



# A Single-Stringer Compression Specimen for the Assessment of the Damage Tolerance of Postbuckled Panels

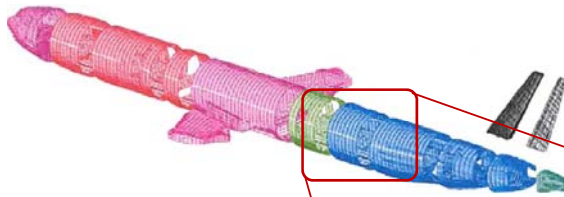
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## Next-Generation All Composite Airframe



Airframes consist of thin skins that are stiffened longitudinally by stringers and circumferentially by frames.

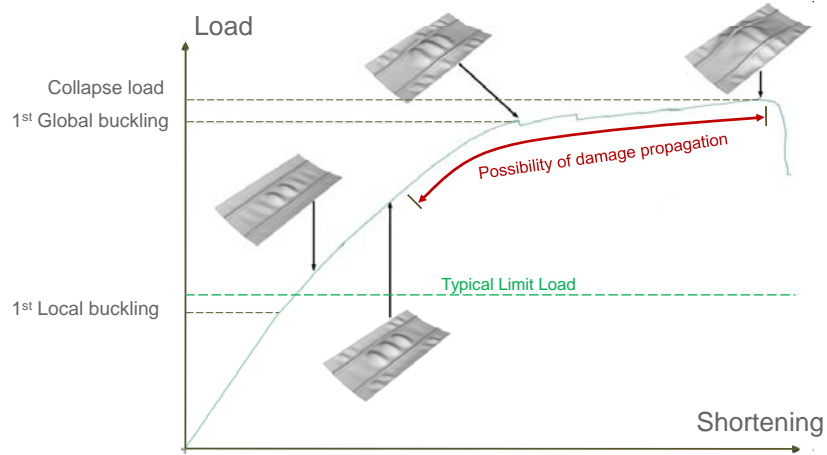
The design of thin structures subjected to compression is challenging, especially for composites.



Composite fuselage

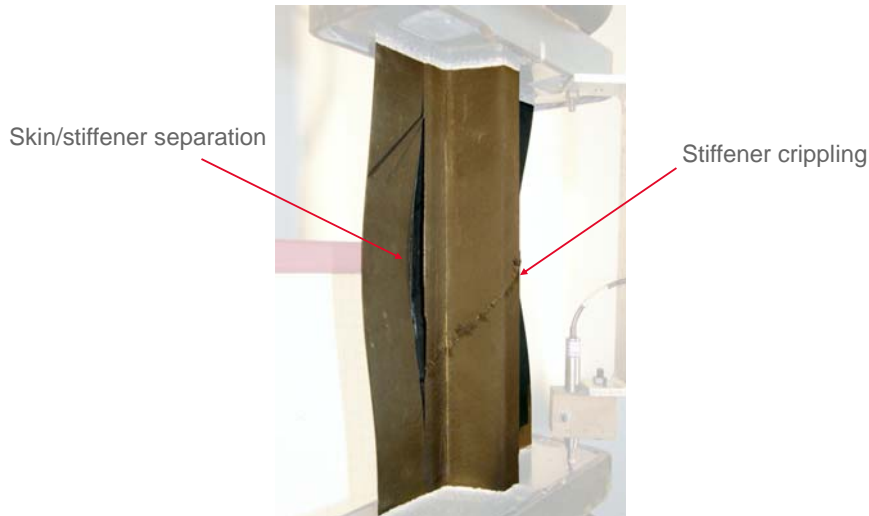
## Postbuckling Response & Collapse of Stiffened Panels

Typical stages in a panel's postbuckling response



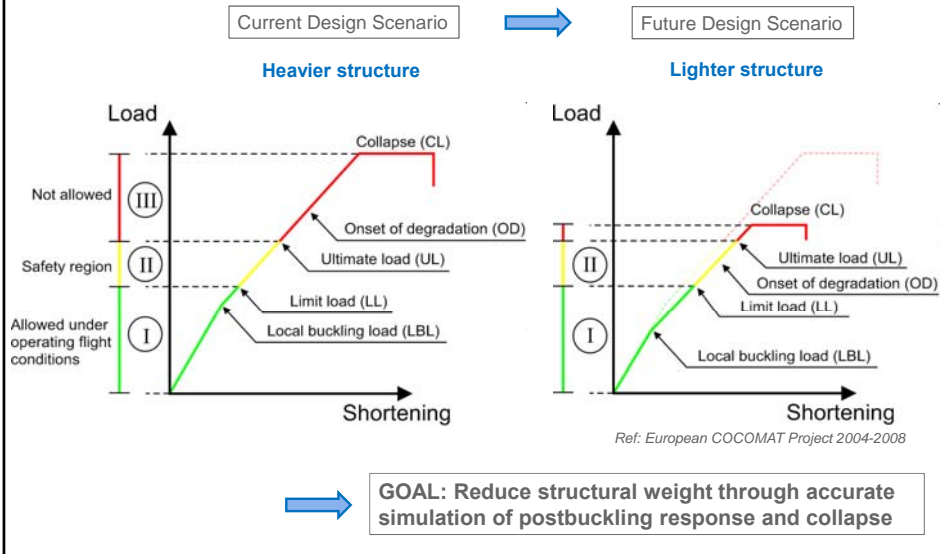
## Skin/Stiffener Failure Modes

Typical damage modes that can result from postbuckling deformations

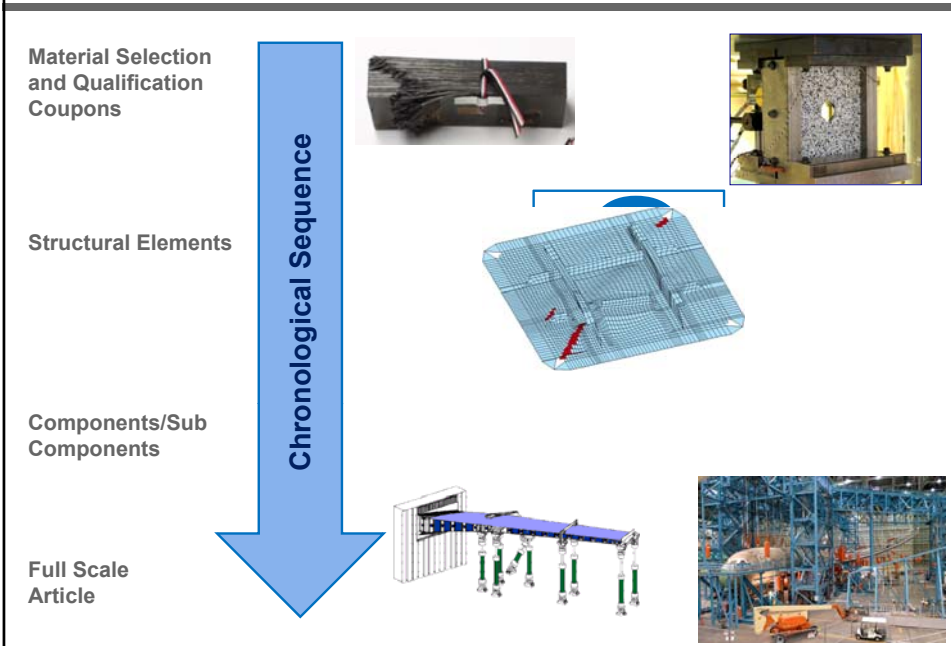


## Expanding the Design Envelope

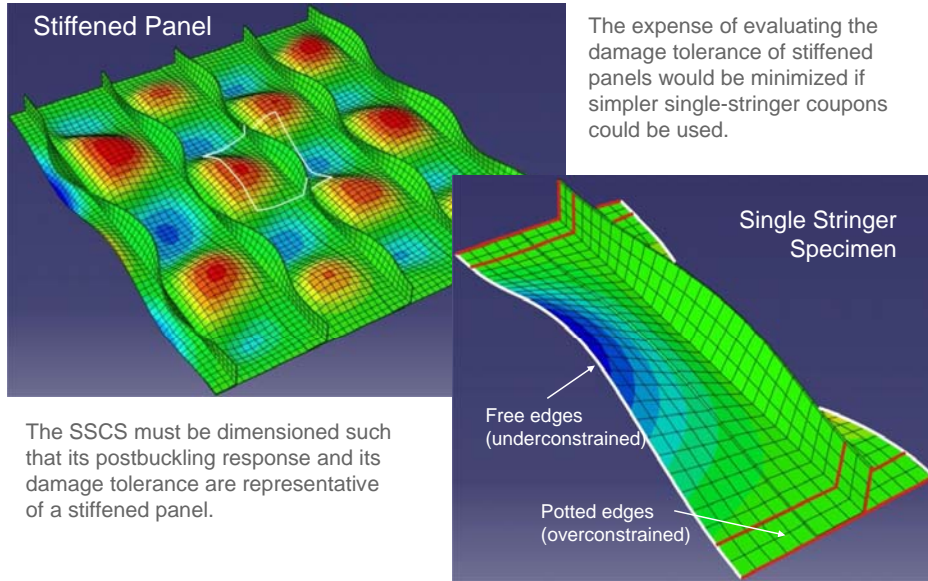
For structural efficiency, the strength reserves within the postbuckling range must be exploited.



## Building Block Approach: Testing for Compression



## Development of a Single-Stringer Compression Specimen (SSCS)



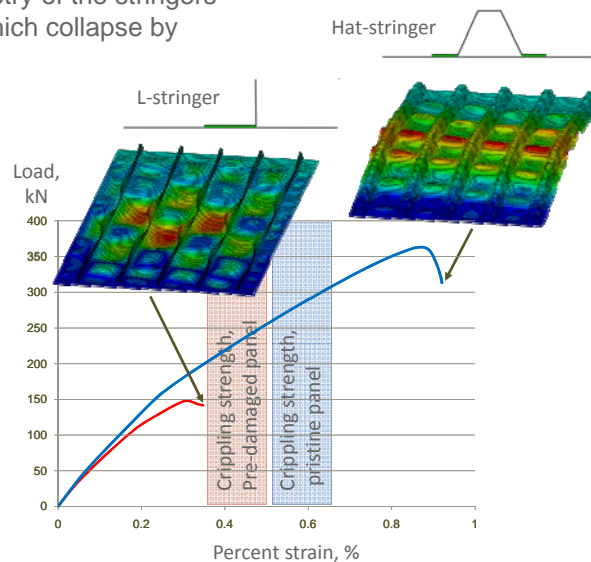
## Design of Stiffened Panels for High Compression Loads

The cross-sectional geometry of the stringers determines the strain at which collapse by global buckling occurs.

Hat-shape stringers allow much higher strain levels than L-shape stringers.

The higher operating strains of hat-stiffened panels may induce crippling failure before collapse.

Panels with pre-existing damage may fail at strain levels below 0.5%.



## SSCS Development Plan and Objectives

### Develop parametric models of panel and SSCS

### Design SSCS that is representative of stiffened panel

- Minimize critical response difference between panel and SSCS using criteria: deformation and stress distributions.

### Manufacture and Test SSCS

- Observe response, damage propagation
- Introduce a defect into the flange by using a Teflon strip and investigate residual strength

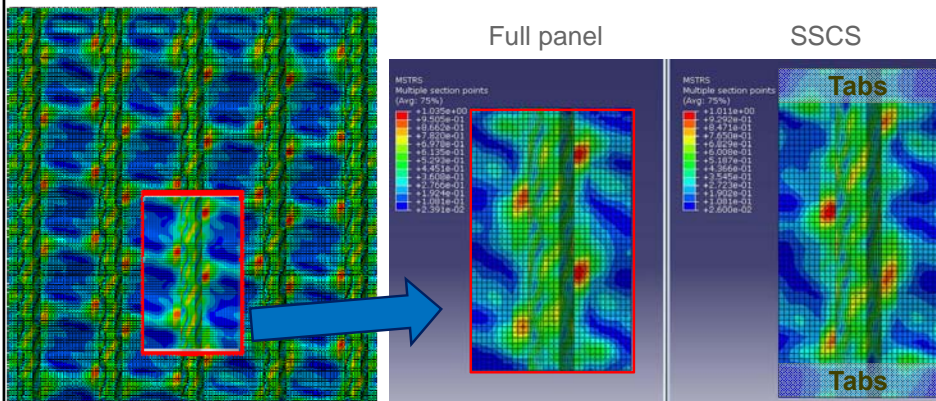
### Analyze SSCS with damage models

- Investigate postbuckling; delamination; intralaminar failures.

## Development of a Single-Stringer Compression Specimen (SSCS)

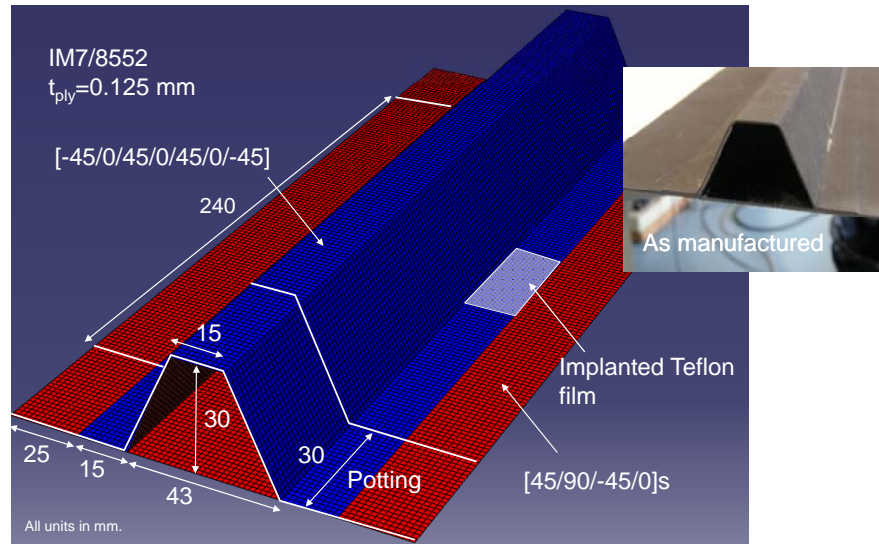
Postbuckling response of 5-stringer panel at 0.5% strain

Strength criterion evaluated on 5-stringer panel and SSCS indicates similarity of crippling load (Maximum Stress criterion)



## Single-Stringer Compression Specimen (SSCS)

Manufacturing process: co-curing



## Development of a Single-Stringer Compression Specimen (SSCS)

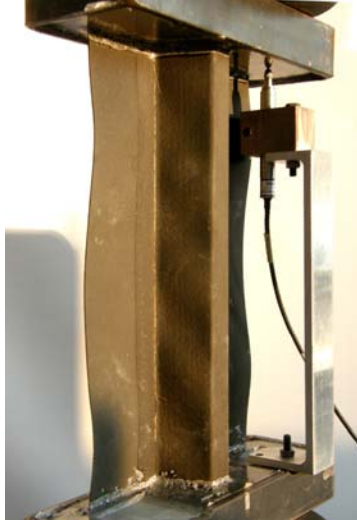
### Manufacturing of end-tabs

Composition: Epoxy + Aluminum powder

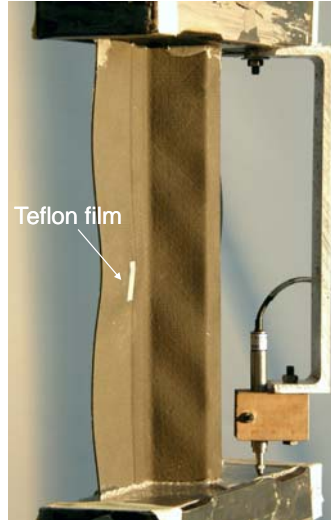


## Testing of SSCS

SSCS immediately before failure (approx. 4% global strain)

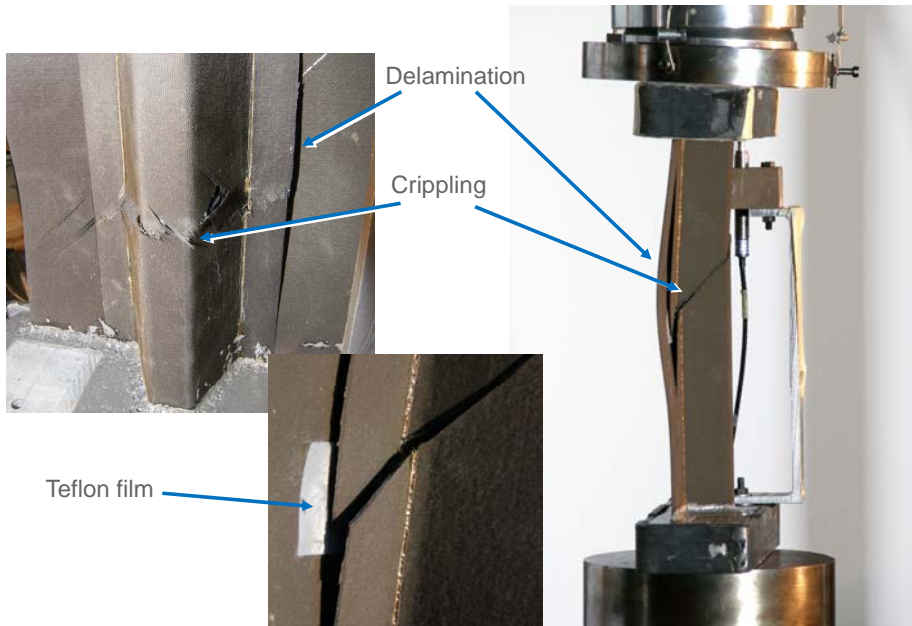


Nominally pristine specimen



With embedded delamination

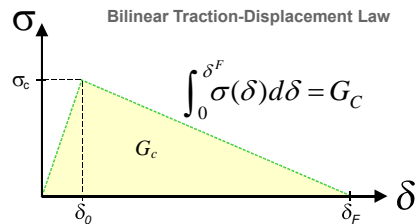
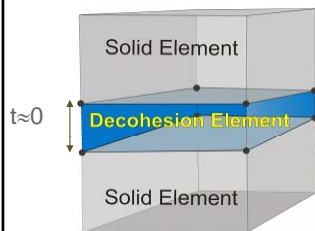
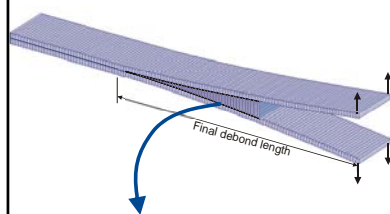
## SSCS Modes of Failure: Delamination and Crippling



## Analysis Methodology

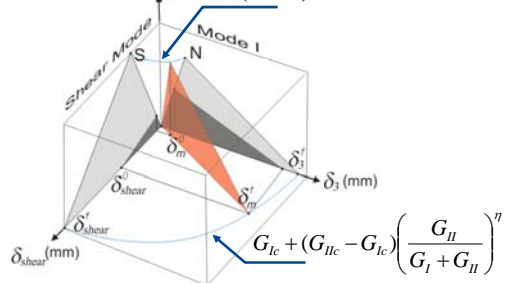
- Analysis was performed in Abaqus/Standard
- For efficiency, shell elements were used
- All damage modes are captured with two user-written subroutines:
  - ✓ **Delamination (skin/stringer separation)**  
→ Cohesive elements (UEL)
  - ✓ **Ply Damage (Crippling)**  
→ Continuum Damage Model (UMAT)

## Cohesive Elements for Structural Analysis



Mixed-Mode Fracture

$$\left( \frac{\langle \sigma_z \rangle_+}{T} \right)^2 + \left( \frac{\tau_{xz}}{S} \right)^2 + \left( \frac{\tau_{yz}}{S} \right)^2 = 1$$

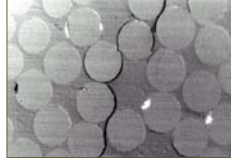


Ref: Dávila, et al., Proc. of the AHS, Structures Specialists Meeting, 2001.

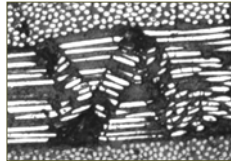
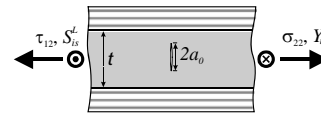
# Advanced Failure Criteria for Laminated Composites

## LaRC02/04 Criteria

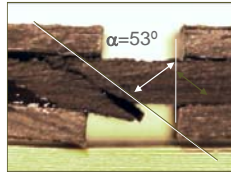
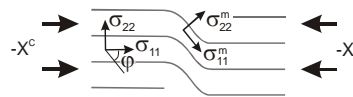
- In-situ matrix strength prediction
- Advanced fiber kinking criterion
- Prediction of angle of fracture



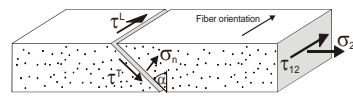
Matrix Tension & Shear



Fiber Compression



Matrix Compression and Shear



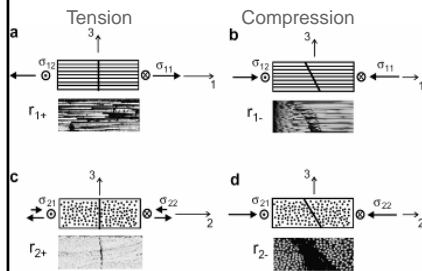
References:

- LaRC02: Dávila et al., JCM, 2005
- LaRC04: Pinho et al., NASA TM, 2005

# Progressive Damage Analysis

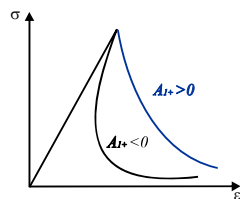
(Maimí/Camanho 2007)

## Damage Modes:



## Damage Evolution:

Thermodynamically-consistent material degradation takes into account energy release rate for each mode and element size.



## Representation of damage:

$$\mathbf{H} = \frac{\partial^2 G}{\partial \sigma^2} = \begin{bmatrix} 1 & -\nu_{12} & 0 \\ (1-d_1)E_1 & E_1 & 0 \\ -\nu_{12} & 1 & 0 \\ E_1 & (1-d_2)E_2 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & (1-d_6)G_{12} \end{bmatrix}$$

$$d_i = 1 - \frac{1}{f_i} \exp(-A_i(1-f_i))$$

$f_i$ : LaRC04 failure criteria as activation functions

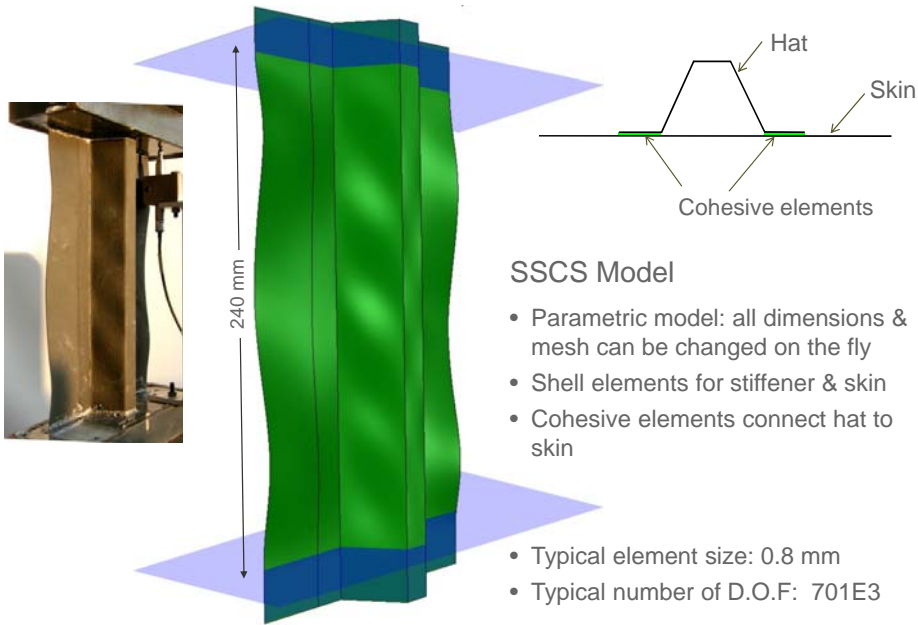
$$i = F^+; F^-; M^{y+}; M^{y-}; M^s$$

Bazant CBT: 
$$A_i = \frac{2l^* X_i^2}{2E_i G_{ci} - l^* X_i^2}$$

Critical (maximum) finite element size: 
$$l^* \leq \frac{2E_i G_{ci}}{X_i^2}$$

Ref: Maimi et al., Mechanics of Materials, 2007

## Analysis of SSCS

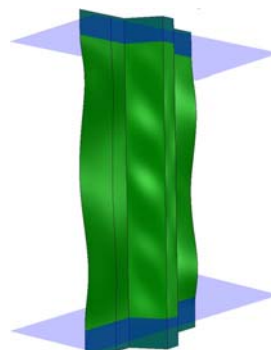


**SSCS Model**

- Parametric model: all dimensions & mesh can be changed on the fly
- Shell elements for stiffener & skin
- Cohesive elements connect hat to skin

- Typical element size: 0.8 mm
- Typical number of D.O.F: 701E3

## Material Properties – IM7-8552



**Ply Properties** [Ref: Camanho et al., CS&T, 2007]

Engineering Moduli (MPa)

$E_{11}$	$E_{22}$	$G_{12}$	$\nu_{12}$	$\alpha_1$	$\alpha_2$
150E3	9.08E3	5.29E3	0.32	-5.5E-6	26.8E-6

Ply Strengths (MPa)

XT	XC	YT	YC	SL
2323.	1200	62.3	199.8	92.3

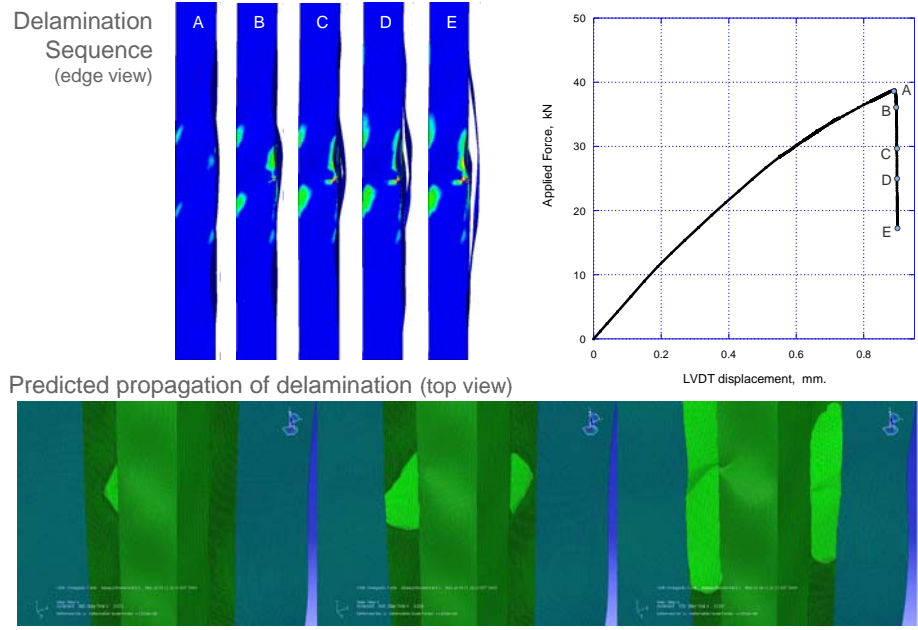
Ply Fracture Toughnesses (N/mm)

GF(+)	GF(-)	GMI	GMI
81.5	106.3	0.277	0.788

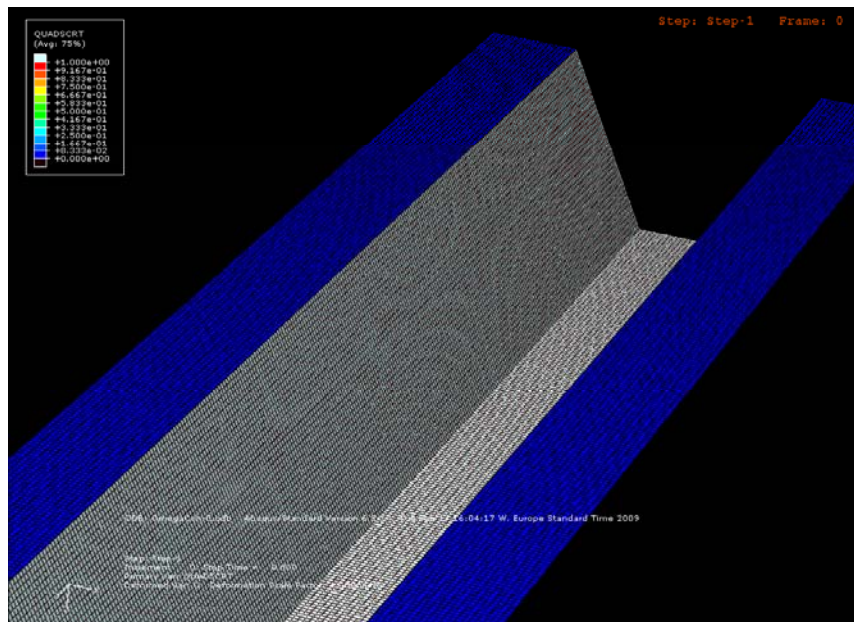
**Interlaminar Properties**

$G_{Ic}$ (N/mm)	$G_{IIc}$ (N/mm)	$\sigma_{zz}$ (MPa)	$\sigma_{xz}$ (MPa)	B-K
0.277	0.788	50.	100	1.6

## Analysis of SSCS – Nominally Pristine Specimen

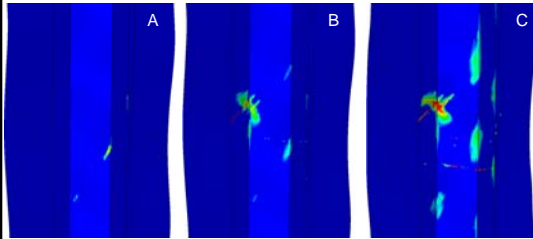


## Delamination Propagation under Hat Stiffener

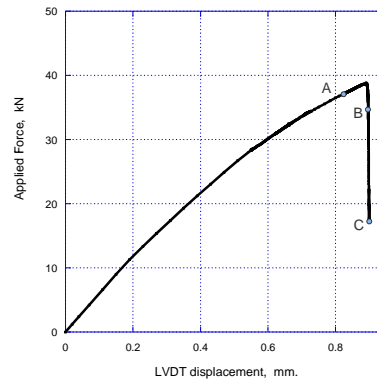
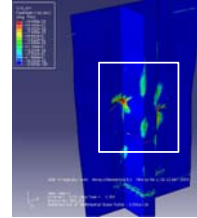
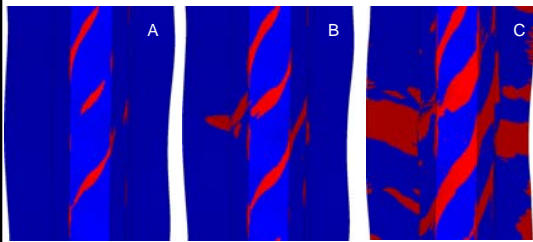


## Analysis of SSCS – Nominally Pristine Specimen

Fiber Damage

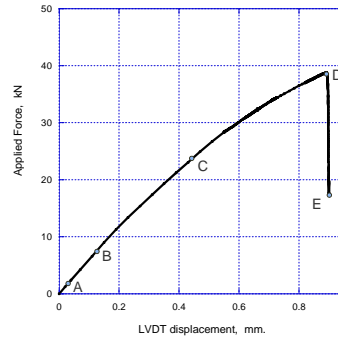
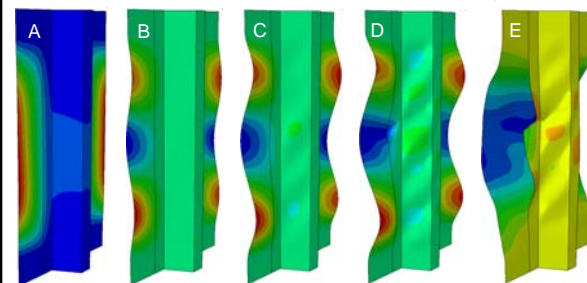


Matrix Damage



## Analysis of SSCS – Nominally Pristine Specimen

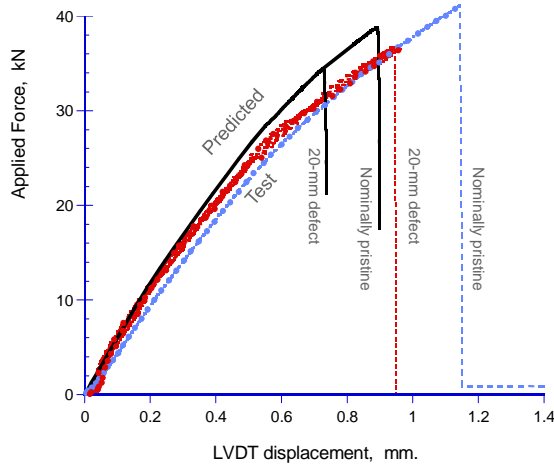
Out-of-plane response



Linear deformation  
 First buckling  
 Initiation of matrix damage  
 Initiation of delamination  
 Collapse

## Test/Analysis Correlation

Load-deflection results for analyses and tests with and without embedded delamination



Improving the Predictions

1.  $E_{11}=150$  MPa?
2. Effect of initial imperfections?
3. Toughness of skin/stiffener interface?
4. Residual adhesion of Teflon?
5. Boundary conditions?

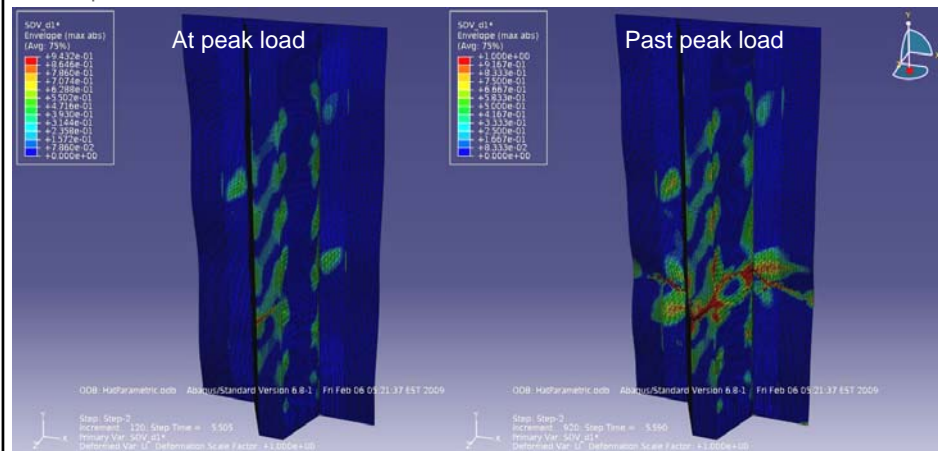
## Achieving Solution Convergence

Damage prevents convergence in Quasi-static analyses

- Loss of Ellipticity/No Quasi-Static equilibrium state exists.

Solution past point of convergence difficulties is necessary:

- To ensure highest peak load has been realized & obtain same damage state as in test.
- Convergence of solution deep into collapse was obtained by combining Q.S. & dynamic procedures.



## Summary

- SSCS were designed to represent the postbuckling response and damage tolerance of much larger multi-stiffener panels.
- Pre-existing delamination induced with a 20-mm-long Teflon insert resulted in a 0-15% reduction in collapse load.
- Parametric FEM models of SSCS were developed in Abaqus. All damage modes are represented using user-written LaRC damage model and cohesive elements.
- The propagation of fracture is unstable and static equilibrium solutions cannot be obtained. A combination of quasi-static and implicit dynamic procedures were used to successfully predict the collapse load of the structure as well as solutions representing the complete fracture of the component.

## Ongoing Model Enhancements

1. Two or more postbuckling deformation modes were observed for the skin:
  - ➔ initial imperfections will be applied to determine if all observed modes can be reproduced by the model.
2. The predicted collapse loads are 10-20% lower than the experiment:
  - ➔ the  $G_c$  obtained from a 0/0 DCB has been shown in the literature to be about 4X lower than the  $G_c$  of skin/stringer interfaces.
3. The experimental load-deflection response displays more nonlinearity than the model.
  - ➔ add nonlinear effect of compression on the Modulus  $E_{11}$