Composite Materials Specimen Design for Validation of an Energy-Based Multi-Axial Characterisation Methodology

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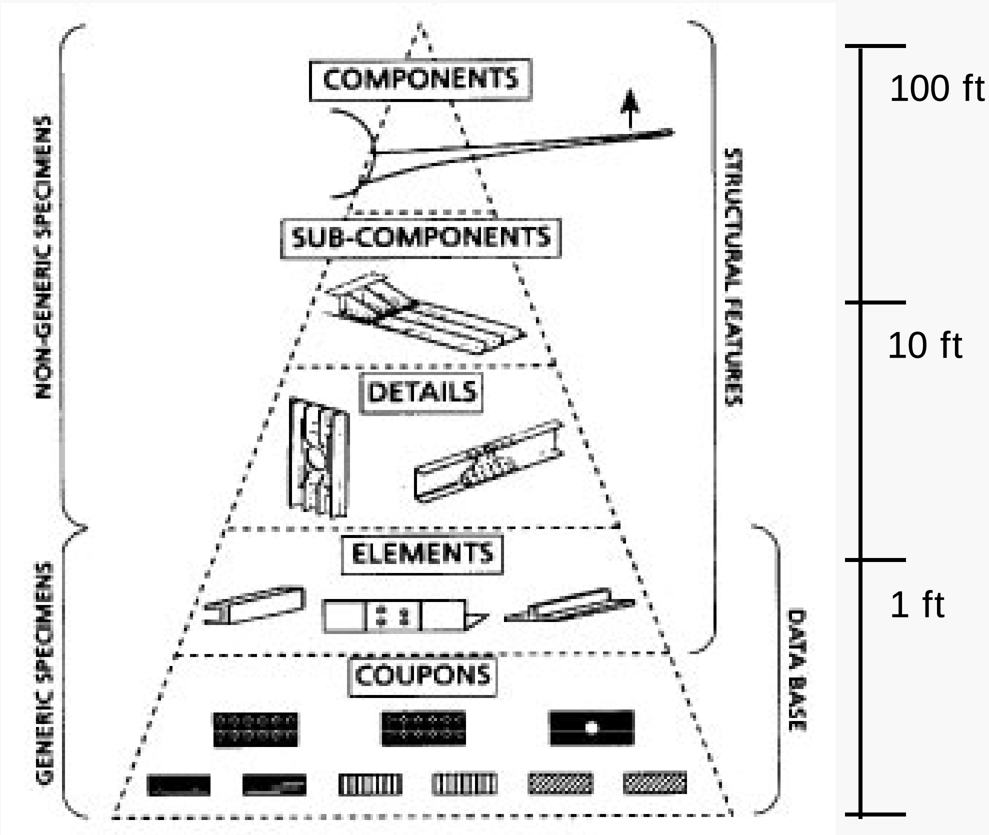
Overview

- Motivation
- Length Scale
- Multi-Axial Characterisation
- Validation Specimen Design
- Summary

Motivation: Economics

- CMH-17 Building Block Approach (BBA) Pyramid of Tests



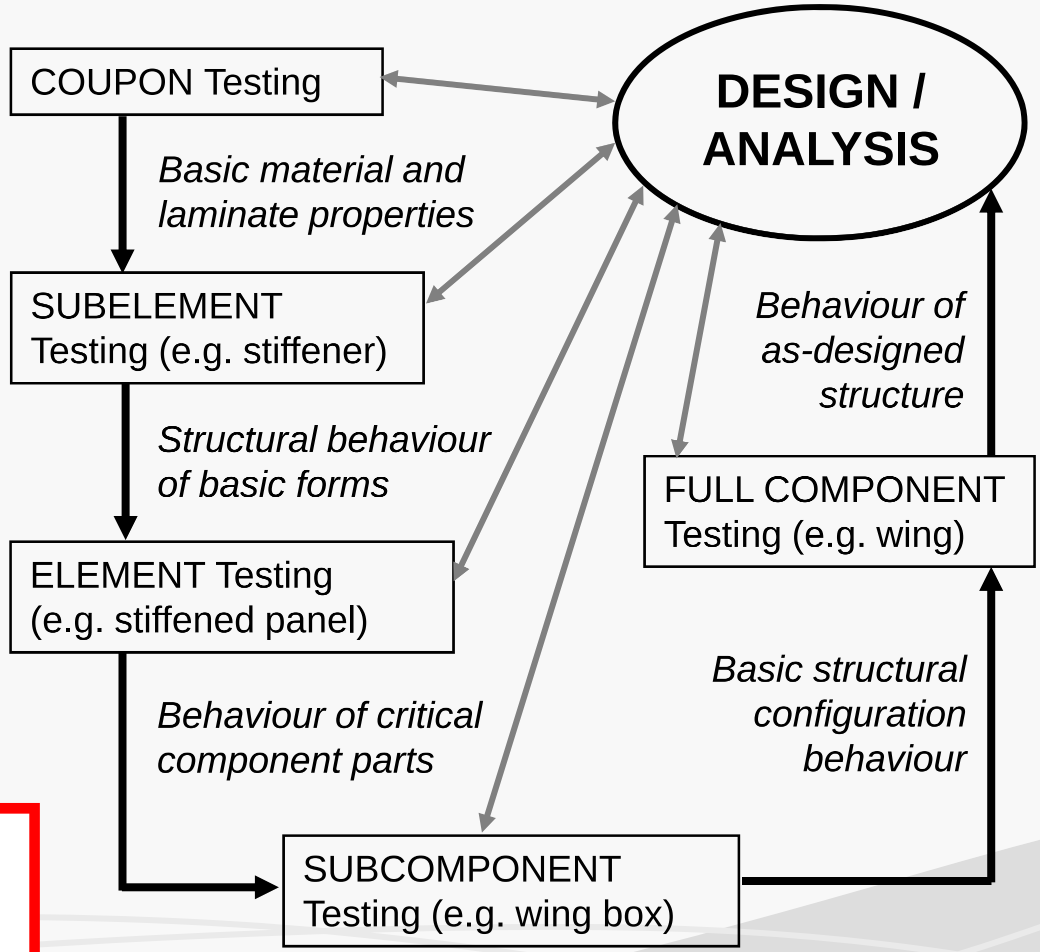
	# Specimens
Material Selection	380
Manufacturing Process Dev.	1800
Material Allowables	8000
Elements/Subcomponents	2200
Component Testing	**10**
Full Scale Airframe	3
Total # Specimens	12,393
Elapsed Time (Historical):	~10 years

BBA devised to compensate for inability of current composite material design/characterisation methodology to adequately describe structural performance over a four orders of magnitude dimensional scale range.

BBA is based on single-axis testing that requires extrapolation to real-life loading scenarios, leading to further cost and design conservatism

Length Scale

- Current design/analysis
  - Extensive testing utilised to establish material "allowable stresses" and other parameters
  - Mechanism-based models exist in isolation at several scales
- Parameters transferred to progressively higher levels of structural complexity
  - Knockdown factors
  - Various empirical and semi-empirical approaches
  - Models are unlinked and do not account for damage mode and length scale interactions
- A one-way process with little chance for iteration



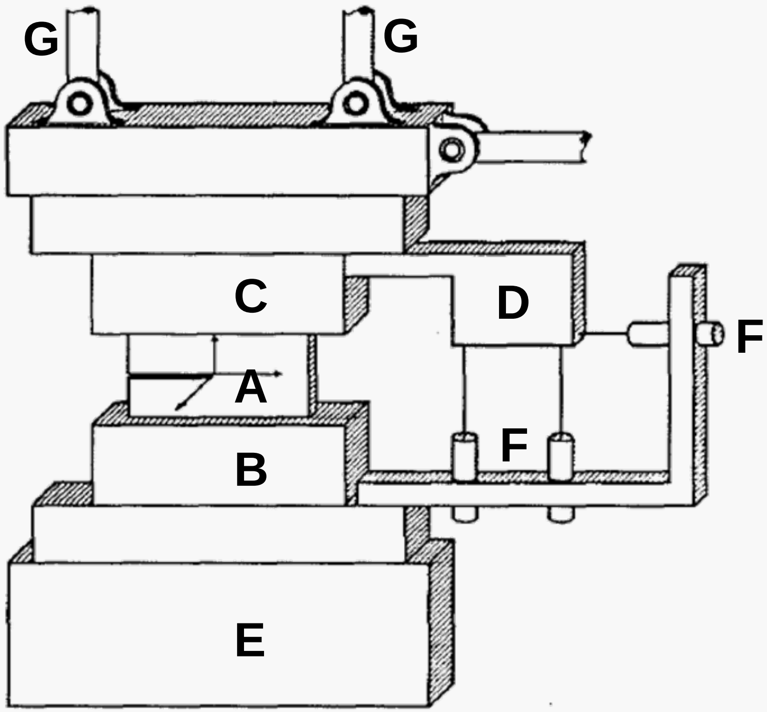
Inability to address length scale issues is a key driver for the high cost of BBA

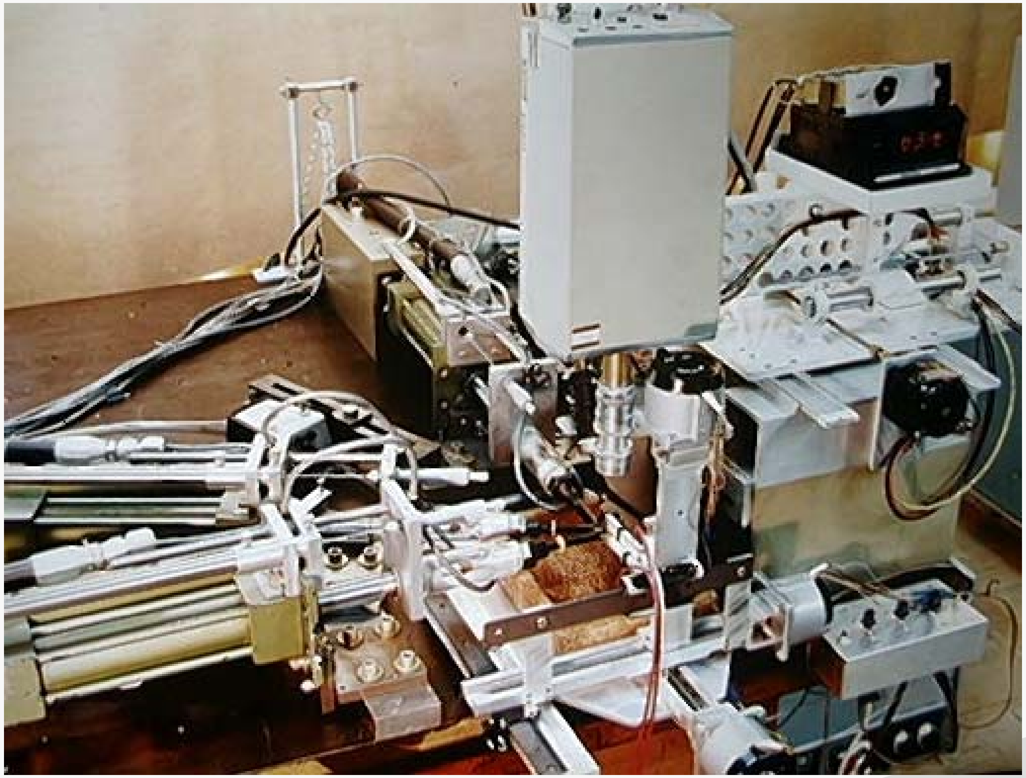
Multi-Axial Characterisation

- Multi-axial loading machines developed to apply combined loading on characterisation specimens
- Different combinations of combined loading are applied in order to sample the loading space
- Loading machines are highly automated and involve complex robotic actuators and sensors
- Data processing involves manipulation of massive amounts of data

Multi-Axial Characterisation

- 1970: NRL developed 3-DOF (in-plane) loader

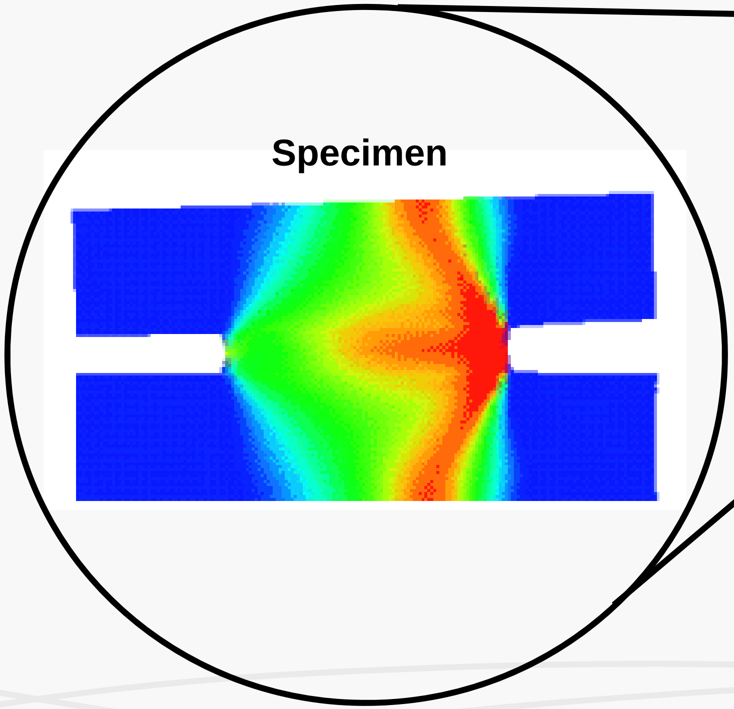


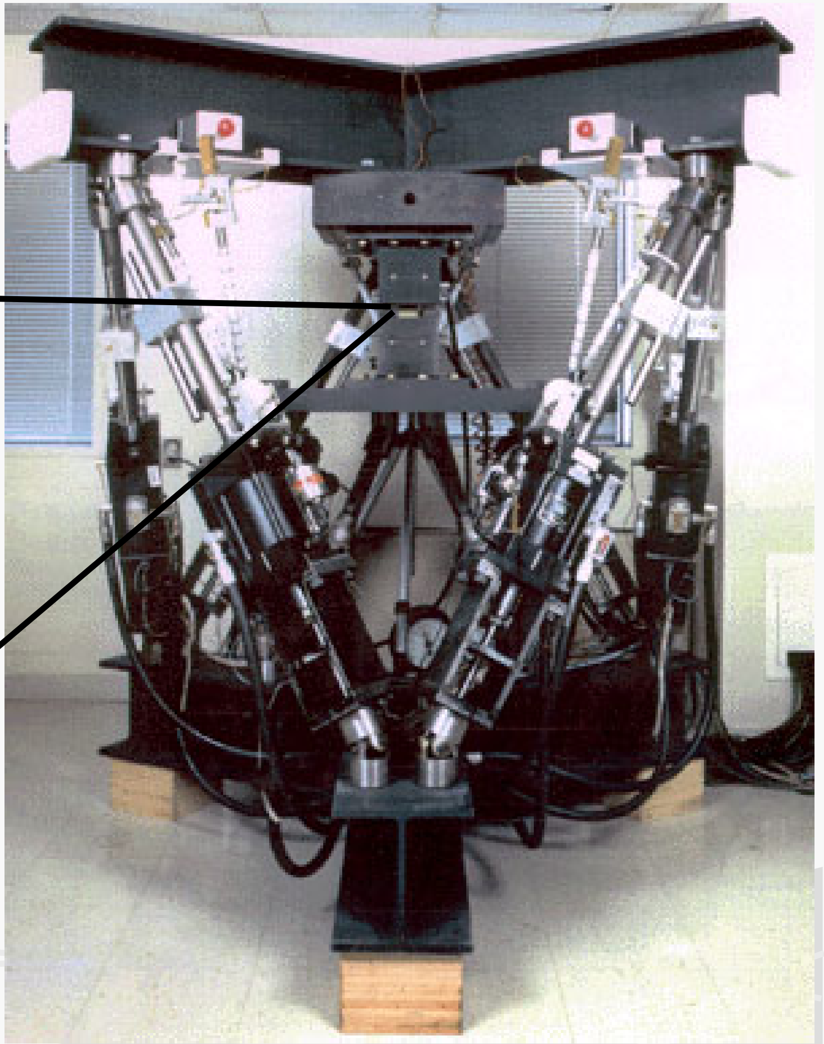


A: Specimen
B: Fixed grip
C: Moveable grip
D: 6-D DCLVDT transducer
E: 3D loading cell
F: DCLVDT
G: Actuator

Multi-Axial Characterisation

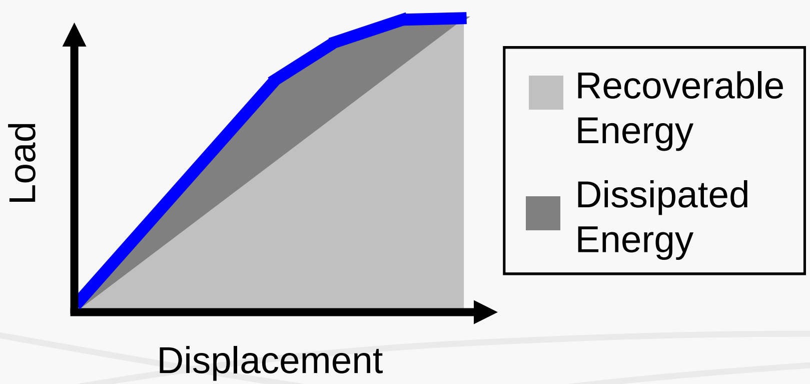
- 6-DOF loader based on hexapod frame





Multi-Axial Characterisation

- Multi-axial characterisation approach is based on the concept of Dissipated Energy Density (DED)
  - DED can be determined experimentally from nonlinear behaviour
  - Nonlinearity associated with irreversible damage processes
  - DED function (ϕ) obtained to relate strain to DED
  - DED function incorporated into nonlinear material constitutive law



COMPUTE COEFFICIENTS OF ϕ THAT MINIMISE THE SYSTEM OF EQUATIONS DERIVED FROM THE ENERGY BALANCE:

$$\int_0^{u_r} t_u q_v dq^v - \frac{1}{2} t_s u_t u^v = \int_{\partial V} \phi(\varepsilon_i(x_j)) dx_j$$

Applied Energy **Recoverable Energy** **Dissipated Energy**

ADEPT

- “**A**pplication of **D**issipated **E**nergy Density to com**P**osite s**T**ructures”
- Four-year collaborative research project (2006 – 2010)
- Objectives:
  - Build upon and extend the NRL data-driven multi-axial material characterisation approach to develop a cost-effective methodology (compared to BBA) for the determination of mechanical behaviour in complex composite structures subjected to realistic loading conditions
  - Validate the methodology through testing on coupons and substructures at ambient conditions with a focus on issues of length scales manifested across this range
  - Develop an overall approach to couple the methodology with commercial software for calculating stress state and assessing overall structural behaviour

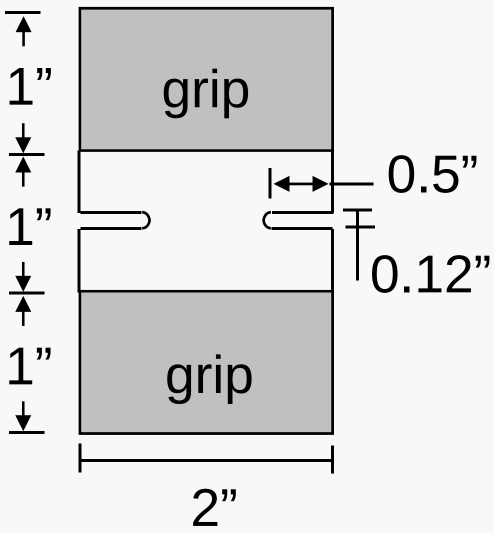
Validation Specimen Design

- Specimens need to be designed for testing at a range of different length scales
  - Characterisation
  - Open Hole Tension specimens
  - Ply drop
  - Stiffened panel

- Goal of testing is to achieve two convergent aspects
  - Investigate key length scale effects experimentally
  - Characterise failure at each length scale
    - Validate analysis methodology
    - Understand how to link between scale levels

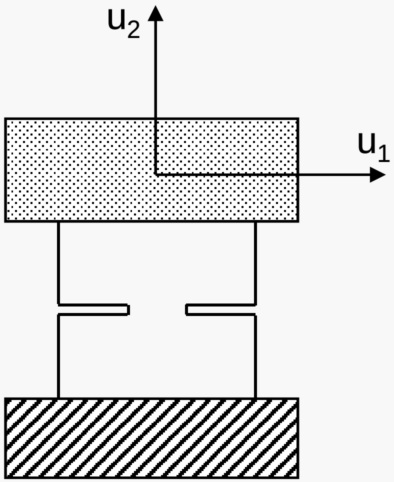
Characterisation Specimens

- Size: Based on limits of 6-DOF loader
  - Grip size, failure load
- Disturbance of strain field → Notch
  - Ensure failure in gauge region
- Symmetry preferred → Double Notch
- Lay-up based on $[\theta,-\theta]$
  - Lay-up based on previous work on characterisation methodology
  - Coupling effect (asymmetry) required for 3D characterisation
  - Ply thickness constant for all layers
- Scale effects: $[\theta,-\theta]_{16}$ and $[\theta_4,-\theta_4]_4$

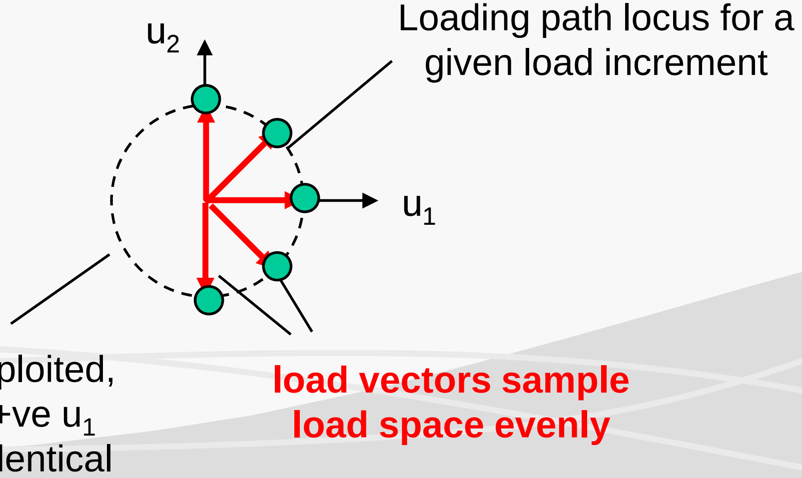


Characterisation Specimens

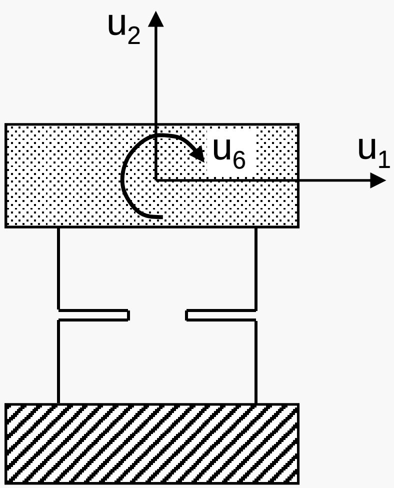
- Total number of specimens controlled by number of individual loading paths
- Current sampling scheme is uniform, and exploits symmetry



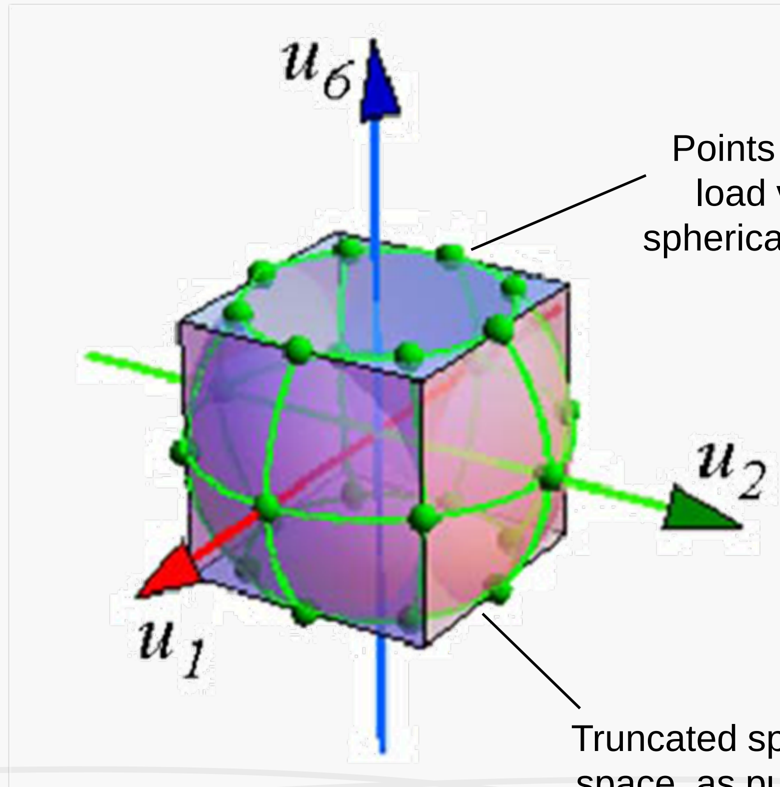
2-DOF
5 loading paths



Characterisation Specimens



3-DOF
24 loading paths

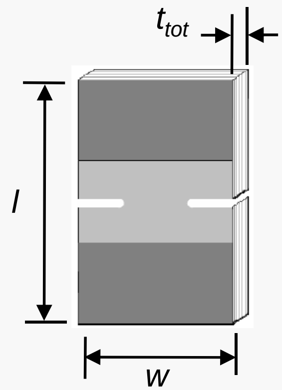


Points show chosen load vectors on a spherical loading space

Truncated sphere loading space, as pure u_6 motion not sampled

Characterisation Specimens

- Number of specimens also controlled by:
  - Number of different angle ply lay-ups, [+θ,-θ]
  - Number of changes in length scale
    - Length, width and total thickness of specimen
    - Ply thickness



- Separate task looking at using a reduced scheme
  - Define metrics for quality of data, use to optimise load vectors, both off-line and on-line planning

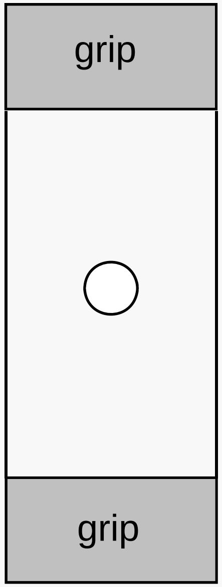
Characterisation Specimens

- Current project uses a 4-DOF space:
  - *Number of paths* = 72
  - *Number of lay-ups* = 4 (from two plates)
  - *Number of scale effect variations* = 2 (ply thicknesses)
  - *Number of repetitions of each specimen* = 2

- Characterisation requires 1152 specimens
  - 144 × $[15,-15]_{16}$
  - 144 × $[30,-30]_{16}$
  - 144 × $[60,-60]_{16}$
  - 144 × $[75,-75]_{16}$
  - 144 × $[15_4, -15_4]_4$
  - 144 × $[30_4, -30_4]_4$
  - 144 × $[60_4, -60_4]_4$
  - 144 × $[75_4, -75_4]_4$

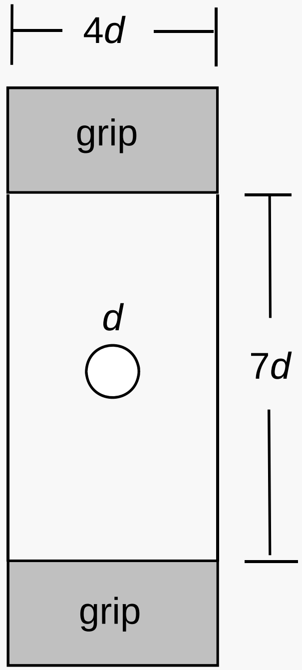
Open Hole Specimens

- OH for validation at coupon level using a standard specimen
- Goal to represent real structural details, (e.g. bolted joint)
- Scale effects drives specimen design
  - “In-plane” scaling of geometry (length/width)
  - Ply thickness at two variations
- Possible to investigate open hole specimen in tension and bending to get tension/compression behaviour



Open Hole Specimens

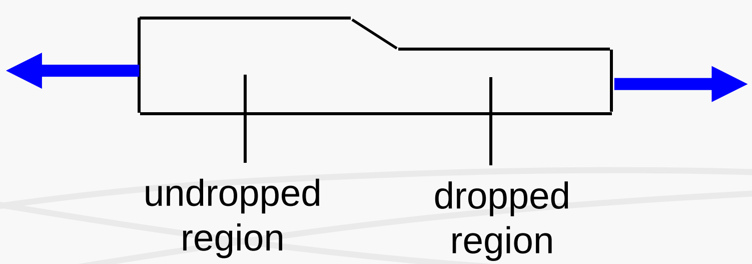
- Size of hole necessary to constitute a significant structural detail
  - 0.5” and 1.0” hole sizes selected
- Edge distances set based on hole diameter
- Lay-up based on [45,0,-45]
  - 90° not used to prevent excessive transverse cracks
- Scale effect: $[45,0,-45]_{4S}$ and $[45_4 ,0_4 ,-45_4]_S$
- 36 specimens
  - d = 0.0: 6 × $[45,0,-45]_{4S}$, 6 × $[45_4 ,0_4 ,-45_4]_S$
  - d = 0.5: 6 × $[45,0,-45]_{4S}$, 6 × $[45_4 ,0_4 ,-45_4]_S$
  - d = 1.0: 6 × $[45,0,-45]_{4S}$, 6 × $[45_4 ,0_4 ,-45_4]_S$

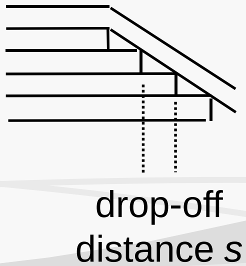


d = 0.5”, 1.0”

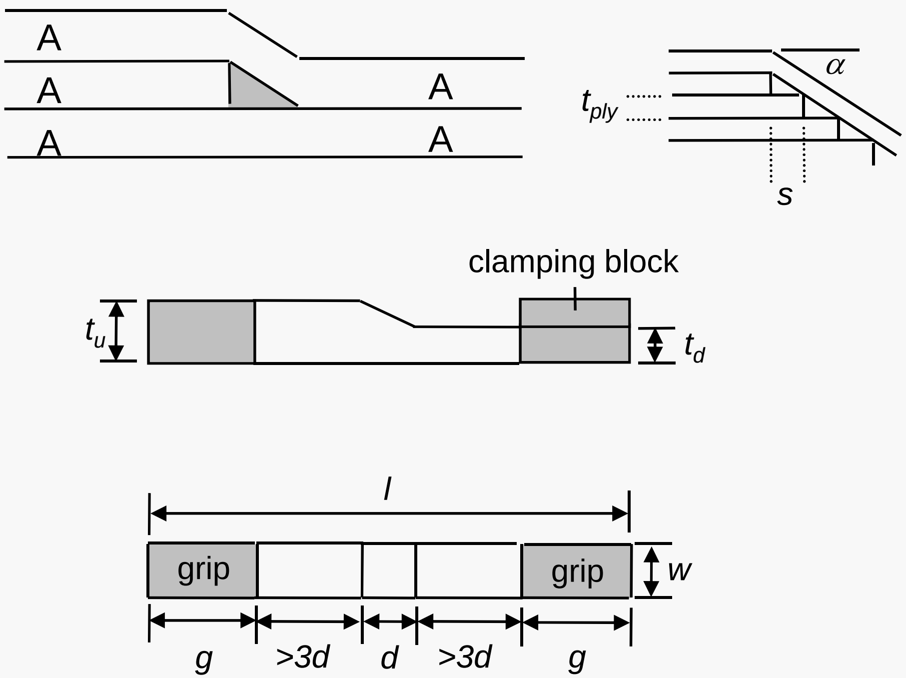
Ply Drop Specimens

- Ply drop for validation at another structural detail
  - Out-of-plane stresses feature prominently
  - Ply drops are common in design and a key type of structural detail
- Ply drops generate interlaminar stresses due to two main effects
  - Termination effect: Load transfer from undropped to dropped region
  - Offset effect: Load mismatch between two regions
- Additional interlaminar and transverse stresses due to:
  - Poisson's mismatch: Strain mismatch between two regions
  - Angle mismatch between plies
- Use of ply drop specimens
  - Promote out-of-plane failure mechanisms
  - Capture effects related to this specific structural detail





Ply Drop Specimens

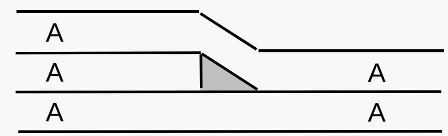


- 12 specimens
  - 6 × A = $[45,0,-45]_{2S}$
  - 6 × A = $[45_2,0_2,-45_2]_S$

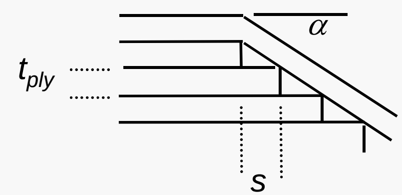
- A is a sublaminate block of 12 plies [45,0,-45]
  - $[45,0,-45]_{2S}$
  - $[45_2,0_2,-45_2]_S$
- t_{ply} = 0.005”
- $t_u = 36t_{ply}$ = 0.18”
- s = 0.04”, α = 7.4°
- $d = 12s$ = 0.5”
- g = 2” (set by machine)
- $l > 7d+2g$ = 8”
- $w > 3d$ = 1.5”

Ply Drop Specimens

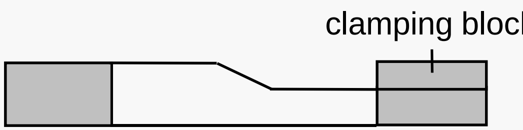
- Aim to represent a "real" configuration
  - proportion of dropped plies set to 33%



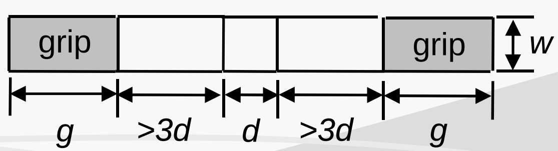
- Laminate based on A-block sub-laminate
  - Allow for drop-off of a laminate block
  - Allows for ply thickness effects to be studied
  - Overlaminate minimises interaction with edge stresses
  - 90° plies removed to prevent excessive matrix cracking



- Ply drop-off length, *s*
  - Aim for ply drop angles, α, around 10-20 for significant out-of-plane effects
  - However, want to drop-off 1 ply at a time, to avoid creating another length scale
  - Minimum practical distance that plies can be placed with accuracy is 1 mm,
    - so *s* = 1 mm (0.04")

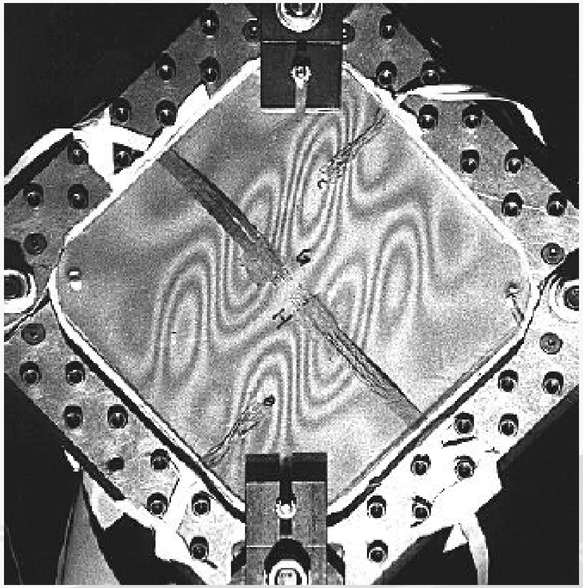


- Specimen lengths:
  - Drop-off region, *d*, set by length to drop off 12 plies
  - Dropped and undropped region at least 3*d* to minimise interaction with grips
  - Grip dimension (*g*,*w*) comparable to specimen width to avoid edge effects



Stiffened Panel

- Stiffened panel for substructure validation
- Representative of typical aerospace structure
  - Postbuckling control surface
- Three blade stiffeners co-cured to thin skin
- Lay-up:
  - Skin: quasi-isotropic [25/50/25]
  - Stiffener: [37.5/50/12.5]
- Panel loaded in shear in picture frame rig
- Number of panels to be determined



Summary and Outlook

- Multi-axial characterisation approach being pursued to represent realistic loading conditions
  - Approach is based on concept of dissipated energy density
  - Data-driven, highly automated, multi-dimensional characterisation
- Length scale issues a key focus in order to address shortcomings of the building block approach
- Validation specimens designed based on:
  - Experimental investigation of length scale effects
  - Assessment of suitability of multi-axial characterisation
- Specimen manufacture underway, testing expected to start late 2008 / early 2009
- Validated methodology to be part of a cost-effective characterisation approach, incorporated within a commercial software tool

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Thank you

Questions?