Damage simulation in composite materials:

why it matters and what is happening currently at NASA in this area

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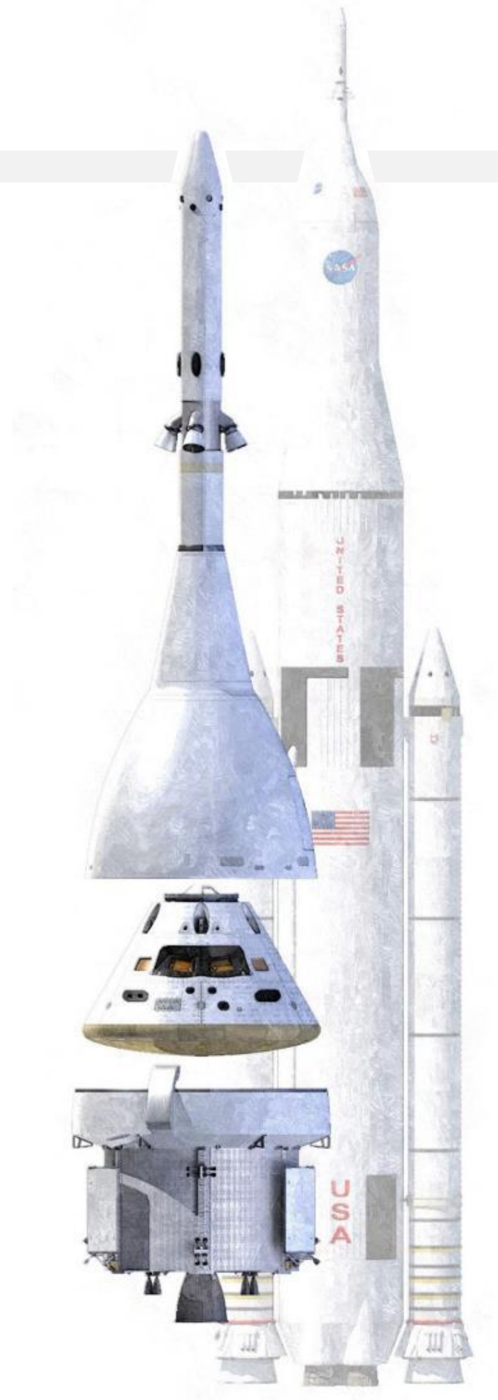
[2]NASA Langley Research Center (National Institute of Aerospace)
[3]Johnson Space Center (Jacobs)
[4]NASA Langley Research Center

Use of lightweight composite materials in space and aircraft structure designs is often challenging due to high costs associated with structural certification. Of primary concern in the use of composite structures is durability and damage tolerance. This concern is due to the inherent susceptibility of composite materials to both fabrication and service induced flaws. Due to a lack of general industry accepted analysis tools applicable to composites damage simulation, a certification procedure relies almost entirely on testing. It is this reliance on testing, especially compared to structures comprised of legacy metallic materials where damage simulation tools are available, that can drive costs for using composite materials in aerospace structures.

The observation that use of composites can be expensive due to testing requirements is not new and as such, research on analysis tools for simulating damage in composite structures has been occurring for several decades. A convenient approach many researchers/model-developers in this area have taken is to select a specific problem relevant to aerospace structural certification and develop a model that is accurate within that scope. Some examples are open hole tension tests, compression after impact tests, low-velocity impact, damage tolerance of an embedded flaw, and fatigue crack growth to name a few. Based on the premise that running analyses is cheaper than running tests, one motivation that many researchers in this area have is that if generally applicable and reliable damage simulation tools were available the dependence on certification testing could be lessened thereby reducing overall design cost. It is generally accepted that simulation tools if applied in this manner would still need to be thoroughly validated and that composite testing will never be completely replaced by analysis.

Research and development is currently occurring at NASA to create numerical damage simulation tools applicable to damage in composites. The Advanced Composites Project (ACP) at NASA Langley has supported the development of composites damage simulation tools in a consortium of aerospace companies with a goal of reducing the certification time of a commercial aircraft by 30%. And while the scope of ACP does not include spacecraft, much of the methodology and simulation capabilities can apply to spacecraft certification in the Space Launch System and Orion programs as well.

Some specific applications of composite damage simulation models in a certification program are (1) evaluation of damage during service when maintenance may be difficult or impossible, (2) a tool for early design iterations, (3) gaining insight into a particular damage process and applying this insight towards a test coupon or structural design, and (4) analysis of damage scenarios that are difficult or impossible to recreate in a test. As analysis capabilities improve, these applications and more will become realized resulting in a reduction in cost for use of composites in aerospace vehicles. NASA is engaged in this process from both research and application perspectives. In addition to the background information discussed previously, this presentation covers a look at recent research at NASA in this area and some current/potential applications in the Orion program.



Damage simulation in composite materials: Why it matters and what is happening currently at NASA in this area

August 2017

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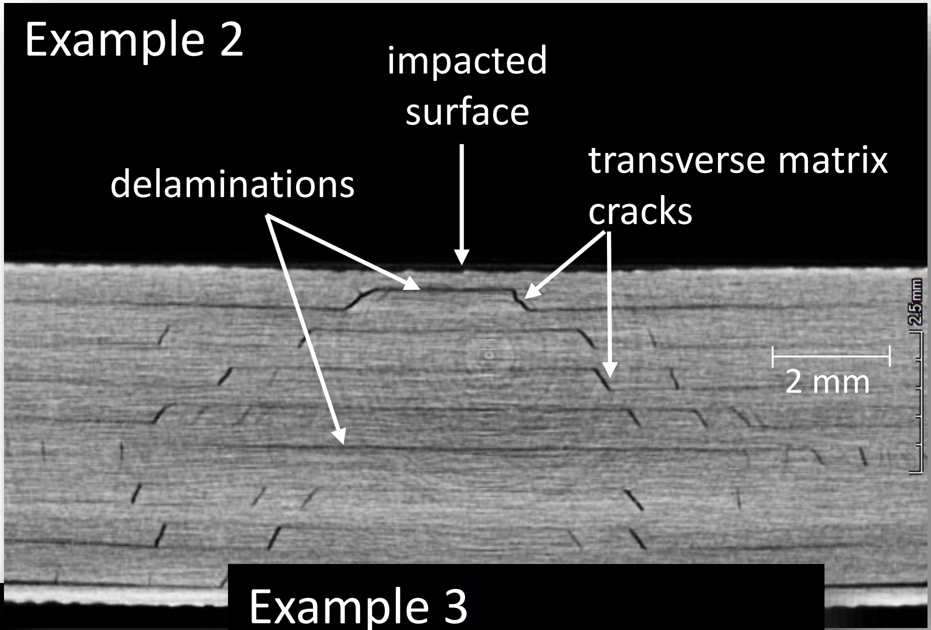
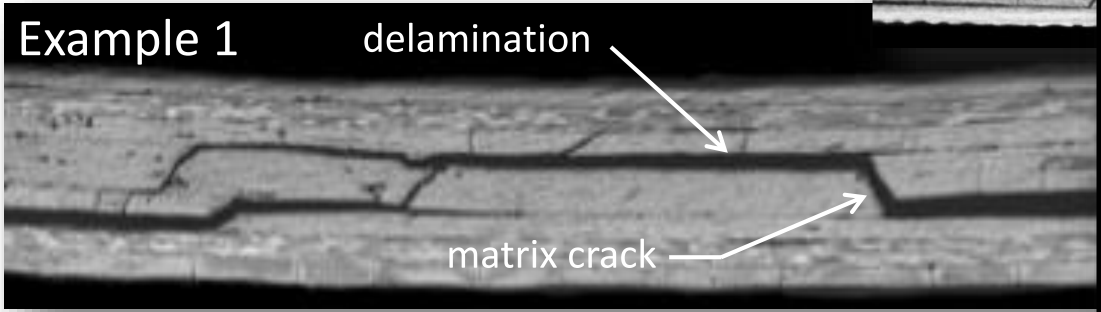
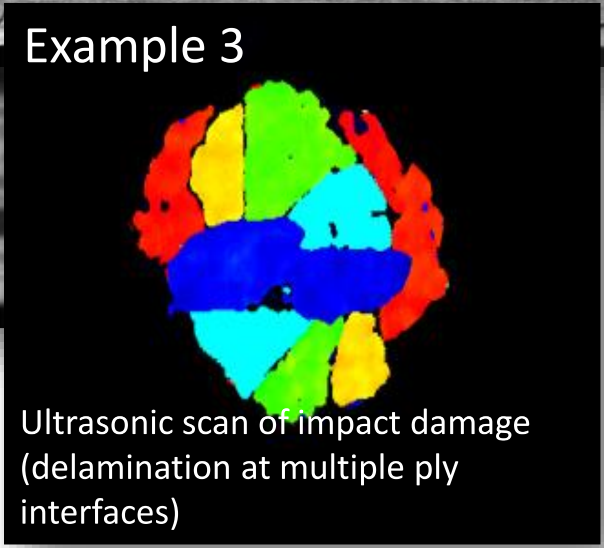
Background

- Composites are susceptible to manufacturing flaws and damage from transverse loads

- Damage may not be visible externally but still cause a reduction in strength



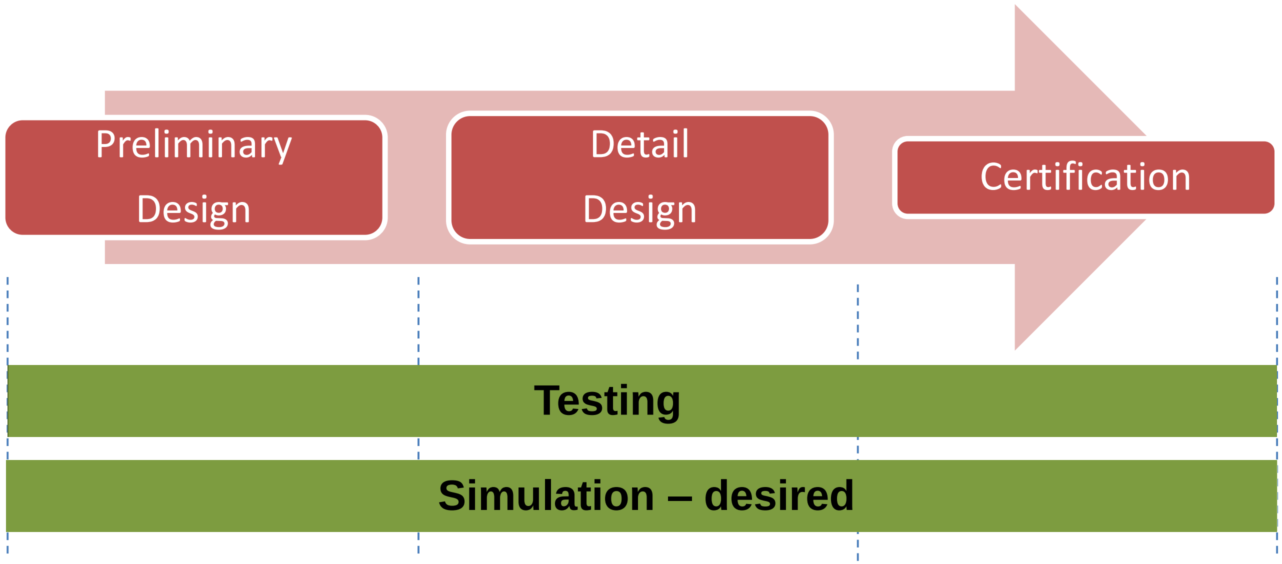




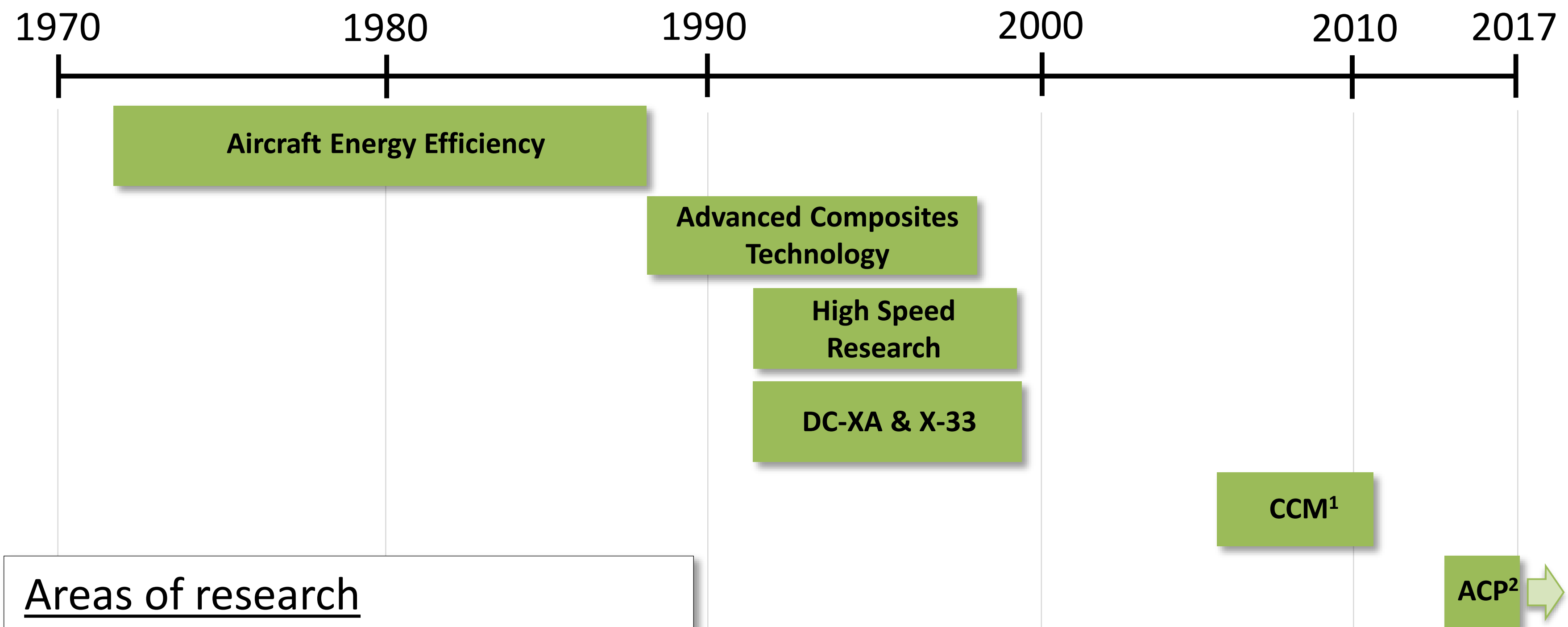
Background

- Design and certification process for composite aerospace structures:
  - Heavily reliant on tests
  - Expensive & time consuming
  - Damage simulation tools may reduce the need for some testing
    - manufacturing flaw
    - compression after impact
    - worst case credible damage
    - damage initiation

damage tolerance (manufacturing flaw, compression after impact, worst case credible damage)



What has NASA done in the past?



Areas of research

- Composite material advances
- Non-destructive evaluation
- Fabrication technology
- **Numerical simulation**

[1]Composite Crew Module
[2]Advanced Composites Project

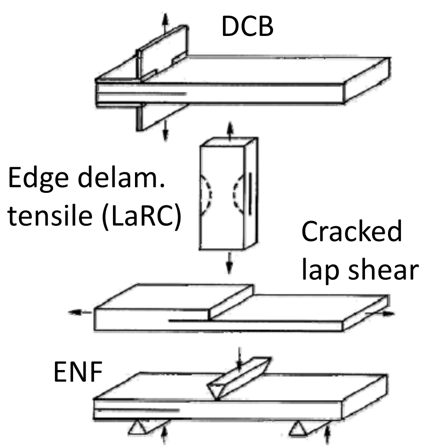
Source: Tenney, D.R., Davis, J.G., Pipes, R.B, Johnston, N. 2009. NASA composite materials development: lessons learned and future challenges. NASA Report LF99-9370.

What has NASA done in the past?

1970s	1980s	1990s	2000 - present
Work to improve material toughness Hand layup fabrication First composite aircraft structures:	Damage tolerant designs Toughened materials Advanced tape placement machines Composite interlaminar fracture tests:	Automatic fiber placement machines Textile evaluations **Structural analysis and design methods** Stitched composites Cost efficient primary structures:	Primary aircraft structures: Advanced fabrication capabilities: **Advanced numerical simulations:**

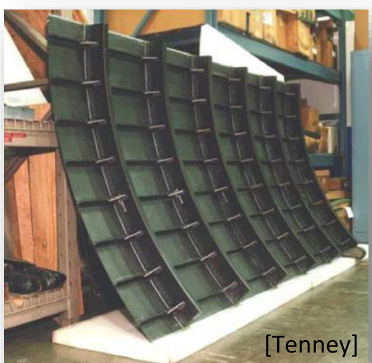
1970s:

1980s:

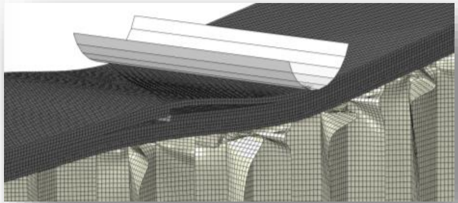


[Tenney]

1990s:



2000 - present:



All Nippon Airways Boeing 787-8 (JA801A) at Okayama Airport. October 2011.

What is NASA doing now?

- Advanced Composites Project (LaRC, 2015-2019)
- Tool development (selected)
  (1) Adaptive Fidelity Shell, 2014-present (M. McElroy)
    - Advanced Composites Project
    - Space Act Agreement: Swerea SICOMP
    - Space Act Agreement: Rice University
    - Space Act Agreement: North Carolina State University

  (2) Extended interface element, 2013-present (N. de Carvalho)
    - Advanced Composites Project
    - Advanced Composites Consortium
- Application
  (1) Orion back shell (A. Estes)

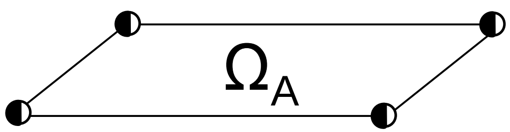
  (2) Orion heatshield (NESC)

Adaptive Fidelity Shell Model

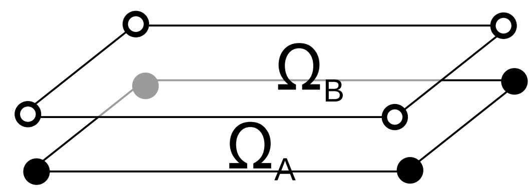
Model developer: Mack McElroy (JSC)

Element formulation summary: Floating Node Method* + VCCT

(1) Undamaged Element



(2) Split Element



$$K^{(e)} = \begin{bmatrix} \left[K^{(e)}_{\Omega_A}\right]_{24x24} & [0] \\ [0] & [0]_{24x24} \end{bmatrix}_{48x48}$$

$$K^{(e)} = \begin{bmatrix} \left[K^{(e)}_{\Omega_A}\right]_{24x24} & [0] \\ [0] & \left[K^{(e)}_{\Omega_B}\right]_{24x24} \end{bmatrix}_{48x48}$$

Key features:

- Discrete, mesh-independent, representation of delaminations and transverse matrix cracks
- Low(er) mesh fidelity
- High computational efficiency
- User friendly

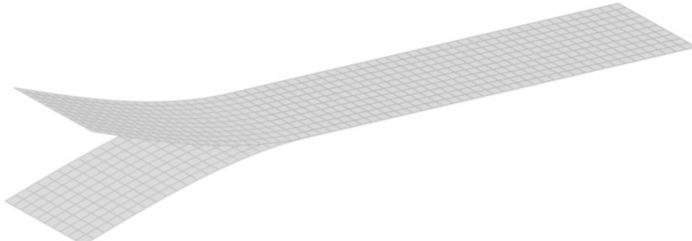
} Cost effective analysis tool

○ = floating node (FN)
● = real node (RN)
◐ = RN and unused FN

*Chen, B.Y., Pinho, S.T., De Carvalho N.V., Baiz, P.M., Tay, T.E. 2014. “A Floating Node Method for the Modelling of Discontinuities in Composites,” *Engineering Fracture Mechanics* 127:104-134.

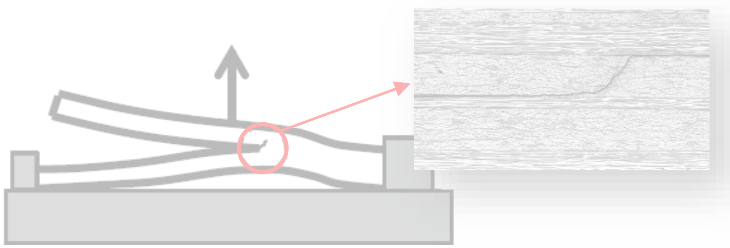
Adaptive Fidelity Shell Model

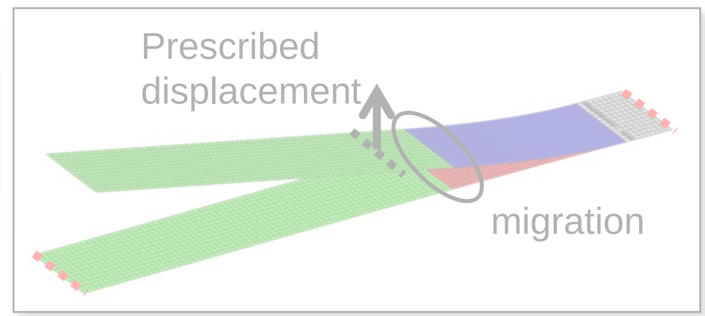
Example 1: Double cantilever beam



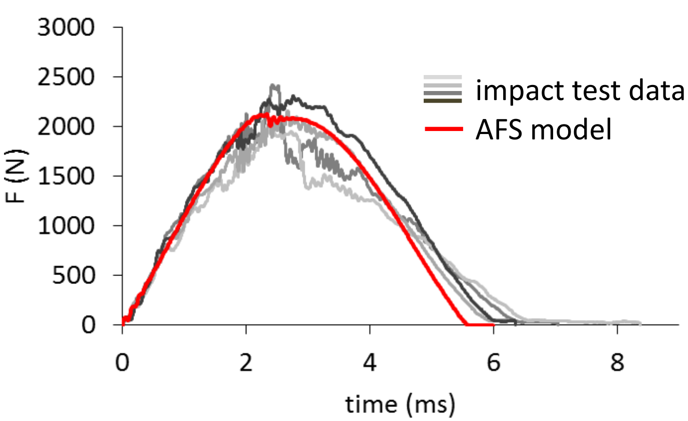
	Mesh size	Runtime
AFS	1.0 mm	37 minutes
	2.5 mm	6 minutes
	5.0 mm	1.5 minutes
High fidelity [Krueger]	**1.0 mm**	**31 hours**

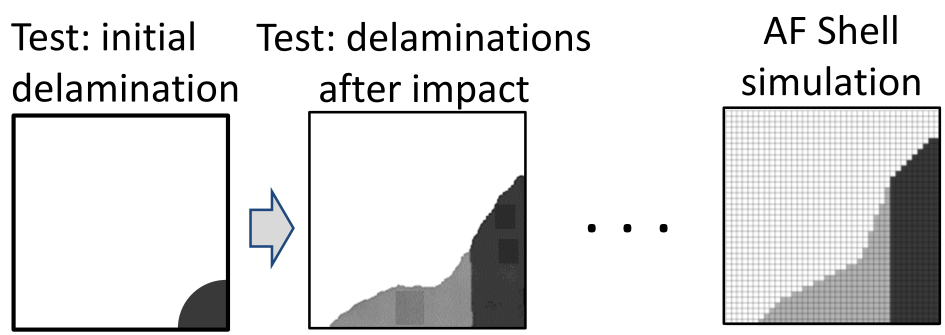
Example 2: Delamination Migration





Example 3: Low-velocity impact (progressive damage)



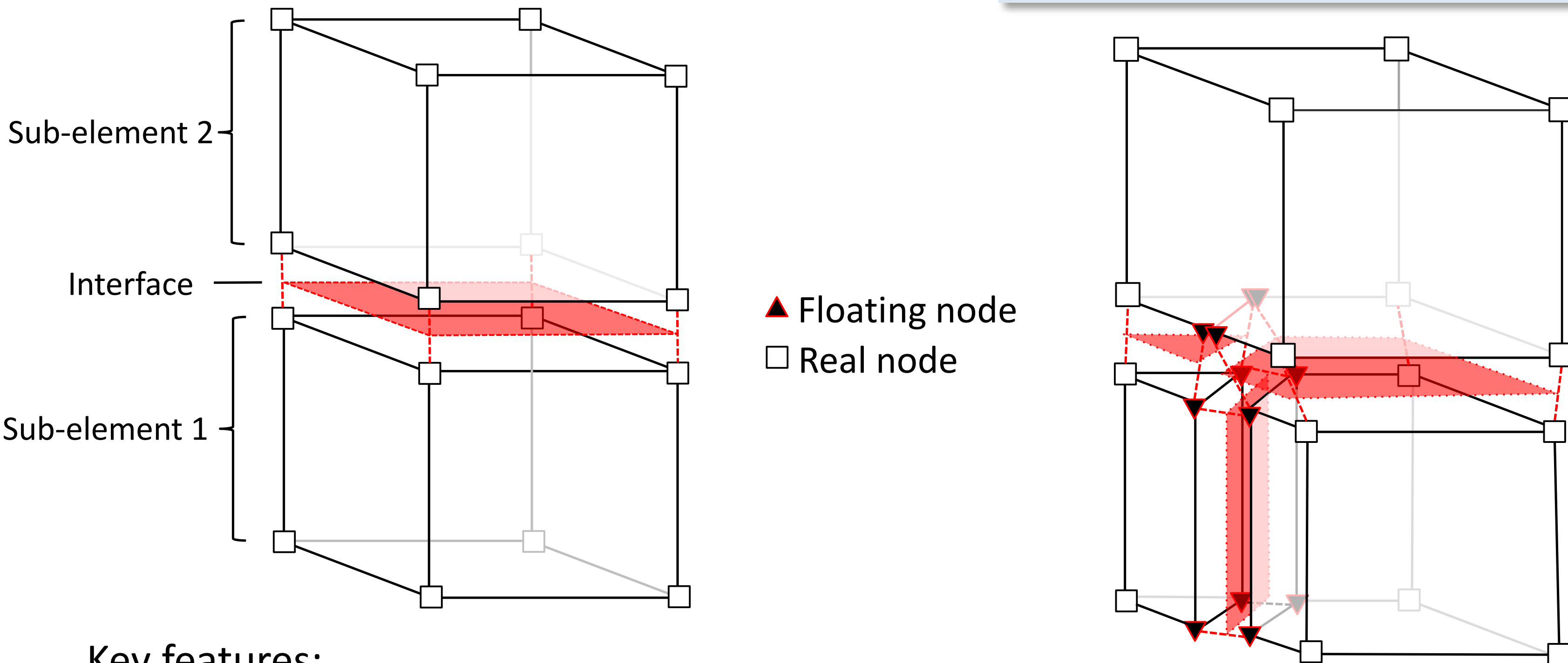


Extended Interface Element

Model developer: Nelson de Carvalho (LaRC, NIA)

One extended interface element

Illustration of matrix crack/interface kinematics



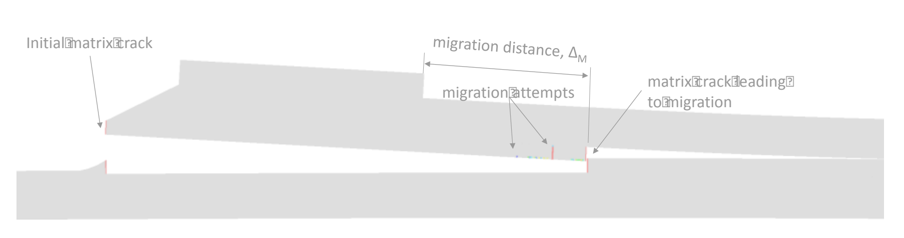
Key features:

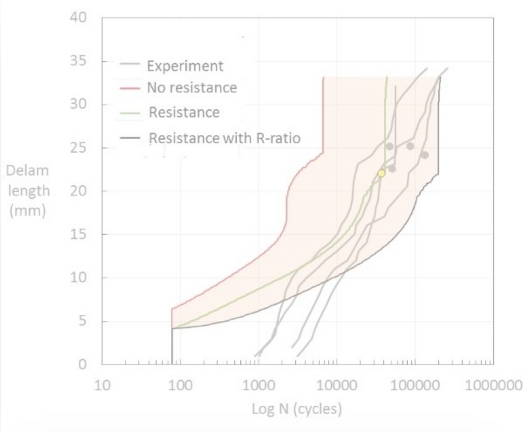
- Discrete, mesh-independent, representation of crack tip kinematics (matrix cracks/delaminations/interaction)
- Discrete crack approach compatible with both CZ/VCCT (quasi-static/fatigue)
- Unlimited number of cracks (crack density not set ‘a priori’)

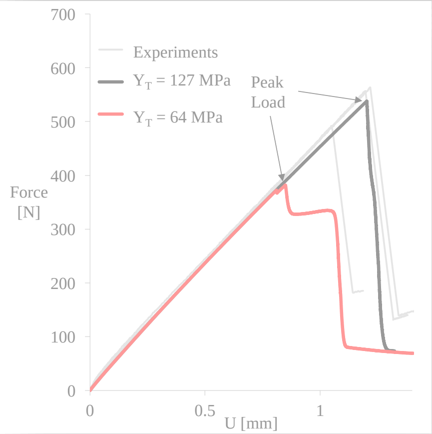
Extended Interface Element

Example 1: Delamination/matrix crack interaction

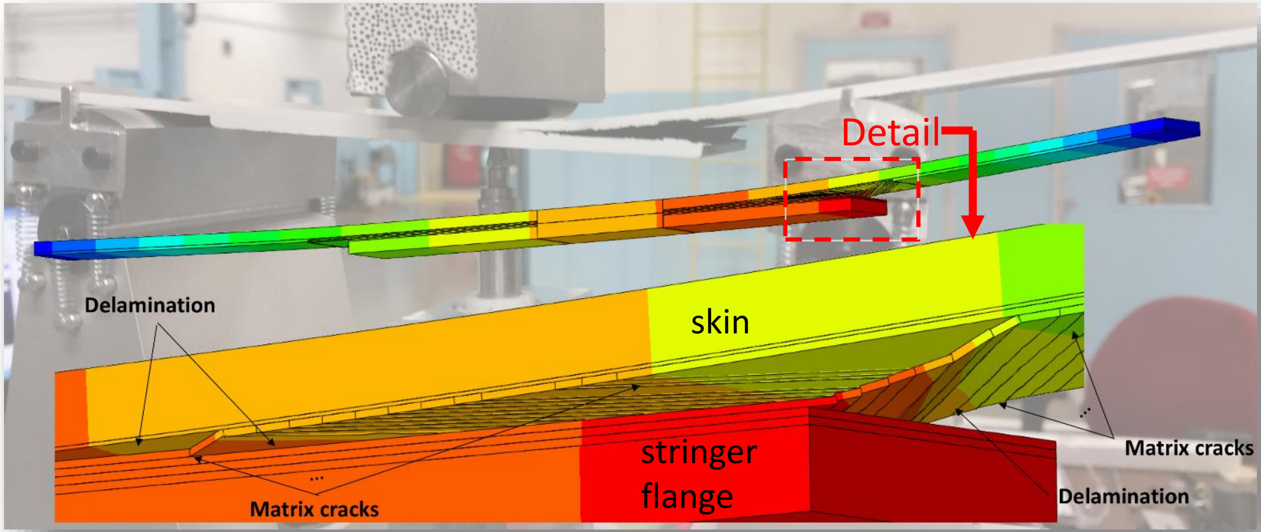
Simulation results



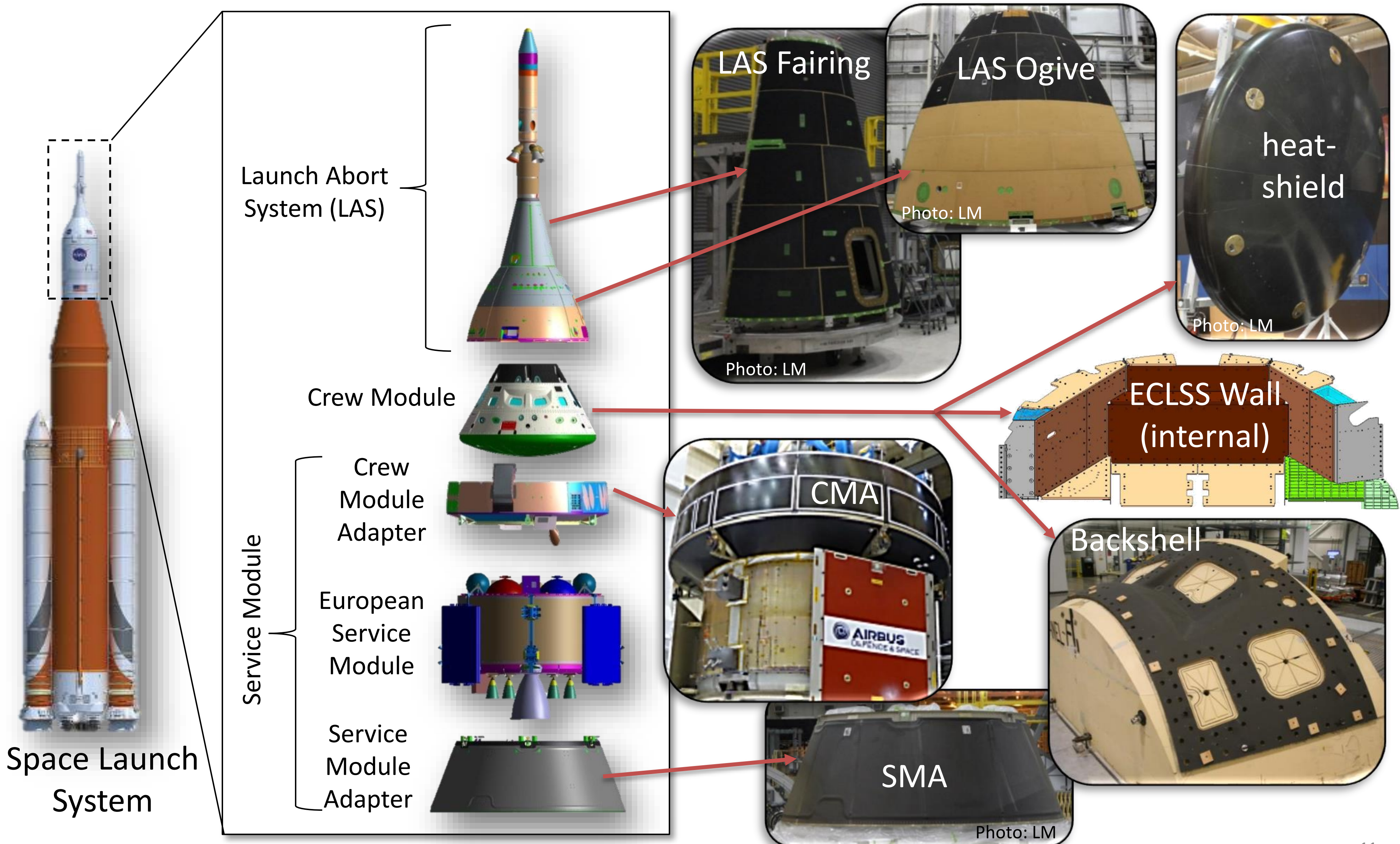




Example 2: “Skin-stringer debonding”



Applications: Composites on Orion

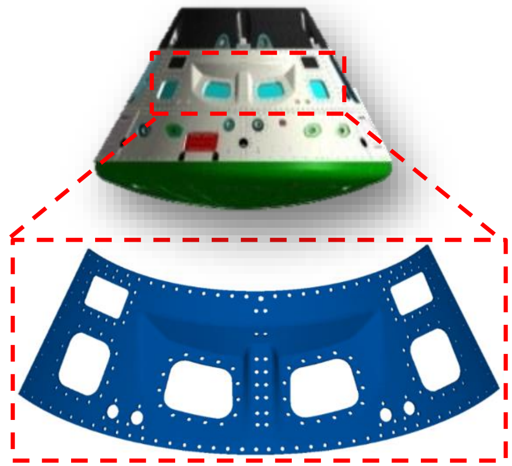


Orion Backshell

Analyst: Ashley Estes (JSC, Jacobs)

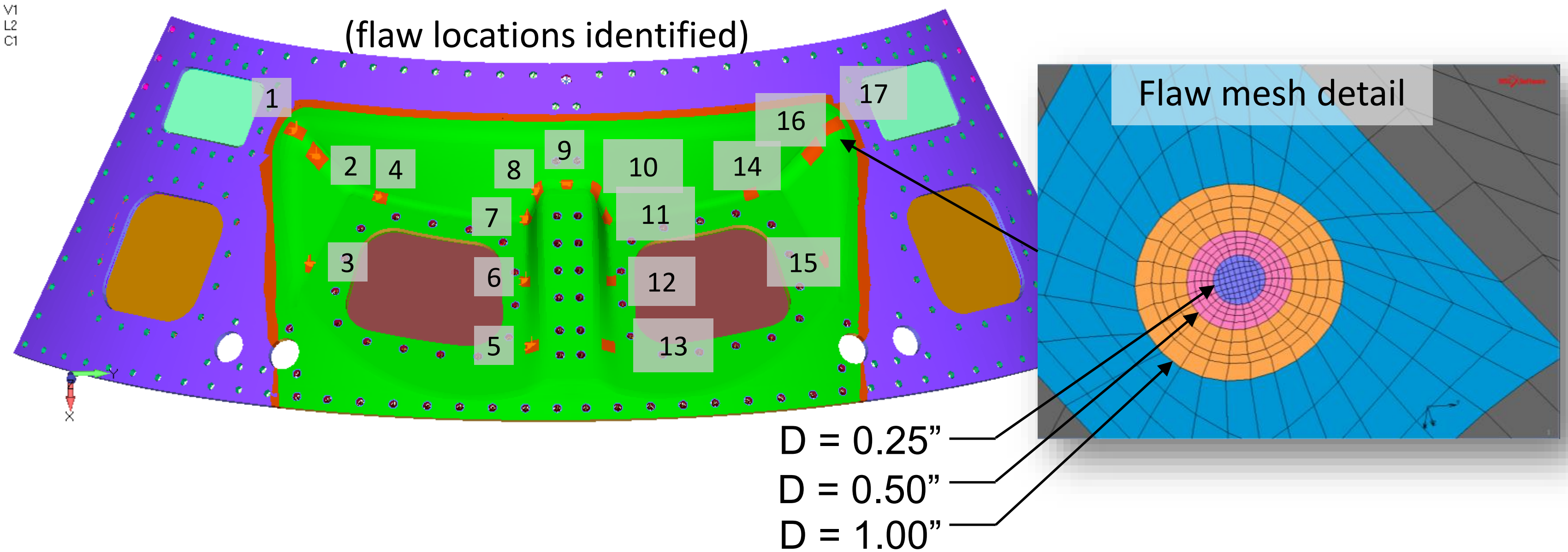
- Finite element model where damage tolerance of embedded flaws can be evaluated (VCCT)
- Difficult to test
- Flight loads can be applied
- Any flaw size and location can be evaluated
- Quick evaluation of design changes

Orion crew module



Panel F: composite sandwich

Panel F Finite element model
(flaw locations identified)

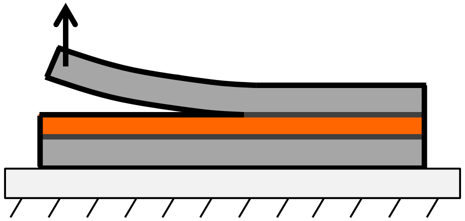


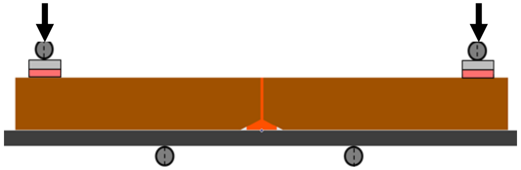
Orion Heatshield

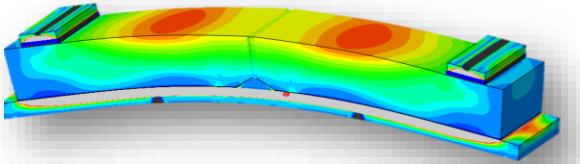
Analyst: NESC

- Thermal tiles (AVCOAT) bonded to heatshield carrier structure
- Damage tolerance concerns in AVCOAT tiles and at bondline

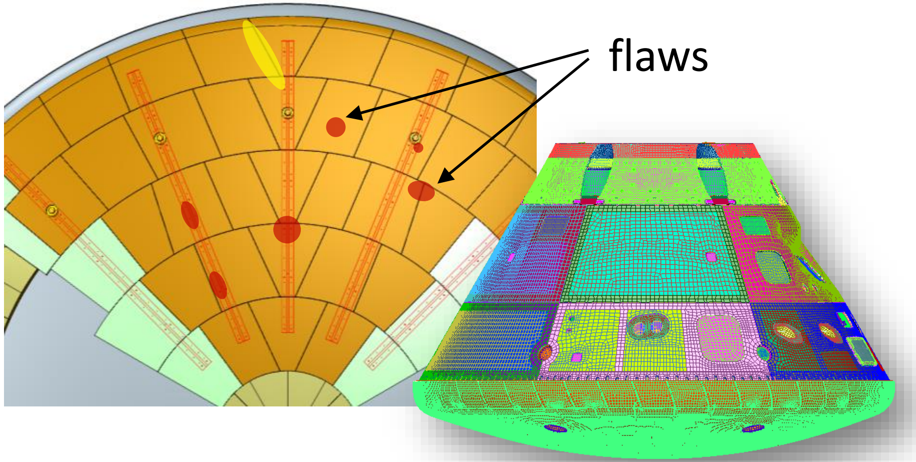
- Material characterization
- Model validation







- Full scale model with embedded flaws in heatshield
- Re-entry thermal/mechanical loads applied
- Equivalent test is not possible



Summary

- Certification of composite aerospace vehicles is time consuming and expensive

- Composite damage simulation tools may lower certification expenses by reducing the amount of testing
  - Tool development
  - Application & integration into design/analysis practices

Two main challenges to realize benefits

Summary: What is NASA doing?

- Advanced composites project (LaRC)

- Tool development (selected)
  - Extended interface element (de Carvalho, LaRC)
  - Adaptive fidelity shell element (McElroy, JSC)

- Application
  - Orion backshell damage tolerance
  - Orion heatshield damage tolerance

Summary: What *isn't* NASA doing?

- Effective agency wide sharing of state-of-the-art software tools
- Development of engineering tools for composites damage simulation/fracture control
- Material characterization of non-metallic materials for model validation
- Integration of composites damage simulation into standard fracture control and M&P practices (Orion)

Questions?

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