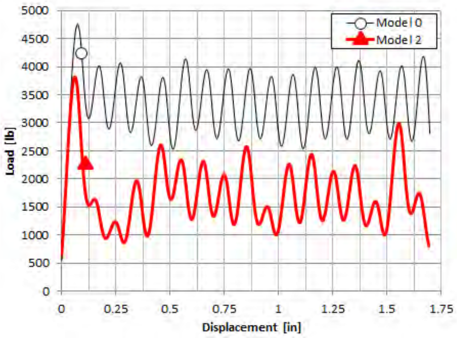
- *All MAT54 parameters were varied in the UD sinusoid crush model to determine which parameters greatly influenced the crush model*
- *Some results were logical, like the effect of the* ***compressive strength and failure strain parameters, XC and DFAILC***

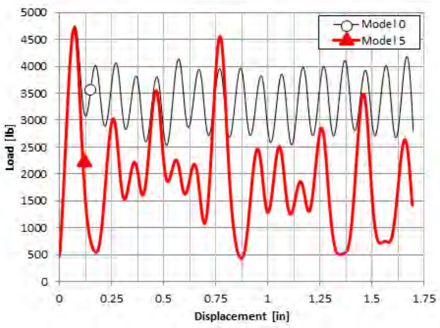


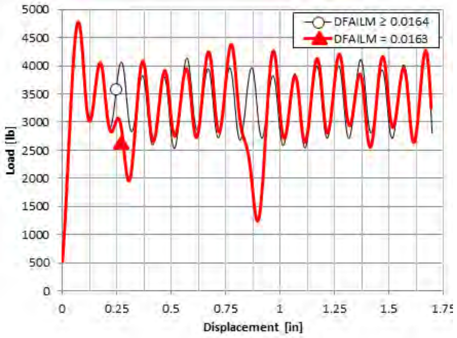


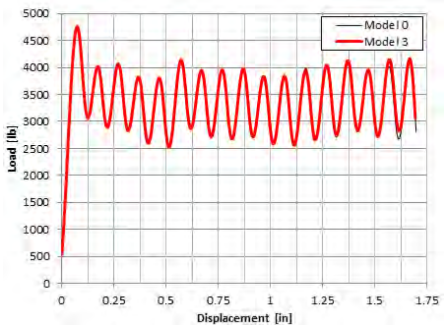
- *Other results raised questions, such as the influence the transverse failure strain parameter, DFAILM, had on the stability of the crush model*
- *DFAILM is the transverse failure strain for both tension and compression*

Increasing DFAILM

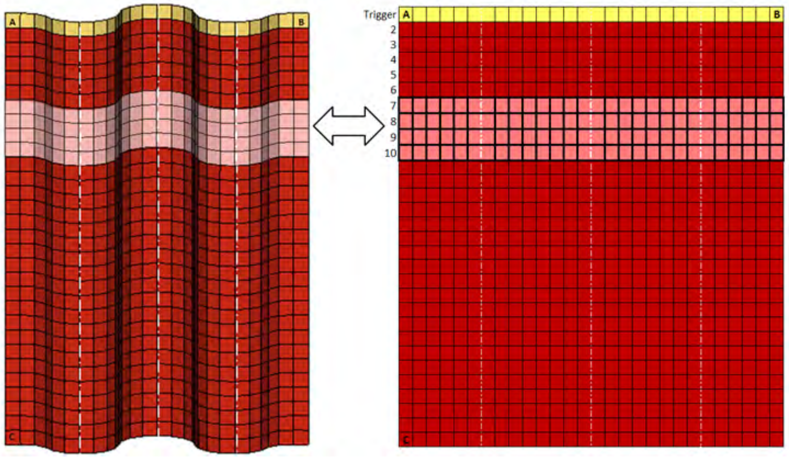


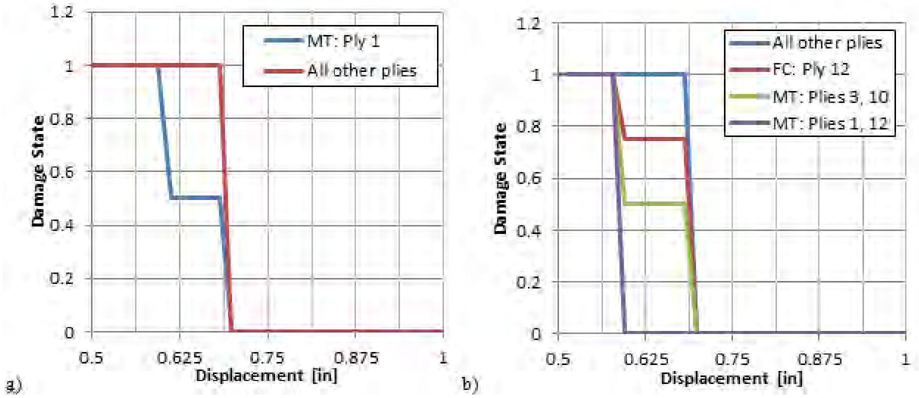


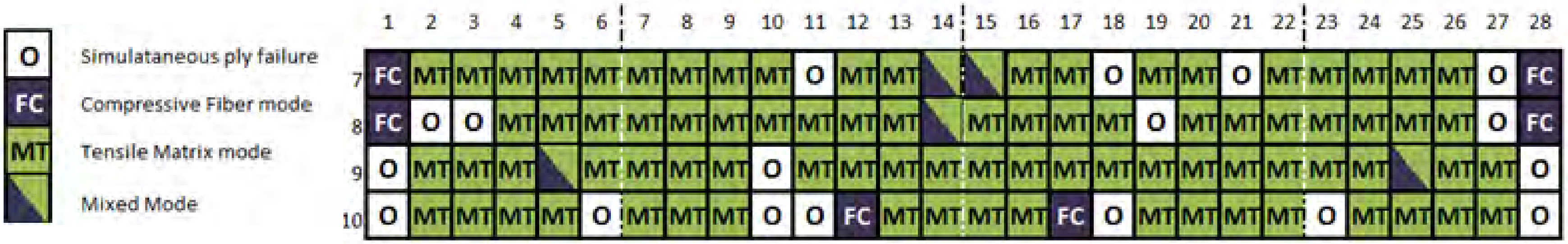




- *History variables keep track of the strength-based failures in the plies*
- *Data from these variables showed that 'matrix tension' failure was dominant*







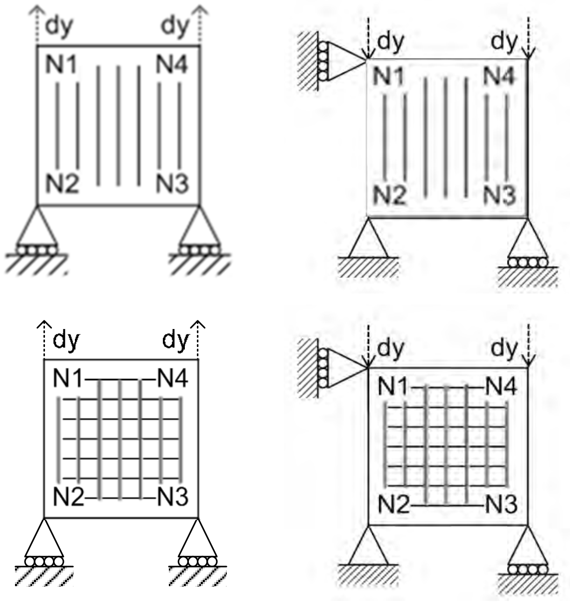
O	Simulataneous ply failure
FC	Compressive Fiber mode
MT	Tensile Matrix mode
◪	Mixed Mode

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
7	FC	MT	MT	MT	MT	MT	MT	MT	MT	MT	O	MT	MT	◪	◪	MT	MT	O	MT	MT	O	MT	MT	MT	MT	MT	O	FC
8	FC	O	O	MT	MT	MT	MT	MT	MT	MT	MT	MT	MT	◪	MT	MT	MT	MT	O	MT	MT	MT	MT	MT	MT	MT	O	FC
9	O	MT	MT	MT	◪	MT	MT	MT	MT	O	MT	MT	MT	MT	MT	MT	MT	MT	MT	MT	MT	MT	MT	MT	◪	MT	MT	O
10	O	MT	MT	MT	MT	O	MT	MT	MT	O	O	FC	MT	MT	MT	MT	FC	O	MT	MT	MT	MT	O	MT	MT	MT	MT	O

Single-element study

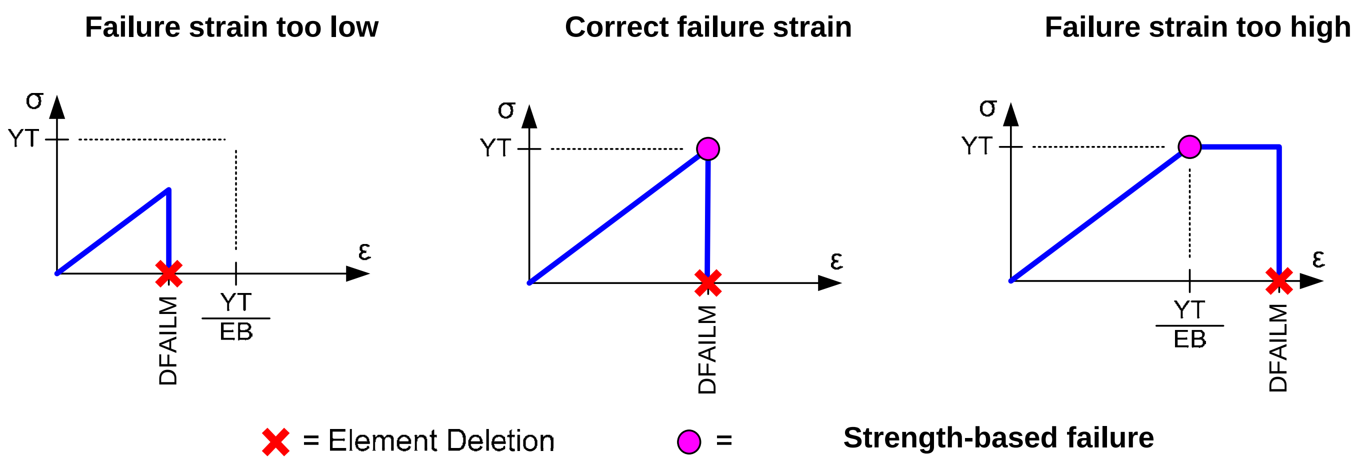
- *To fully understand the MAT54 material model, single element simulations were constructed which tested the element in basic tensile and compressive loading conditions*
- *In-depth single element simulations study*
- *MAT54 input parameters using simple layups:*
  - *UD [0]12*
  - *UD [90]12*
  - *cross-ply 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*

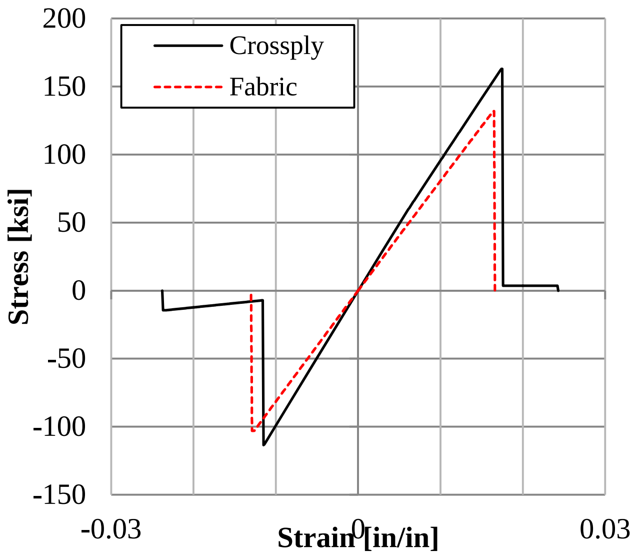

Failure strain too low

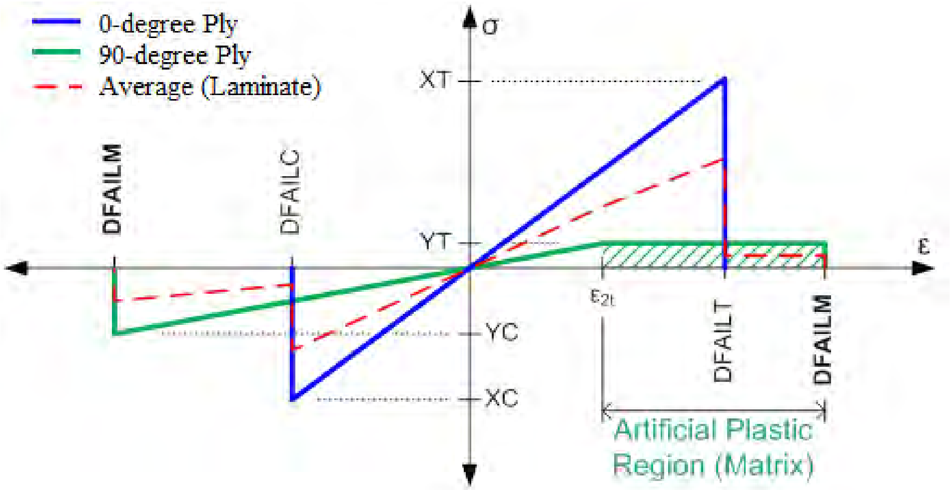
Correct failure strain

Failure strain too high

✖ = Element Deletion ● = **Strength-based failure**

- *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*

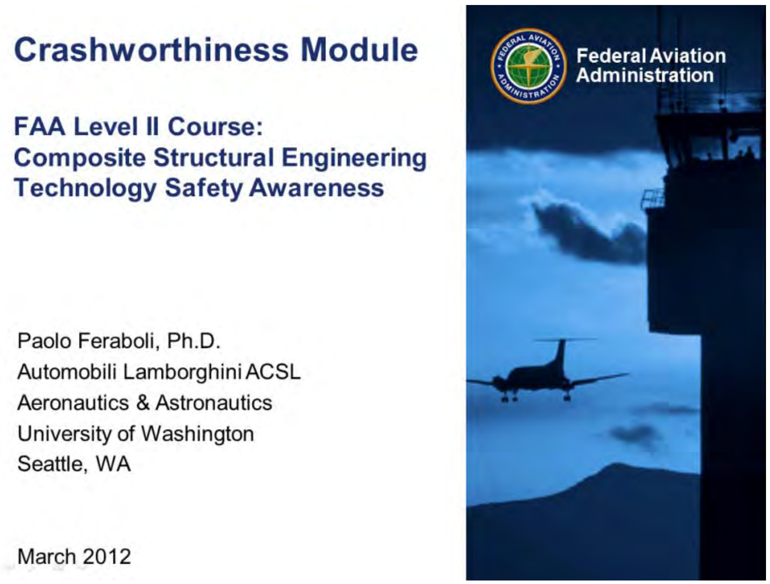




Educational

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*

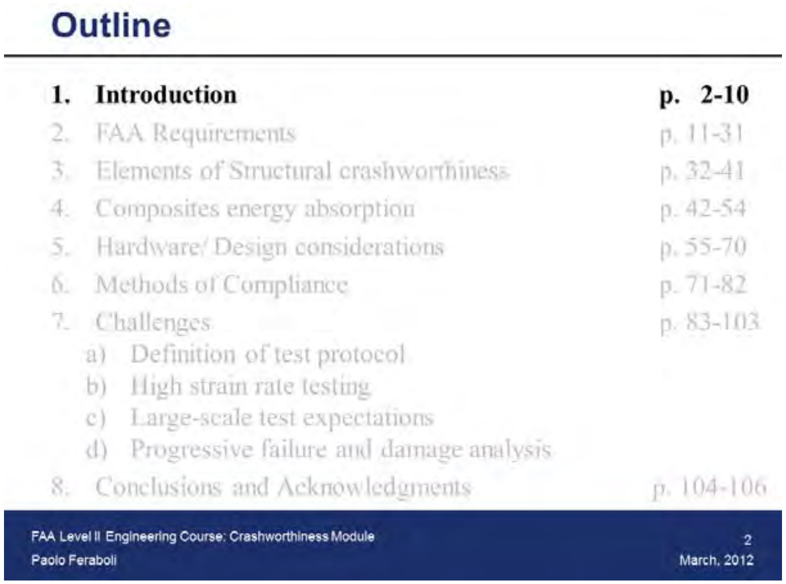


Crashworthiness Module

FAA Level II Course:
Composite Structural Engineering
Technology Safety Awareness

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

March 2012



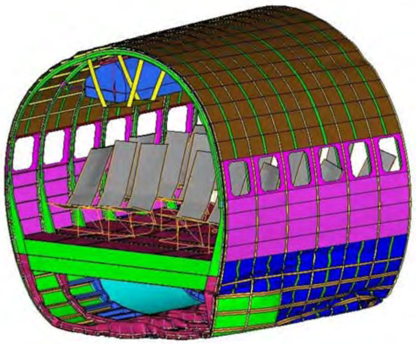
Outline

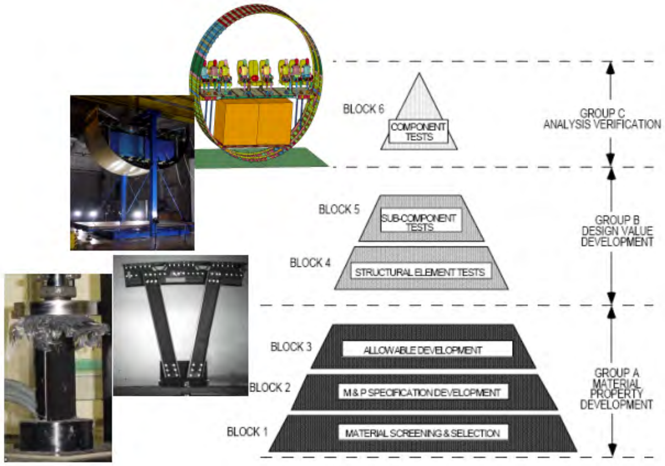
FAA Level II Engineering Course: Crashworthiness Module
Paolo Feraboli
2
March, 2012

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*

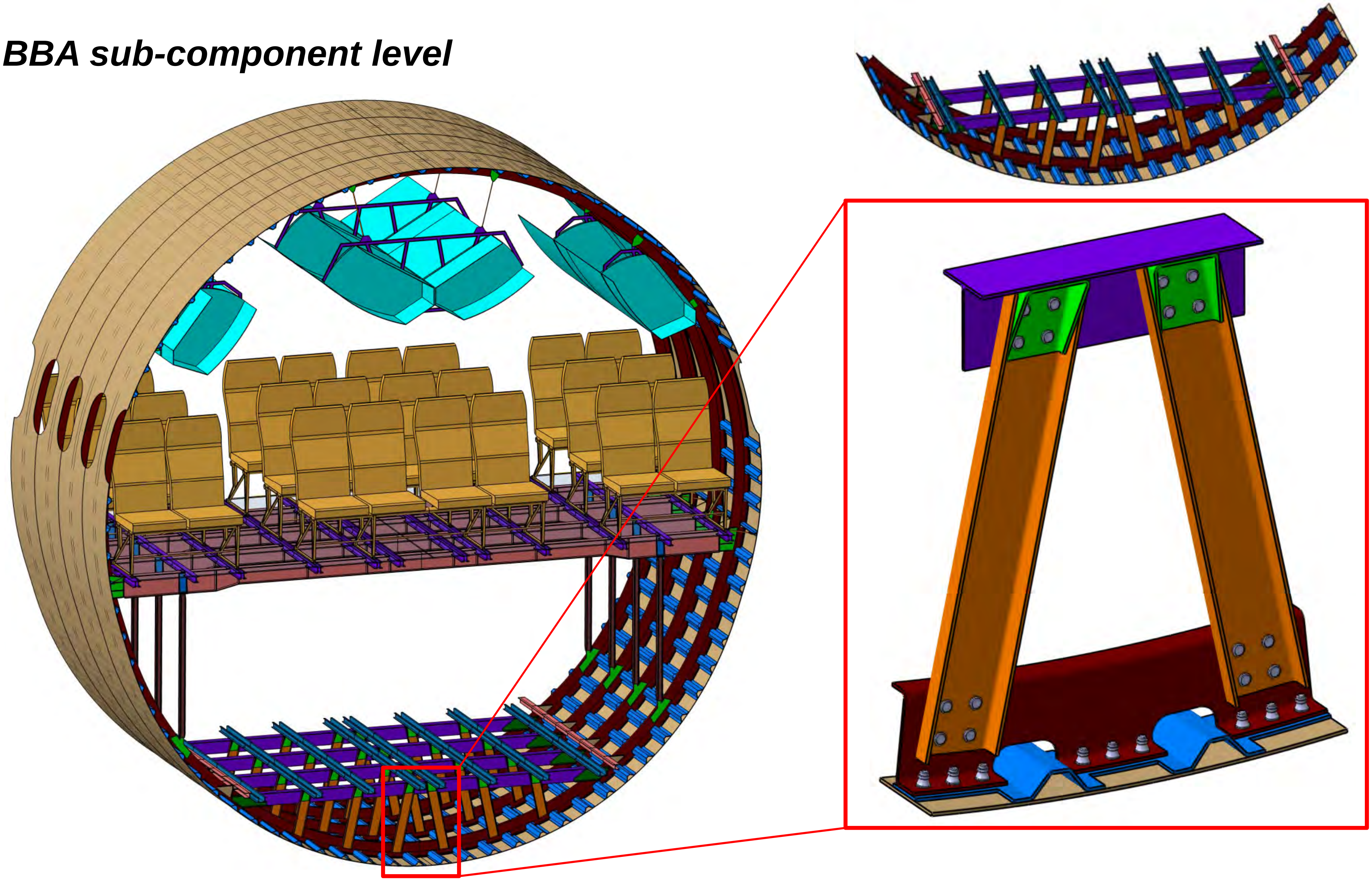




Courtesy: Boeing

- 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.)
- 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
- 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*