The Challenges of Determining the Strength of Composites

Michael R. Wisnom
Why are there such huge variations in strengths?

Diverse results from key experiments

Example: fibre compressive strength of IM7/8552 composites

Hao Cui, Cranfield, NWPU Suzhou

Significant variation on measured data depending on laminate geometry and test methods

Data from:
The problem

• After >50 years, there are still many unresolved issues with measuring basic strengths
• Major reason for the lack of progress on failure
• Christensen highlighted the difficulties of performing accurate testing:
  “The data of these observed behaviors must be completely uncorrupted by the inadvertent and uncontrolled influences that almost inevitably creep in.”
• Why is there such variation and what should we do about it?
Reasons for differences

- Definition of strength
- Poor test methods
- Variations in carrying out tests
- Failure depends on factors that are not fully understood or appreciated
How is strength defined?

Potential definitions:

- First damage?
- First fibre failure?
- Load drop?
- Reduction in stiffness?
- Load at max displacement?
- Peak load?
- Specimen disintegration?
Definition of strength – example
Definition of strength – example

• Consistent load drop at 65% of maximum tensile stress
• Load drop is very small and could easily be missed
• No obvious damage on outside of specimen
• Able to withstand significant further tensile loading
• Delamination has occurred
• Integrity in compression compromised
Definition of strength

• Failure and hence strength is related to fitness for purpose
• This may vary substantially depending on application
  • If main concern is ultimate load carrying capacity, damage may be acceptable – can even increase strength
  • If leakage is a concern, even one matrix crack may be problematic
• Must always define what is meant by failure
• Cannot take values unquestioned from test reports
How do we define & measure strength of a composite?

Recent online workshop organised with Federico Paris

Proposed definition of strength

- The strength of a unidirectional composite is the maximum stress that the material can sustain under uniform uniaxial loading.
- Other definitions such as damage initiation stress are more subjective.
- Damage detection depends on monitoring.
- SEM and CT show damage before loading due to intrinsic defects or residual stresses.
- In-situ strength depends on other factors.
- May be useful in design, but not appropriate as basic material parameters.
- May be considerable damage before maximum stress, but valid as a measure of material performance.
- Can be applied to all the principal failure modes.
Problems with test methods

• Tend to fail at point of load introduction
• Stress concentrations, presence of other stress components…
• Damage from grips, excessive pressure…
• Very many studies published
• Can we reach a consensus?

Compression failure at tabs
Variations in carrying out tests

High variability in experimental results, e.g. compressive strength

![Chart showing compressive strength for different samples]
Test lab can have greater effect than material!

Affected by details of test method, specimen preparation, tabbing procedures, clamping pressure...

‘t Hart et al, 1993
Factors not fully understood or appreciated

In UD composites:

• Volume of material tested
• Stress gradient
• Other stress components
• Defects, manufacturing variability

In laminates:

• Multiple failure modes that can interact
• Influence of other plies
• Residual thermal stresses
Measuring tensile strength

- Standard methods are affected by stress concentrations
- Leads to premature failure at grips
- Can be overcome by machining transitions
- Need to be very long and gradual!
- Can chamfer uncured plies
- With great care, grip failures can be eliminated

Gordon, Xu, Wisnom, Kim, 2020
Size effects - scaled UD tensile tests

- UD IM7/8552 carbon/epoxy
- Chamfered plies
- Small coupon 0.5 x 5 x 30 mm
- All dimensions scaled x 2
- Failure is defect controlled

Wisnom, Khan, Hallett, 2008
Data fits Weibull model

Weibull modulus $m=41$

![Graph showing stress vs. volume with a line indicating a Weibull fit. The graph shows a decreasing trend with volume on the x-axis and stress on the y-axis.](image_url)
Scaled flexural and tensile tests

- Tensile failure in 4-point bending and different length tension tests
- UD E-glass / 913 epoxy
- Weibull fits data, m=29
- Fits both length and volume scaling

Wisnom and Atkinson, 1997a
A new accurate simple tensile test

- Hybrids can eliminate stress concentration
- Strain in carbon LOWER at tab
- Eliminates grip failures

Czél, Jalalvand, Wisnom, 2016
Consistent tensile failures

- Gauge section failure followed by delamination
- Much higher failure strain, lower variability
- E.g. 1.86% vs. 1.5% strain for TR30 carbon/epoxy
- Gauge section failure even without end-tabs
Confirms size effect

- Thin TC35/K50 carbon/epoxy (0.024 mm) S2-glass/913 (0.155 mm)
- All dimensions and displacement rates scaled
- Consistent gauge section failures
- Low variability: CV 3-5%

<table>
<thead>
<tr>
<th>Lay-up sequence</th>
<th>Carbon layer failure strain [%] (CV rel. %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[SG₂/TC35₂]₅</td>
<td>2.028 (3.6)</td>
</tr>
<tr>
<td>[SG₄/TC35₄]₅</td>
<td>1.854 (4.9)</td>
</tr>
<tr>
<td>[SG₈/TC35₈]₅</td>
<td>1.784 (2.6)</td>
</tr>
<tr>
<td>[SG₁₆/TC35₁₆]₅</td>
<td>1.560 (5.4)</td>
</tr>
</tbody>
</table>

Wisnom, Cantera, Czél, Jalalvand, 2017
Summary – UD tensile testing

• Strength is a statistical quantity not a single value
• Depends on volume of material
• Weibull model fits the data but there are still some questions
• Do we want strengths that are dependent on a theory?
• Must specify the volume, or establish a range of standard volumes to allow comparisons
• Now that we finally have better methods, can undertake further well controlled tests
• Does strength really follow Weibull?
• Is the volume effect the same for length and area?
Effect of other stress components - shear

- Test carbon angle plies to generate shear and tension
- Glass plies suppress failure at grips
- Thin carbon plies suppress shear cracks and free edge delamination
- Gauge section failure uninfluenced by other modes
Layups tested

- Skyflex TC35 carbon/epoxy, 0.03 mm ply thickness
- Hexcel E glass, 0.127 mm plies, $[0_G/\pm\theta_C]_S$
- Carbon layups: $[0]_s$, $[\pm 5]_s$, $[\pm 10]_s$, $[\pm 15]_s$, $[\pm 20]_s$, $[\pm 25]_s$

- The shear stress increases with $\theta$ but $\sigma_2$ is almost 0

Jalalvand, Fotouhi, Leong, Wisnom, 2017
Failure strain unaffected by shear

- Fibre direction tensile failure strain is not significantly affected by shear
- In multidirectional laminates could not reach such high shear strains without fibre failure in other plies

<table>
<thead>
<tr>
<th>q</th>
<th>fibre direction strain (%)</th>
<th>Shear strain (%)</th>
<th>CV for fibre direction strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.834</td>
<td>0</td>
<td>1.09%</td>
</tr>
<tr>
<td>5</td>
<td>1.853</td>
<td>0.436</td>
<td>3.99%</td>
</tr>
<tr>
<td>10</td>
<td>1.797</td>
<td>0.88</td>
<td>2.58%</td>
</tr>
<tr>
<td>15</td>
<td>1.818</td>
<td>1.402</td>
<td>1.76%</td>
</tr>
<tr>
<td>20</td>
<td>1.766</td>
<td>1.948</td>
<td>4.37%</td>
</tr>
<tr>
<td>25</td>
<td>1.654</td>
<td>2.528</td>
<td>4.41%</td>
</tr>
</tbody>
</table>

Low CV
Effect of transverse compression

- Use thin carbon angle plies to induce transverse compression in central 0º plies
- Lower modulus angle plies replace glass, prevent grip failure
- Skyflex TC33 carbon/epoxy \([\pm 15_6/0_2]_s \ [\pm 20_6/0_2]_s \ [\pm 28_6/0_2]_s\)

![Diagram showing UD carbon layers, angle-ply thin-ply carbon layers, and scissoring induced transverse compression in 0º plies.](image)
Failure not affected by transverse compression

- $[\pm 15_6/0_2]_S$ initial grip failure
- Glass plies added
- All gauge section failures
- Strains measured with video extensometer
- No significant effect of transverse compression on fibre failure strain

Rev, Czél, Wisnom, 2018
Laminate strength - not a material property

- Strength depends on stacking sequence
- Premature failure due to delamination

Wisnom, Khan, Hallett, 2008
QI tension failure mechanism

- Matrix cracking leading to delamination from edge
- Premature fibre failure when plies are dispersed
- Global delamination when plies are blocked

Wisnom, Khan, Hallett, 2008
QI versus UD strength

- No laminates reached the expected strength based on 0° tests
- Cracks in surface 45° plies initiated from tabs
- Tests repeated without tabs, gently chamfered grip faces
- No cracks, full strength achieved, consistent with 0° tests
- Laminate and 0° strength can be reconciled if:
  - premature failure is eliminated
  - volume of 0° plies is taken into account

Xu, Wisnom, Chang, Hallett, 2016
Constraint from adjacent plies

- Very thin carbon plies show higher failure strain
- Constraint from adjacent plies delays formation of critical cluster
- E.g. UD glass/carbon hybrid
- 2.23% failure strain for 0.03 mm ply
- 20% increase over baseline of 1.86%

Wisnom, Czél, Swolfs, Jalalvand, Gorbatikh, Verpoest, 2016
Transverse cracks may reduce strength

- UD thin carbon tests with adjacent 90° plies
- Glass plies to avoid grip failure
- 90° ply thickness varied
- In all cases small reduction in 0° failure strain
- Further work needed to better understand the effect of cracked ply location and orientation

Rev, Leone, Lovejoy, Wisnom, 2020
Summary – laminate tensile testing

- Laminates may fail prematurely due to transverse cracks and delamination
- Depends on stacking sequence
- Can reconcile UD and laminate strength provided premature failure avoided and volume of 0° plies is the same
- Other stress components do not have significant effect
- Constraint from adjacent plies can increase failure strain
- Transverse cracks may reduce failure strain
- Laminate strength is not a material property
Compression testing is even harder!

- Cannot avoid stress concentrations
- Presence of other stress components
- Direct compression tests therefore underestimate true strength

High interlaminar shear stress at same point

Stress concentration of compressive stress

Wisnom, 1991
Flexural tests

- Can avoid grip failure using flexural tests
- For many composites get compressive failure
- Gauge section failure provided rollers are large enough
- Alternatively can used pin-ended buckling rig
Pin-ended buckling tests

- Scaled tests on T800/924 carbon-epoxy show a strong effect of strain gradient
- Failure is due to shear instability at the micromechanical level
- With strain gradient, less stressed fibres support others
- Stressed volume also changes with size

Wisnom, Atkinson, Jones, 1997
Constrained buckling tests

- Rig allows different combinations of compression and bending
- Same T800/924 material
- All specimens similar size
- Same 2 mm thickness
- Demonstrates the effect of the strain gradient, independent of volume

Wisnom, Atkinson, 1997b
Carbon-wood sandwich beam

Top skin, 0.5 mm

Bottom skin, 0.5 mm

Bonded using Araldite epoxy adhesive

Large rollers avoid local failures

Xun Wu, 2020
Sandwich beams – effect of strain gradient

- Vary depth of the beam to change strain gradient
- Keep gauge section dimensions the same
- Increase span to limit loading forces

Increase the core height from $h$ to $H$

Top skin, $t$
Core, $h$
Bottom skin, $t$

Increase span to limit loading forces
Results - effect of strain gradient

- IM7/8552 carbon/epoxy skins, $t = 0.5$ mm
- Core varying from 6 mm to 38 mm
- Little effect of strain gradient above 10 mm thickness
- 1.36% strain - 14% higher than 1.19% in direct compression
- Arguably the best value for this material

(Thomson et al, 2019)
Effect of ply thickness

- Sandwich bending tests
- M40JB / North TP80ep
- Thin plies stronger
- Lower variability of strength
- Greater homogeneity
- Wider issue of the effect of manufacturing process
- Can affect microstructure and fibre alignment

Amacher et al, 2014
Effect of other stress components

- Shear stress reduces compressive strength
- Demonstrated with tubes under combined compression and torsion
- Interaction of other stress components less clear
- Need better tests

Jelf, Fleck, 1994
Summary – compression testing

- Direct compression tests underestimate strength
- Flexural tests can overcome premature failure
- Strain gradient can have a large effect
- Flexural tests with large rollers and sufficient depth can give satisfactory results
- Shear stresses have a big effect
- Use state of the art test methods to investigate:
  - Effect of stressed volume independent of gradient
  - Other stress components
  - Constraint from other plies
  - Stacking sequence
Conclusions – why such large variations?

- Lack of a consistent definition of strength
- Intrinsic variability and effect of manufacturing process
- Poor test methods and variations in carrying them out
- UD strength depends on factors that are not fully appreciated or understood, e.g. stressed volume and stress gradient
- Laminate strength is not a material property - depends on many factors due to the interaction of different failure modes
Implications

• Be more critical about experimental methods and data
• Don’t assume that correlation between models and tests means both are correct
• Use a consistent definition of strength, e.g. The maximum stress that a unidirectional composite can sustain under uniform uniaxial loading
• Values should be stated together with the volume of material and conditions under which it was measured
• Laminate strengths are not material properties - should be referred to as failure stresses rather than strengths
What is the way forward?

• Synthesize the huge amount of work on testing to reach a consensus on the best methods
• Agree on what are the phenomena we don’t fully understand
• Design experimental programmes to systematically address the critical issues
• Organise a series of workshops on the primary failure mechanisms

Fibre direction and transverse tension, compression and shear
References


Wisnom MR, Atkinson JA, “Constrained buckling tests show increasing compressive strain to failure with increasing strain gradient”, Composites 28A, 959-964, 1997b. [http://dx.doi.org/10.1016/S1359-835X(97)00067-5](http://dx.doi.org/10.1016/S1359-835X(97)00067-5)

Wisnom MR, Atkinson JA, Jones MI “Reduction in compressive strain to failure with increasing specimen size in pin-ended buckling tests”, Composites Science and Technology 57, 1303-1308, 1997. [http://dx.doi.org/10.1016/S0266-3538(97)00057-2](http://dx.doi.org/10.1016/S0266-3538(97)00057-2)


Thanks for your attention!

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