Crashworthiness of composite structures: Experiment and Simulation

Francesco Deleo, Bonnie Wade and Prof. Paolo Feraboli (UW)
Dr. Mostafa Rassaian (Boeing R&T)
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Motivation

- *Complete lack of standards and accepted practices in testing and analysis of composites under crash conditions*

Benefits to Aviation

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

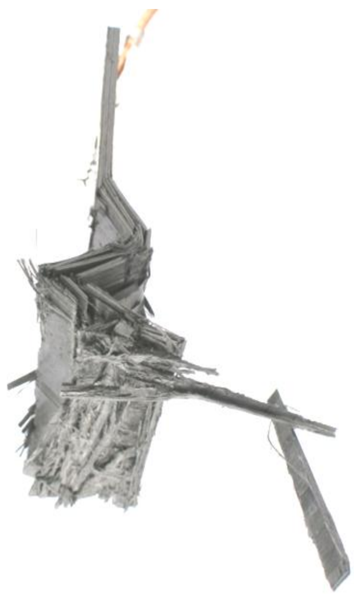
Objective

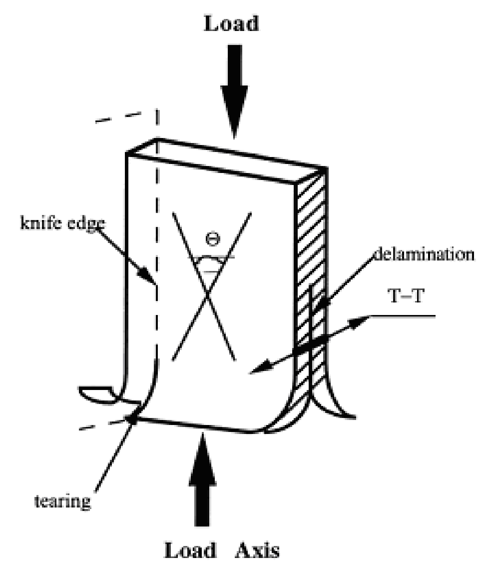
- *Develop experimental practices and analytical guidelines*

Experimental challenges

Crushing is a complex phenomenon

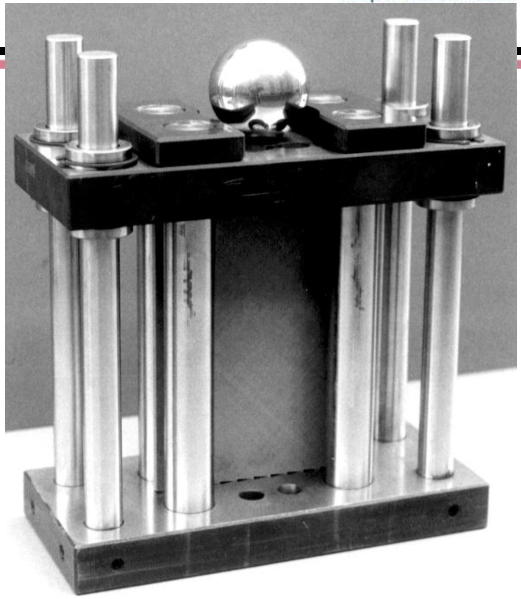
- *The crushing behavior of a composite specimen is not understood*
- *It is a mixture of multiple failure modes:*
  - *fiber tensile breakage, fiber compressive kinking, delamination, matrix cracking, bending of the fronds, and friction.*
- *Attempts have been made at testing a single flat plate specimen under crush conditions*

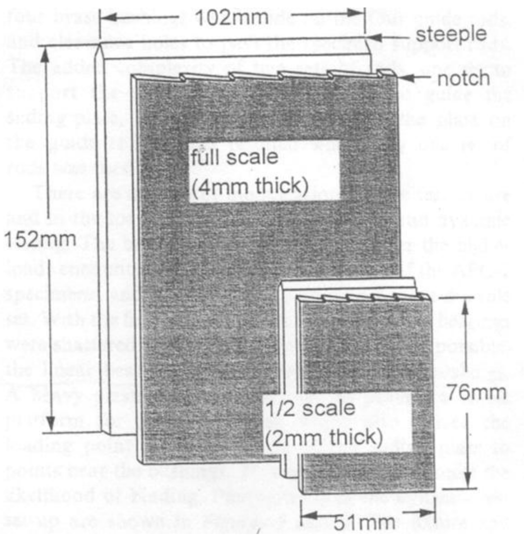




ARL/ NASA fixture:

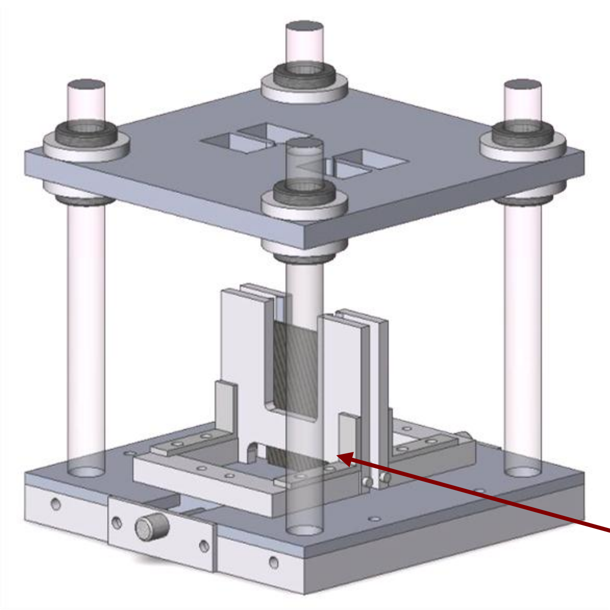
- *Early 1990's*
- *Simplest coupon geometry*
- *Very Complex Fixture*
- *Knife-edge supports all along length of specimen*
- *Over-constraining at crush front prevents "brooming" of the plies and free movement of debris*
- *Produces unrealistic SEA values*
- *Initial push but never became a standard*

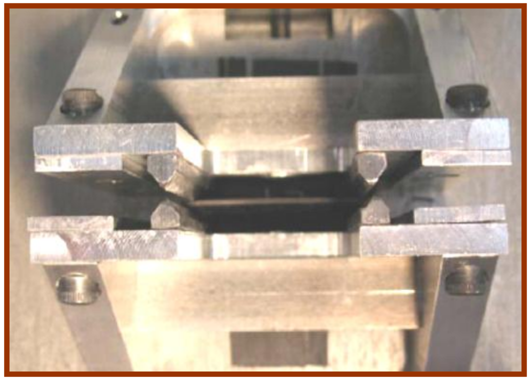


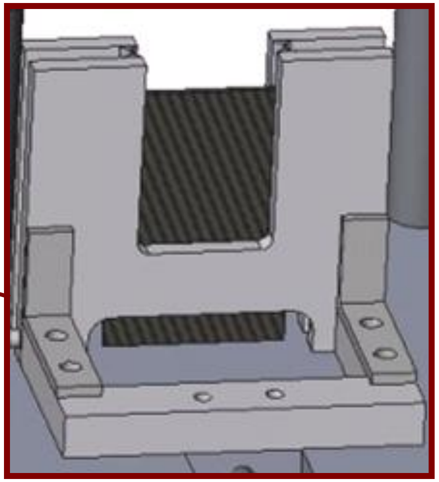


UW modified NASA fixture

- *modified to include effect of variable unsupported height (which was its original limitation)*
- *Crush front is free to deform naturally*



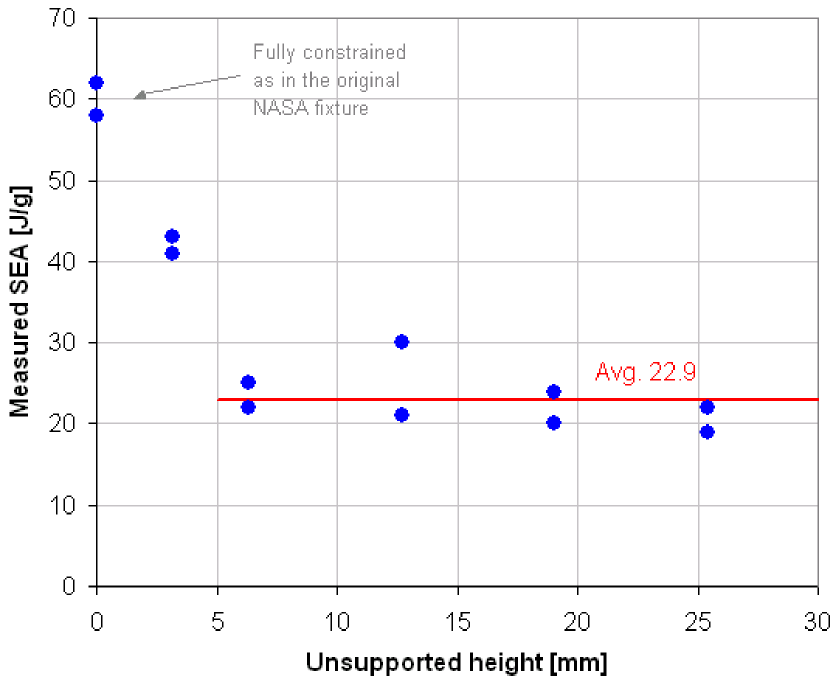




"Development of a modified flat plate test and fixture specimen for composite materials crush energy absorption" – Feraboli P. – Journal of Composite Materials, 43/19, 2009, pp. 1967-1990

UW modified NASA fixture

- Variable unsupported height 0.0 - 1.0 in. at different increments
- T700/2510 carbon/epoxy TORAYCA plain weave fabric used in the AGATE program



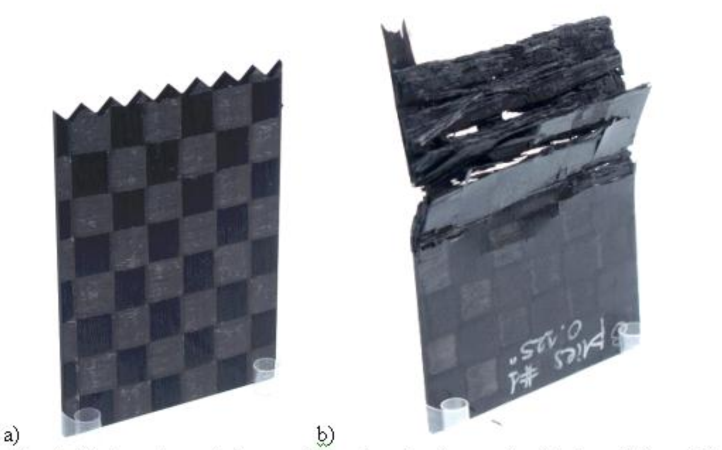


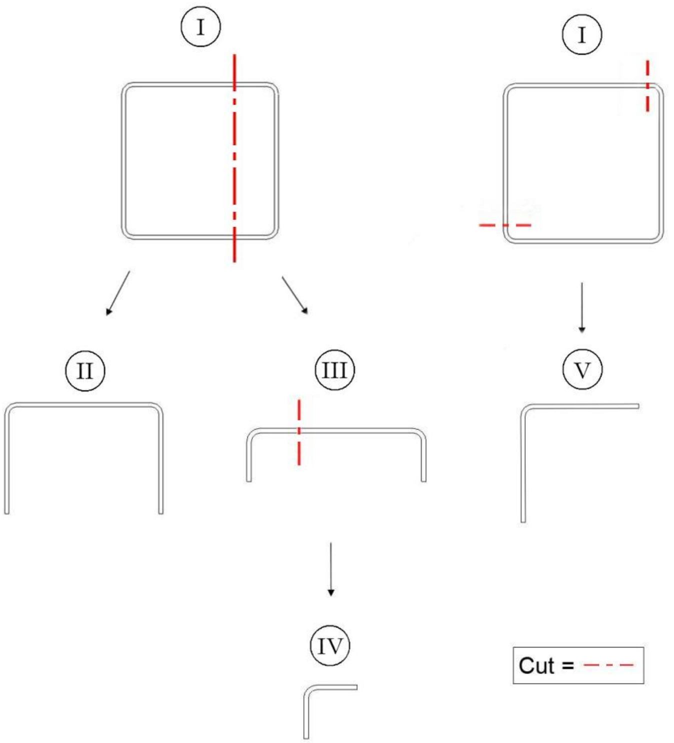
Figure 19 a, b. Flat specimen, before crushing showing the saw-tooth trigger (a), and after crushing (b) at 12.5 mm of unsupported height.

Conclusions

- *Flat plate fixture poses several questions*
  - *Unknown boundary condition effects*
  - *Difficulties for dynamic testing*
  - *Variable unsupported height effects*
  - *Not all the relevant failure mechanisms may be captured*
- *For the TORAY material there appears to be an asymptotic SEA at around 23 J/g at quasi-static rates*

Indirect measurement of flat SEA

- *Need to overcome flat fixture limitations*
- *Manufacture single tubular specimen*
- *Same material, processing and molder as flat plate specimens (autoclave cure on male mandrel by Toray CompAm)*
- *Machine to obtain 5 different specimen geometries*
  - *Square tube*
  - *Two C-channels*
  - *Two corner elements*



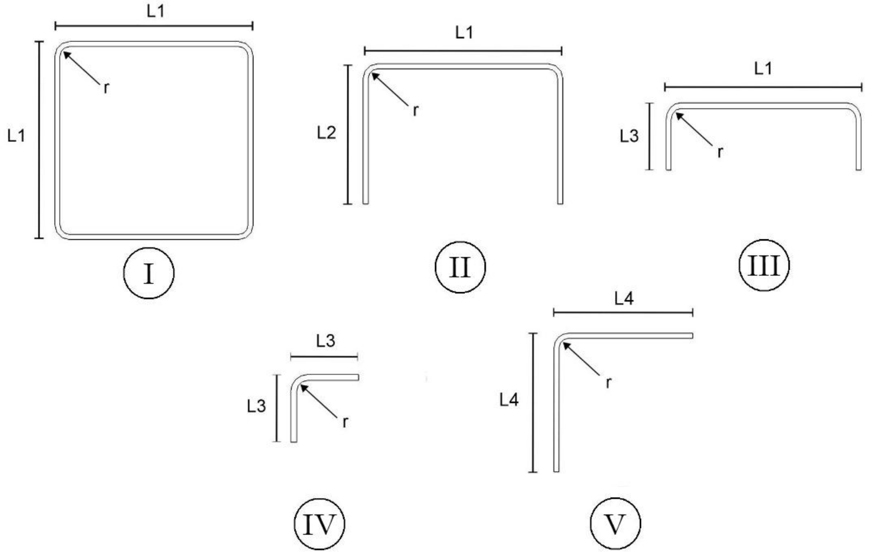
"Crush energy absorption of composite channel section specimens" – Feraboli, P., Wade, B., Deleo, F., Rassaian, M. – Composites (Part A), 40/8, 2009, pp. 1248-1256

Multiple shapes based on tubular specimen

- *Objective to isolate effects of curvature from flat segments*

Table I. Summary of the five specimens considered and associated key geometric features.

Specimen No.	Shape	Outer Dimensions	Section Length	Portion of cross section affected by one corner
I	Tube	L1 x L1	S_I	¼ S_I
II	Large Channel	L1 x L2	S_{II}	½ S_{II}
III	Small Channel	L1 x L3	S_{III}	½ S_{III}
IV	Small Corner	L3 x L3	S_{IV}	S_{IV}
V	Large Corner	L4 x L4	S_V	S_V



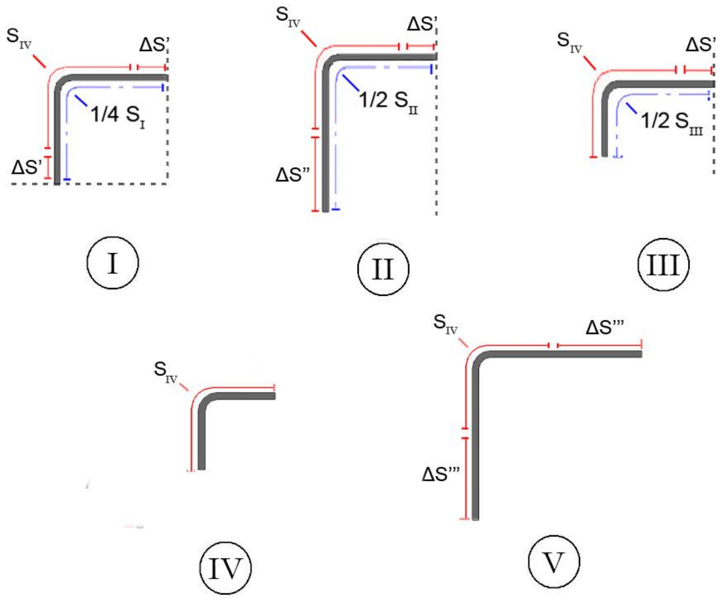
Procedure

- *Divide each cross section into portions influenced by adjacent corner*
- *Specimen IV (small corner) is the repetitive unit common to all shapes*
- *Each section perimeter is expressed as function of corner element length plus some flat segment length*

$$S_i = \begin{cases} \frac{1}{4} S_I & \text{for specimen I} \\ \frac{1}{2} S_{II} & \text{for specimen II} \\ \frac{1}{2} S_{III} & \text{for specimen III} \\ S_{IV} & \text{for specimen IV} \\ S_V & \text{for specimen V} \end{cases}$$

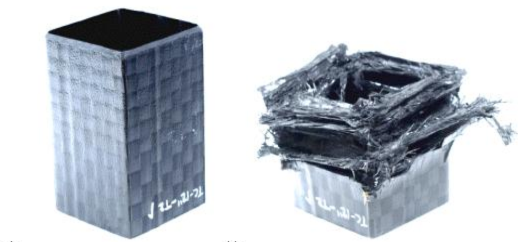
$$\Delta S = \begin{cases} 2\Delta S' & \text{for specimen I} \\ \Delta S' + \Delta S'' & \text{for specimen II} \\ \Delta S' & \text{for specimen III} \\ 0 & \text{for specimen IV} \\ 2\Delta S''' & \text{for specimen V} \end{cases}$$

$$\Delta S = S_i - S_{IV}$$



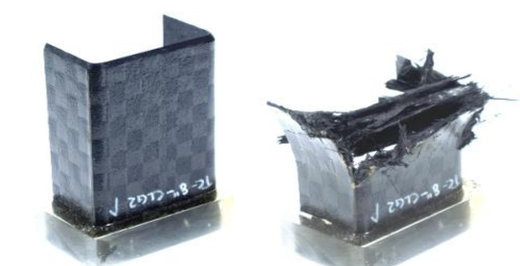
Results

- *All specimens crush in stable fashion*
- *All specimens except tube need potting for stability*



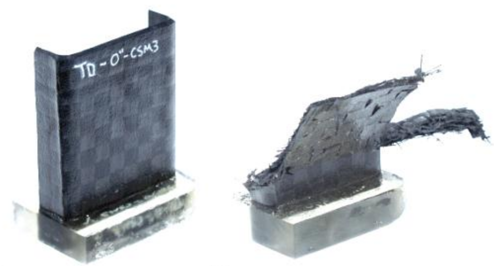
a) b)

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



a) b)

Figure 8 a, b. Large C-channel, specimen II, before and after crush testing.

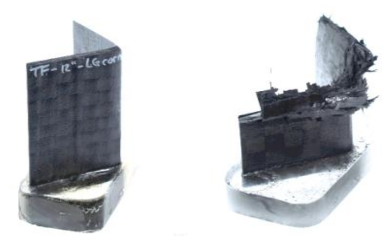


a) b)

Figure 9 a, b. Small C-channel, specimen III, before and after crush testing.

a) b)

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



a) b)

Figure 11 a, b. Large corner element, specimen V, before and after crush testing.

Results

- *Small corner has greatest SEA, large corner the lowest*

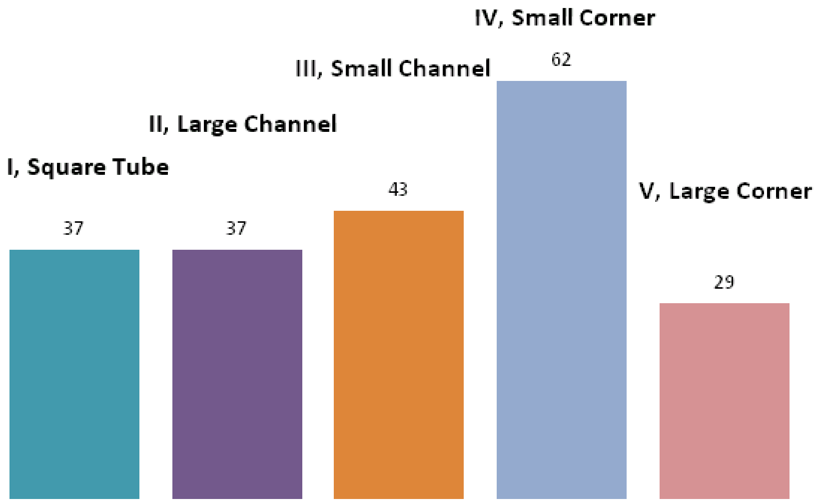


Table III. Summary of crush test results for all five specimen geometries

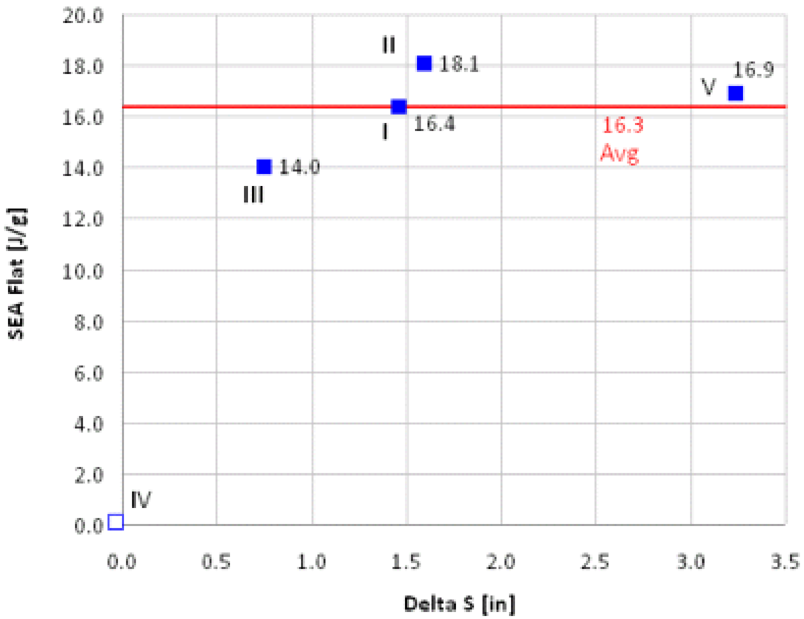
Specimen No.	Shape	Peak Force (kN)	Average Crush Force (kN)	Crush Efficiency	Average SEA (J/g)	CoV (%)
I	Tube	39.9	23.8	1.68	36.9	10
II	Large Channel	21.6	13.0	1.66	36.8	9
III	Small Channel	17.1	10.7	1.60	42.7	3
IV	Small Corner	7.5	4.9	1.53	62.3	11
V	Large Corner	15.3	9.4	1.63	31.6	8

Analysis of results

- *If we subtract the corner element SEA, which is our reference, we can infer the in-situ SEA of the flat section*
- *Each section has a different amount of perimeter that is flat vs. curved*
- *An average of <u>16 J/g as in-situ strength can be extrapolated</u>*

$$\Delta S = S_i - S_{IV}$$

$$SEA_i = \left(\frac{S_{IV}}{S_i}\right) SEA_{IV} + \left(\frac{\Delta S}{S_i}\right) SEA_f$$

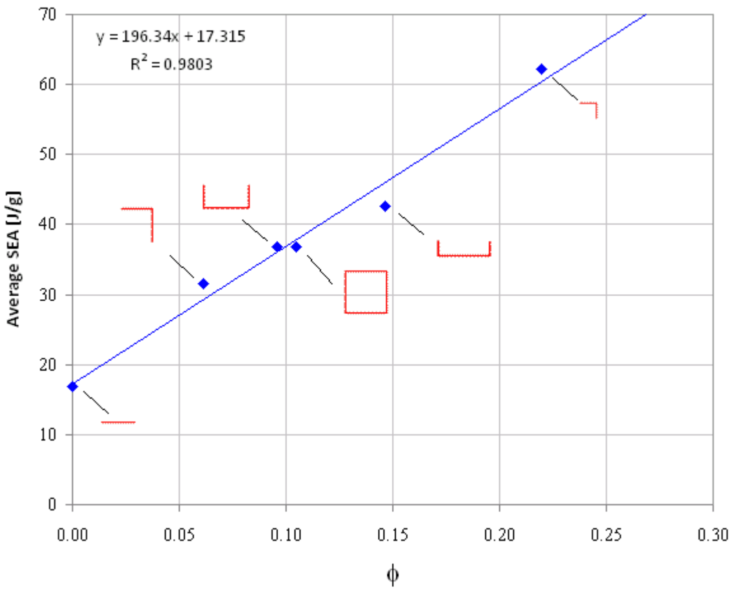


Effect of curvature

- *Plot SEA with respect to dimensionless parameter f = indicator of degree of curvature of cross section*

$$\phi = \frac{l}{S_i} = \frac{\pi \cdot r}{2 \cdot S_i} \qquad (7)$$

where l is the arc length, given by the product of the radius r and the angle $\pi/2$, and S_i is length of the cross section influenced by the corner, as defined in eq. (1).



Conclusions

- *In-situ SEA of flat segments appears to be around 16 J/g, slightly lower than the coupon-measured asymptotic 23 J/g*
- *Degree of curvature greatly influences the SEA*
  - *SEA of corner is ~60 J/g, SEA of flat is ~20 J/g*
- *The more curved the specimen, the higher the SEA*
- *SEA not material property but structure's property:*
  - *Highly geometry dependent*

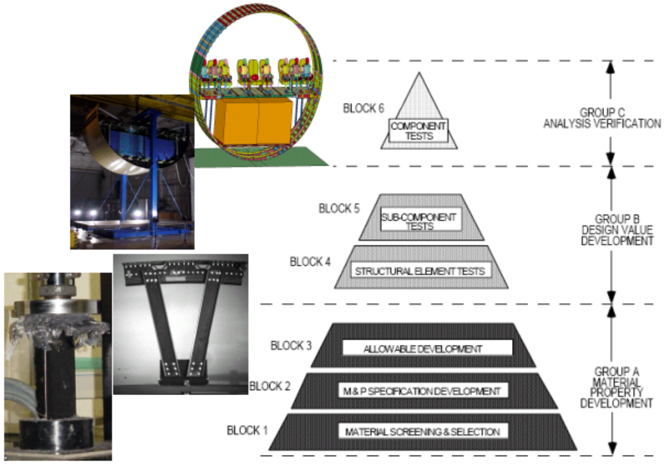
Analysis challenges

Damage in composites

- *Composites are non homogeneous (two distinct phases of fiber and matrix), hence damage can initiate and propagate in many ways*
- *Many failure mechanisms can occur (fiber breakage, delamination, cracking, etc.). Strong Implications on damage initiation and propagation. Damage growth is not self-similar.*
- *Many failure criteria have been proposed over the last 40 years*
    - ***Micromechanics approach (micromechanics)***
        - *Based on the physical properties of the constituents (i.e. fiber, resin)*
    - ***Lamina-based failure criteria (first-ply failure)***
        - *Max stress, Tsai-Wu, Tsai-Hill, etc.*
        - *Based on the single ply properties*
- *Do not account for stacking sequence effects and processing defects*

Failure initiation

- *Commercial airliners are certified by analysis supported by test evidence*
- *Analysis methods are the key to certification*
- *The Boeing Company utilizes the Building Block Approach, which is a semi-empirical approach that relies on laminate-level allowables and failure criteria*
- *Boeing Research & Technology - Structures Technology Group*
- *Advanced Analysis Team responsible for 787 Crashworthiness Certification, (group led by Dr. Mostafa Rassaian)*
- *First CFRP fuselage certified: only 1/2 section of barrel segment tested in drop tower*



Challenges in crashworthiness simulation

- *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*
  - *It cannot account for delamination damage*

MAT54 characteristics

- *LS-DYNA considered benchmark for impact and crash analysis*

- *MAT 54: Material failure modeled using Chang/Chang criterion.*
- *<u>Failure occurs if stresses exceed strengths</u>*
- *4 criteria: tensile fiber and matrix modes, compressive fiber and matrix modes*

- *<u>Failure can also occur if strains exceed maximum strains:</u>*
- *4 criteria: matrix strain, shear strain, strains for fiber tension and compression*

- *Each time step, plies of the MAT54 elements are checked and modified using "progressive damage"*
- *Once all plies have failed element is deleted*

"Crushing of composite structures: experiment and simulation" - Deleo, F., Wade, B., Feraboli, P., Rassaian, M. -<u>AIAA 50th Structures, Dynamics and Materials Conference</u>, Palm Springs, CA, May 2009, Paper No. 2009-2532-233

Example of MAT54 in LS-DYNA

- *Commercial FEA codes use material models (or material cards)*
- *These comprise material properties based on coupon-level test data*
  - *Tension/ Compression and shear: modulus, strength, strain to failure*
- *Everything else is a mix of mathematical expedients, correction factors that either cannot be measured by experiment (alpha and beta) or have no direct physical meaning (e.g., the SOFT parameter, which is a crash front softening factor) - These need to be calibrated by trial and error*

*MAT_054 (ENHANCED_COMPOSITE_DAMAGE)

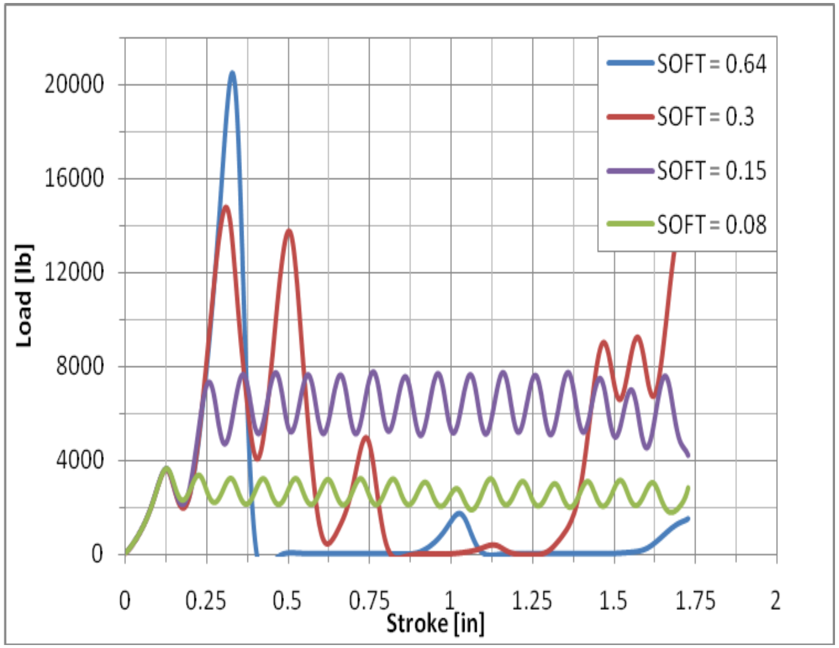
mid	**ro**	**ea**	**eb**	**(ec)**	**prba**	**(prca)**	**(prcb)**
1	1.50E-04	8.11E+06	7.89E+06	1.00E+00	0.043	0	0
gab	**gbc**	**gca**	**(kf)**	**aopt**			
6.09E+05	6.09E+05	6.09E+05	0	3			
xp	**yp**	**zp**	**a1**	**a2**	**a3**	**mangle**	
0	0	0	0	0	0	90	
v1	**v2**	**v3**	**d1**	**d2**	**d3**	**dfailm**	**dfails**
0	0	1	0	0	0	0.013	0.03
tfail	**alph**	**soft**	**fbrt**	**ycfac**	**dfailt**	**dfailc**	**efs**
1.00E-09	0.3	0.5	0.95	1.2	0.02	-0.013	0
xc	**xt**	**yc**	**yt**	**sc**	**crit**	**beta**	
1.03E+05	1.32E+05	1.40E+05	1.12E+05	1.90E+04	54	0.5	

Material properties: elastic

Material properties: strength and strain to failure

Example: crushing of square tube

- *Trial and error procedure to find the "right" SOFT parameter that matches the experiment*
- *Vary only SOFT parameter – every other property remains the same*



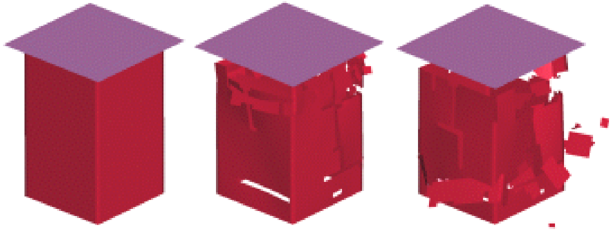


Figure 12. Example of an unstable crushing of the tubular shape with SOFT=0.64 Buckling starts after 2.446millsec at a displacement of 0.3669 inches.

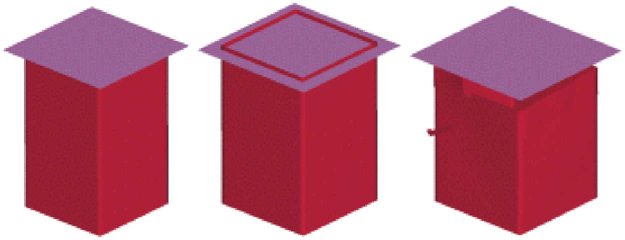


Figure 13. Example of an unstable crushing of the tubular shape with SOFT=0.3. Buckling starts after 3.728millsec at a displacement of 0.5592 inches.

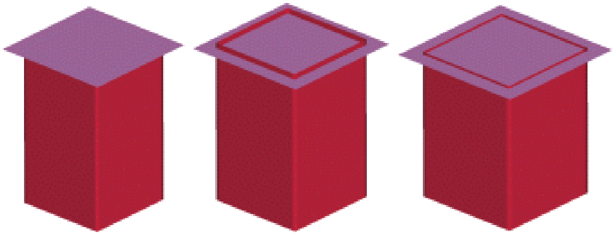


Figure 14. Example of a stable crushing of the tubular shape with SOFT=0.08. No buckling.

Trial and error: finding the "right" SOFT

- *For all geometries it is possible to find a suitable value of the SOFT parameter by trial and error to lead to stable crushing*
- *Each geometry is characterized by a specific value of SOFT that matches the experimental data, while keeping all other parameters unchanged*
- *The same input deck cannot be used to predict all geometries "as-is" to scale from a coupon test to any other geometry*

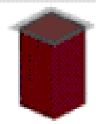
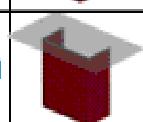
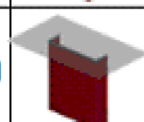
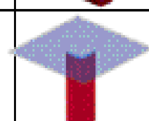
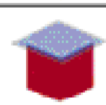
Geometry type		SEA [J/g]	SOFT Calibrated
Tube		36.9	0.085
Large C-channel		42.7	0.23
Small C-channel		36.9	0.22
Small corner		62.30	0.33
Large Corner		31.6	0.21

Table VI. Process of finding the right SOFT value for each geometry type

Geometry Type	SOFT	EA	SEA [J/g]	% change w.r.t Test	Comment
Square Tube	Exp. Data	784.60	30.77		
	0.08	488.40	30.64	-0.4%	Stable
	0.09	549.09	34.45	11.9%	Stable
	0.10	639.26	40.11	30.3%	Stable
	0.15	1123.67	70.50	129.1%	Stable
	0.30	823.83	51.69	68.0%	Unstable @ 0.003728 [s]
	0.64	317.28	19.91	-35.3%	Unstable @ 0.002446 [s]
Large C-Channel	Exp. Data	789.84	28.23	-	
	0.15	348.91	19.95	-29.3%	Stable
	0.20	454.58	25.99	-7.9%	Stable
	0.22	494.65	28.28	0.2%	Stable
	0.30	226.61	12.96	-54.1%	Unstable @ 0.003378 [s]
	0.64	219.80	12.57	-55.5%	Unstable @ 0.00233 [s]
Small C-Channel	Exp. Data	455.48	43.25	-	
	0.20	361.97	35.31	-18.4%	Stable
	0.235	440.17	42.93	-0.7%	Stable
	0.25	474.31	46.26	7.0%	Stable
	0.30	244.84	23.88	-44.8%	Unstable @ 0.005009 [s]
	0.64	105.32	9.47	-78.1%	Unstable @ 0.002912 [s]
Small Corner	Exp. Data	192.40	62.11	-	
	0.30	175.57	53.76	-13.4%	Stable
	0.32	182.26	55.81	-10.1%	Stable
	0.33	202.91	62.13	0.0%	Stable
	0.35	133.62	40.91	-34.1%	Unstable @ 0.005941 [s]
	0.40	75.51	23.12	-62.8%	Unstable @ 0.004194 [s]
	0.64	82.82	25.36	-57.0%	Unstable @ 0.002796 [s]
Large Corner	Exp. Data	504.8503	31.6	-	
	0.2	393.90	29.96	-5.2%	Stable
	0.21	420.02	31.94	1.1%	Stable
	0.22	436.99	33.23	5.2%	Stable
	0.64	82.82	6.54	-79.3%	Unstable @ 0.00233 [s]

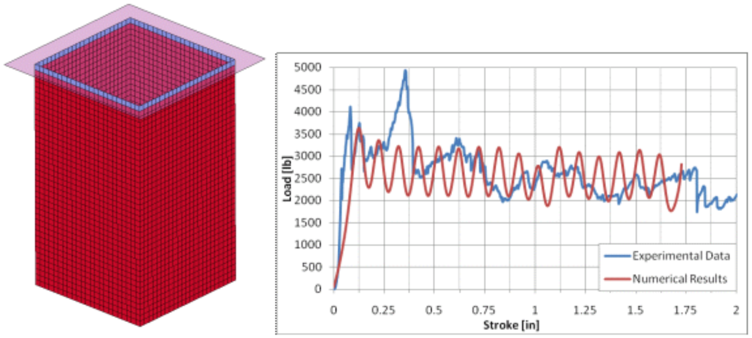


Figure 16. Model geometry and optimal Load-Displacement curve for the square tube specimen

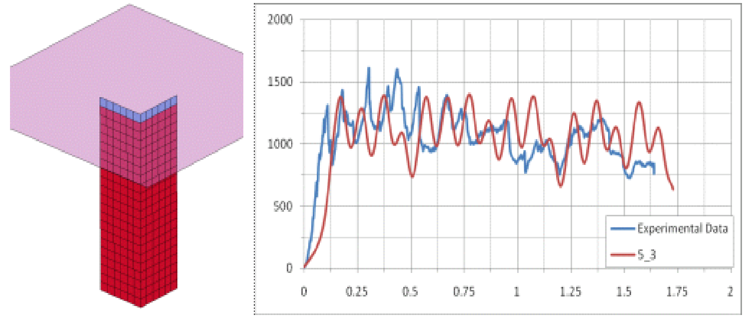


Figure 19. Model geometry and optimal Load-Displacement curve for the small corner specimen

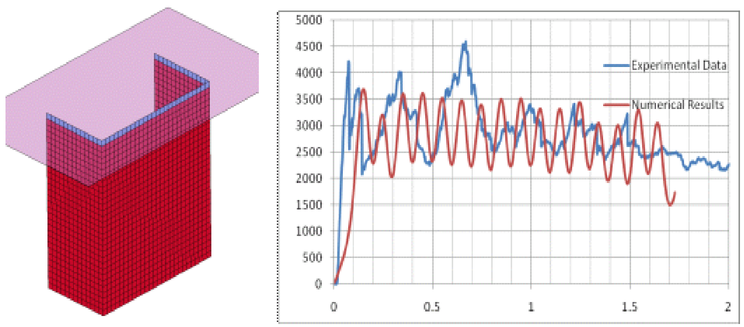


Figure 17. Model geometry and optimal Load-Displacement curve for the large C-Channel specimen.

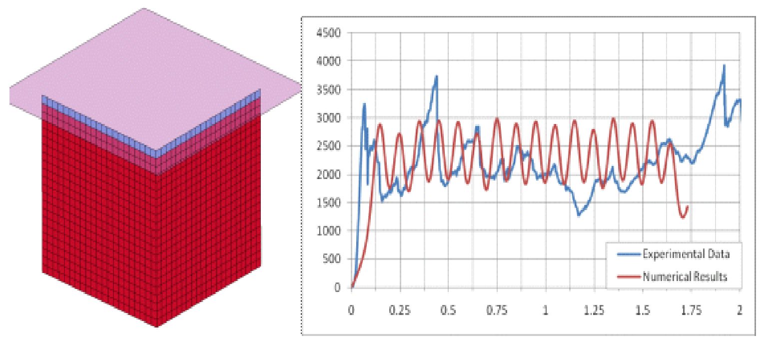


Figure 20. Model geometry and optimal Load-Displacement curve for the large Corner specimen

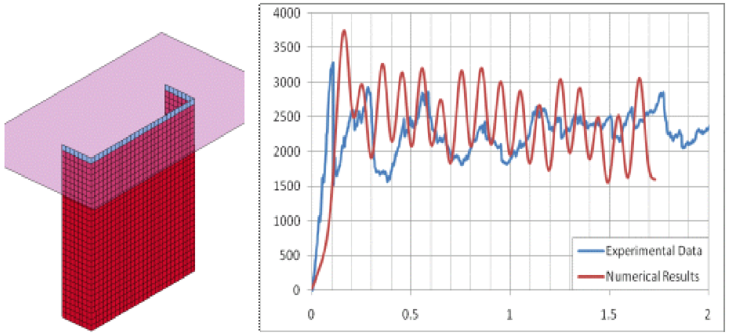
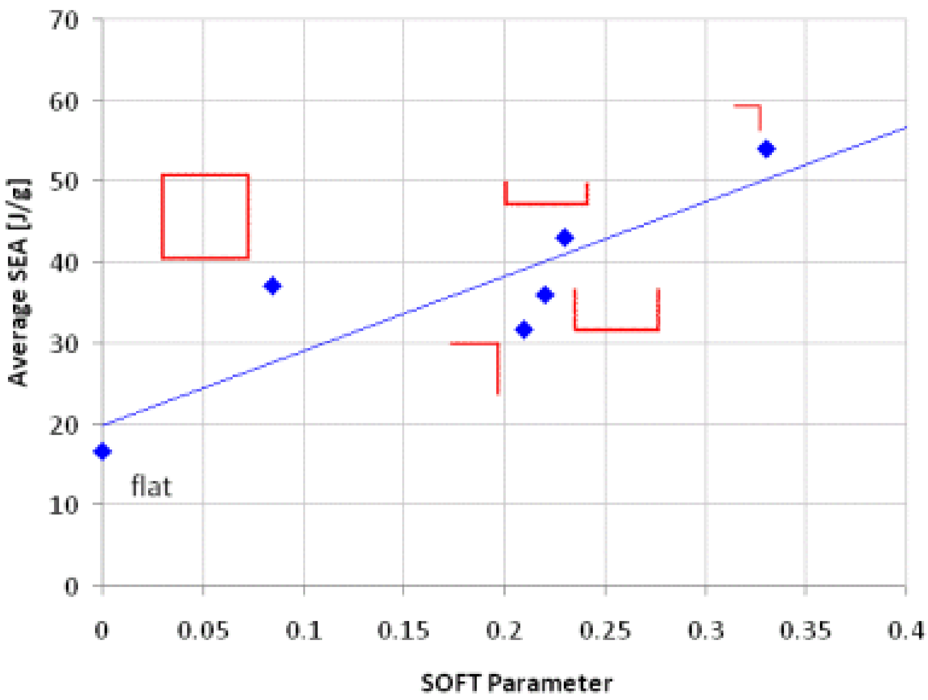


Figure 18. Model geometry and optimal Load-Displacement curve for the small C-Channel specimen.

Observations

- *However, there appears to be a trend between SOFT and SEA*
- *There appears to be a linear correlation between stability, curvature, delamination suppression and and SOFT parameter*



Conclusions

- *Current crash simulation tools are not physics-based and truly predictive*
- *Experimentally it is a challenging task*
- *The need for standards is evident but not straightforward*
- *Modeling strategies require the use of control parameters that cannot be measured experimentally, need to be calibrated by trial and error, and may have no physical significance*
- *However, use of the Building Block Approach to certify by analysis is possible and successful*
- *The need to produce numerical guidelines is very important to prevent users from running in gross mistakes associated with the selection of these parameters.*