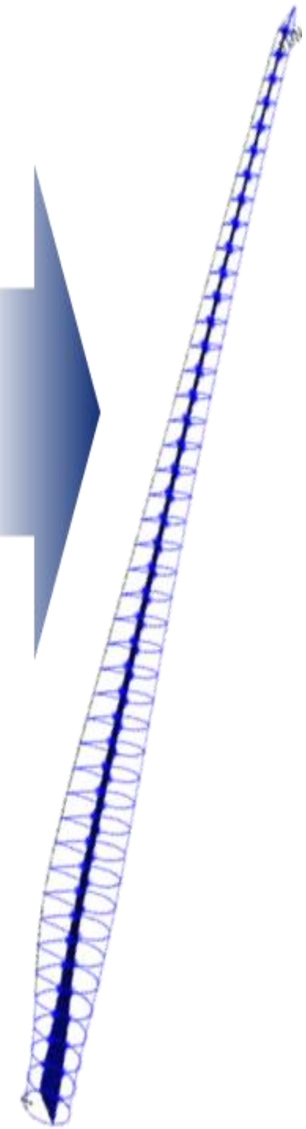
ARPA-E Tensioned Fabric Wind Blades

(Cooperative Agreement DE-AR0000293)



Nov, 2014

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Project Description

ARPA-E Project DE-AR0000293

Program Team

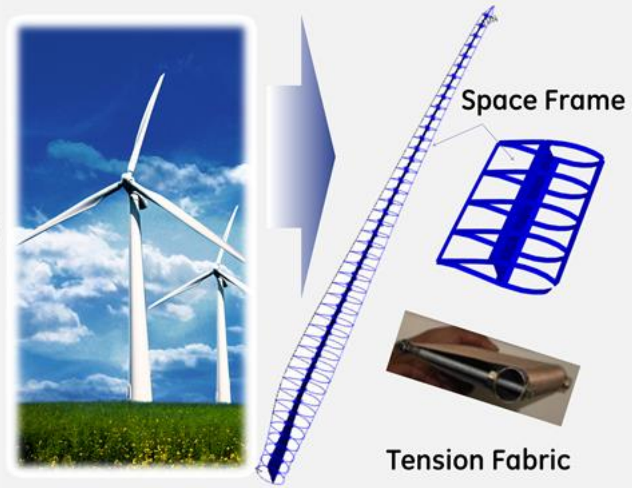
GE Power & Water
Design & Manufacturing

GE Global Research
Materials & Attachments

VirginiaTech *Invent the Future*
Wind Tunnel Test

NREL
Blade Test

3 Year, $5.3M



<u>Program Benefits</u>

- 25% cost reduction
- Less labor, less complexity
- No clam-shell molds
- Modular blade technology
- More automation

- Develop a novel wind blade technology in which a space frame structure is covered by tensioned fabric
- Aim for blade lifecycle cost & LCoE reduction through new blade architecture & manufacturing method

Existing Fabric Structures

Tension Fabric Denver Airport

Wind Turbine
Space Frame Tower

Fabric Airplane

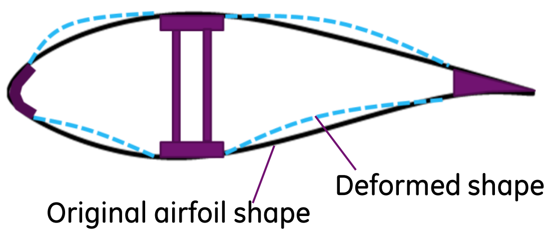
Sail Boat

BMW GINA Concept Car

Tent

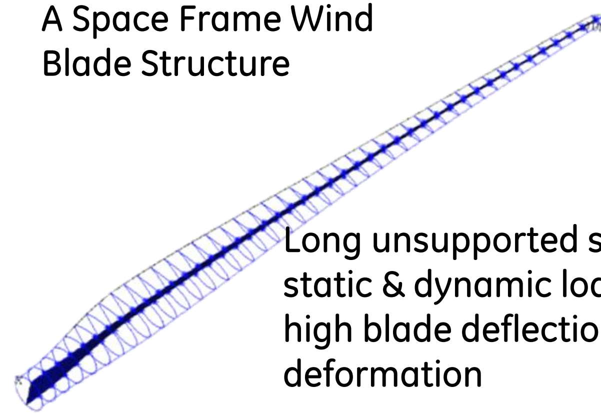
Challenges of Fabric on Wind Blades

Fabric deformation shape under aero pressure



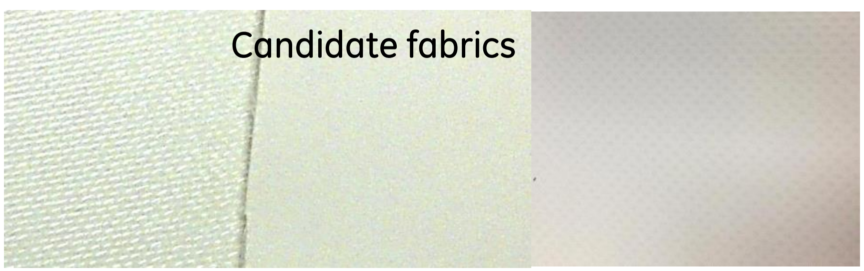
Significant AEP reduction & LCoE increase if high fabric deflection at FWD 50% chord

A Space Frame Wind Blade Structure



Long unsupported span & high static & dynamic load lead to high blade deflection & skin deformation

Fabric pre-tension required to avoid sag under blade deflection to maintain aero shape



Down-selected to glass fiber reinforced fabric:

- Pros:
  - Damage tolerance
  - Environment performance (20-year field exposure)
  - Low relaxation to avoid up-tower re-tensioning
  - Low cost
- *Cons:*
  - ***High modulus leads to high fabric tension load***

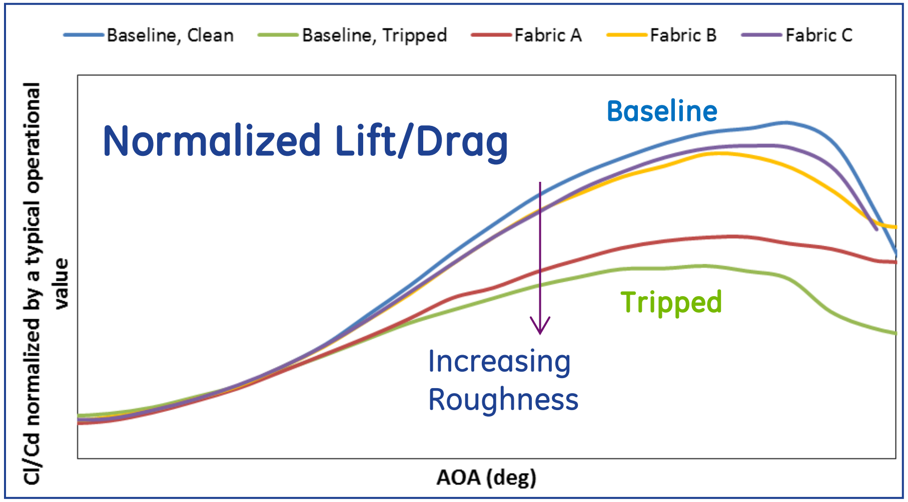
How to apply pre-tension & retain tension on fabric to maintain aero shape in a cost-effective way?

Fabric Roughness Wind Tunnel Test

Test description: 3 candidate fabrics with varying roughness characteristics are wrapped around existing airfoil models and aerodynamically characterized in the VT Stability Wind Tunnel

Goal of the test: Quantify the aero losses due to the roughness characteristics of each fabric on relevant airfoil cross sections and determine if they are viable candidates for fabric down select

Fabric	Description
Fabric A	• High roughness (average and peak)
Fabric B	• Low roughness (average and peak) • High roughness wavelength
Fabric C	• Low roughness (similar to Fabric B) • Low roughness wavelength



Findings:

- Sufficiently high losses for Fabric A that it was no longer considered a viable candidate for down select
- Small losses for Fabrics B and C

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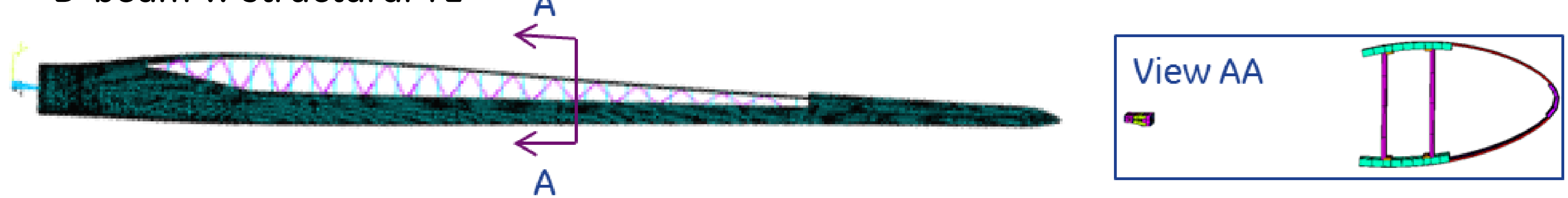
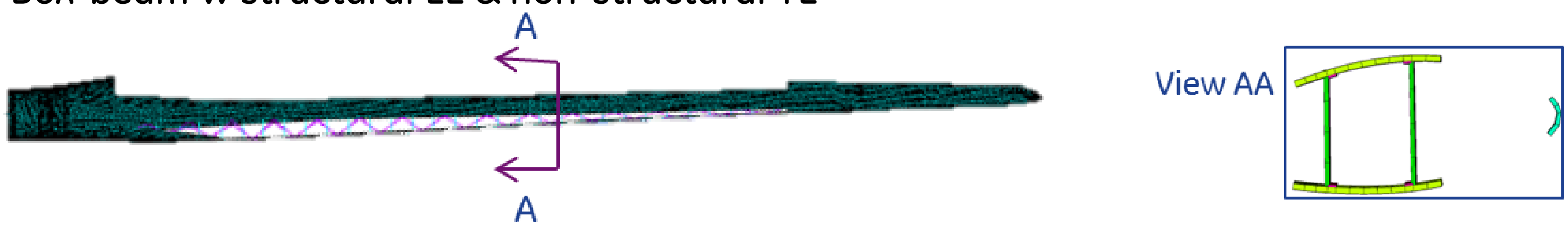
Tensioned Fabric Blade (TFB) Evolution 1: Truss Structures with Fabric Tension & Attachment

Box beam w structural LE & TE

D-beam w structural TE



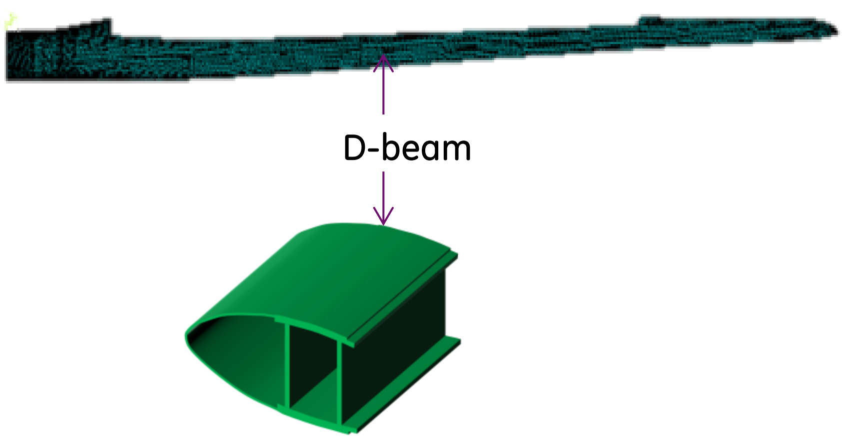
Box-beam w structural LE & non-structural TE

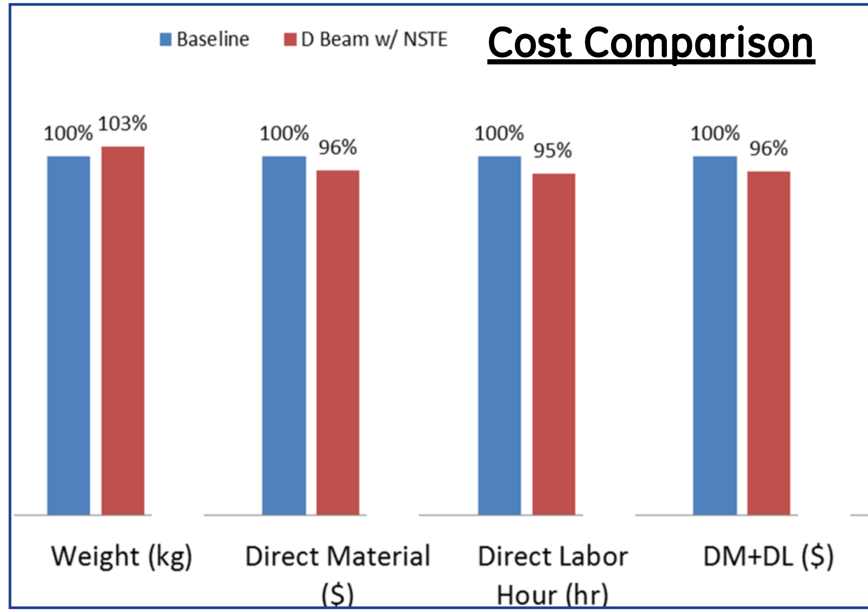


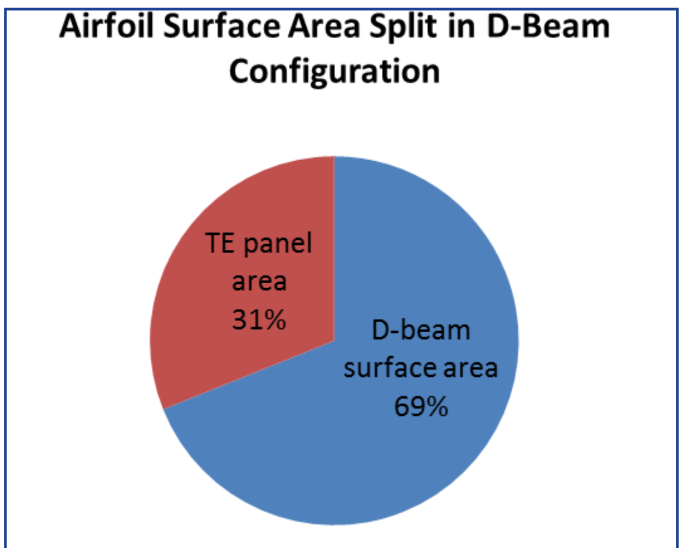
- < 3% weight saving due to added mass to maintain buckling margin of LE/TE/ribs
- Complex fabric pre-tension mechanism
- Significant technical risk on joints & fabric attachment

Unlikely to meet cost saving target

TFB Evolution 2: D-Beam with Non-Structural Trailing Edge (TE)





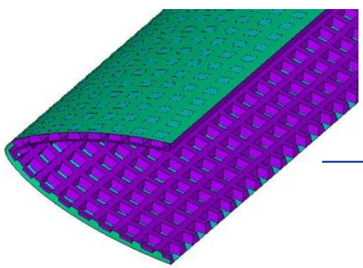


- D-beam designed to take all load.
- Non-structural TE panel to keep airfoil shape
- Small fabric tension load & simpler fabric tension mechanism on TE panels
- Less part count & simpler assembly process

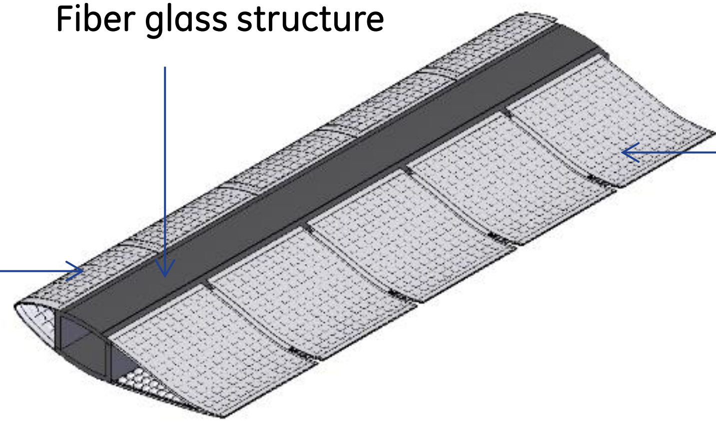
However minimum (4%) direct material (DM) & direct labor (DL) saving, 2/3 structure similar to baseline, unlikely to meet cost saving target

TFB Evolution 3: Box-beam w Non-Structural Leading Edge (LE) & TE

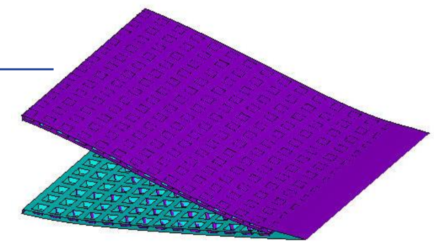
LE Panel
Corrugated thermoplastic structure



Box beam
Fiber glass structure



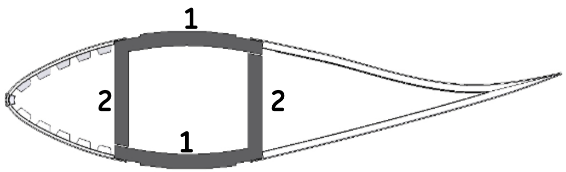
TE Panel
Corrugated thermoplastic structure



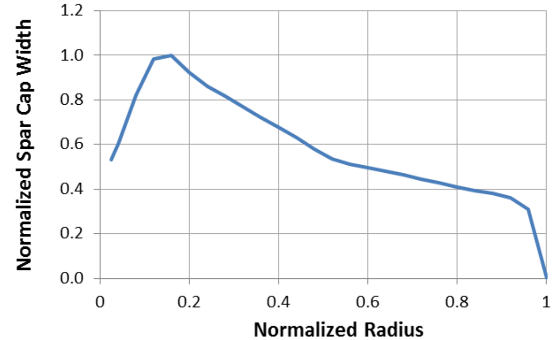
- Pursued more radical change in blade architecture for more cost saving. Down selected concept to box beam w non-structural LE & TE.
- Replaced fabric with thermoplastic for labor saving

Box Beam Design

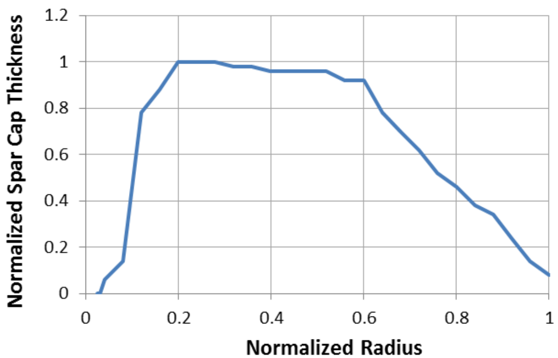
1. Fiber glass spar caps
2. Sandwich shear webs



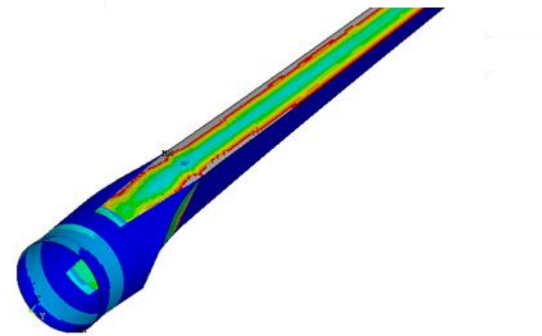
Spar Cap Width Distribution



Spar Cap Thickness Distribution



Fatigue Damage Load Factor Contour

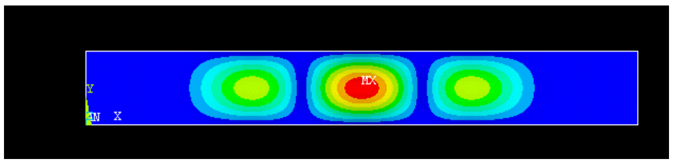


- Box beam designed to take all load.
- Tapered spar cap width to increase structural efficiency.
- Flap & torsional stiffness comparable to baseline, lower edge stiffness.
- Spar cap edges have highest fatigue damage load factor.

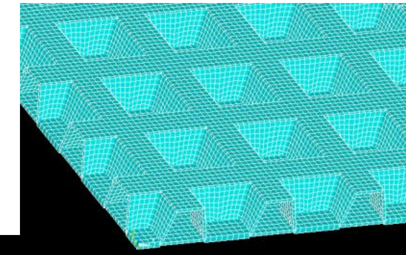
Corrugated LE Panel Design – Buckling Analysis

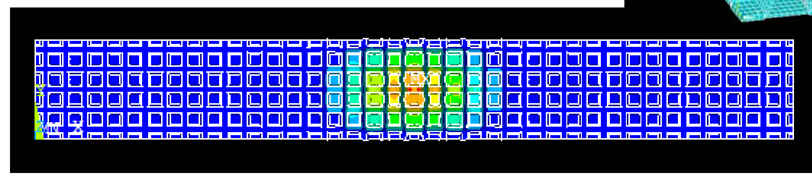
Flat Panel

Constant thickness, Buckling Load Factor (BLF) = 0.9



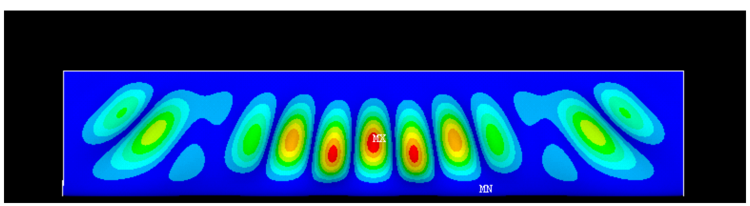
Corrugated panel w same area density, BLF = 3.5



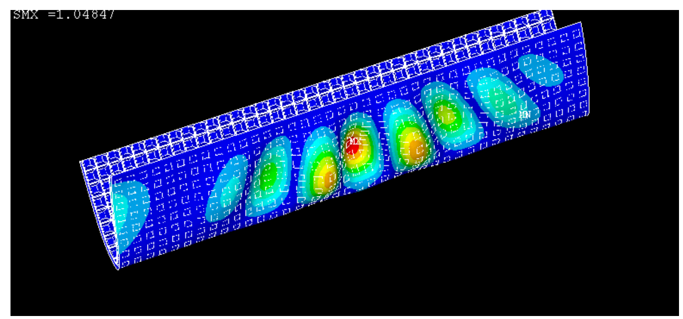


LE Panel w Airfoil Shape

Constant thickness, BLF=0.9



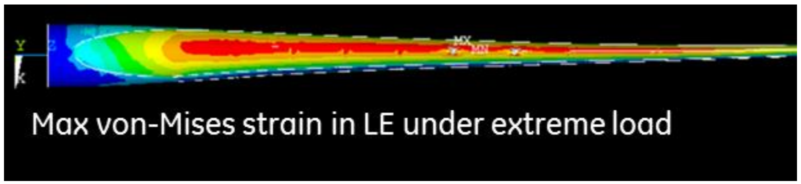
Corrugated LE panel w same area density, BLF=1.8



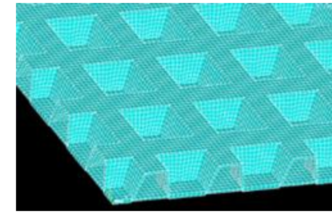
Corrugated structure can potentially increase buckling margin significantly

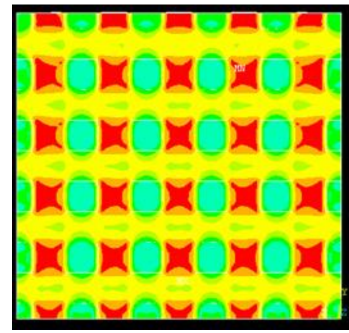
Corrugated LE Panel Design – Static Analysis & Material Test

Static Analysis



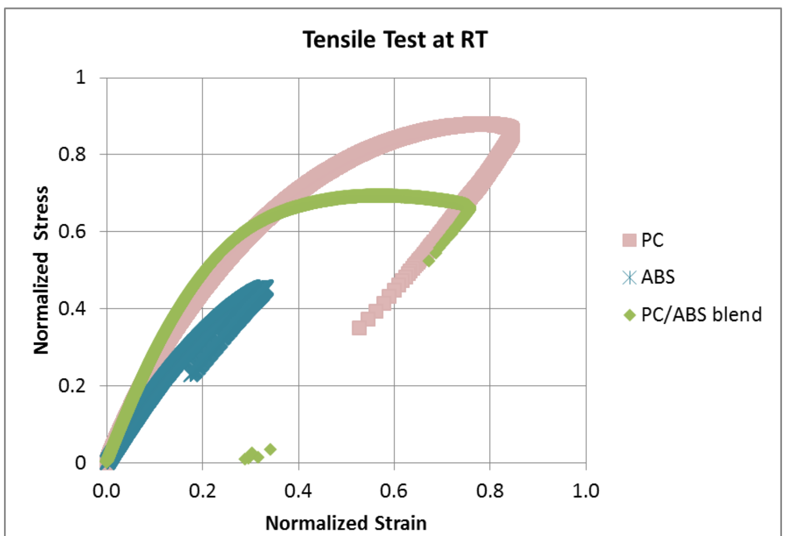
Strain increases by 50% in corrugated panel





Apply LE strain from blade analysis

Thermoplastic Static Tensile Test



Down-selected LE panel material to PC/ABS blend based on static test/analysis results & cost comparison

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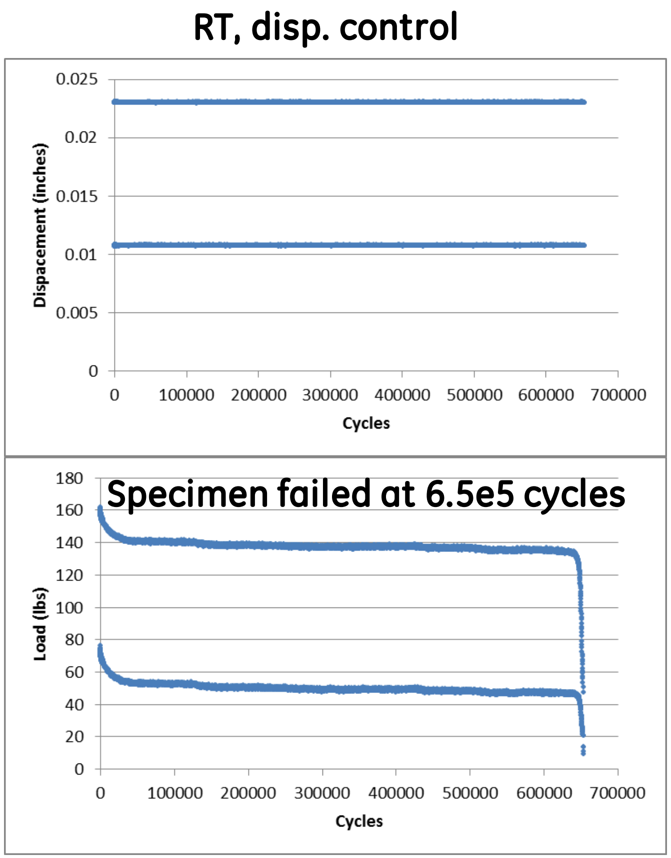
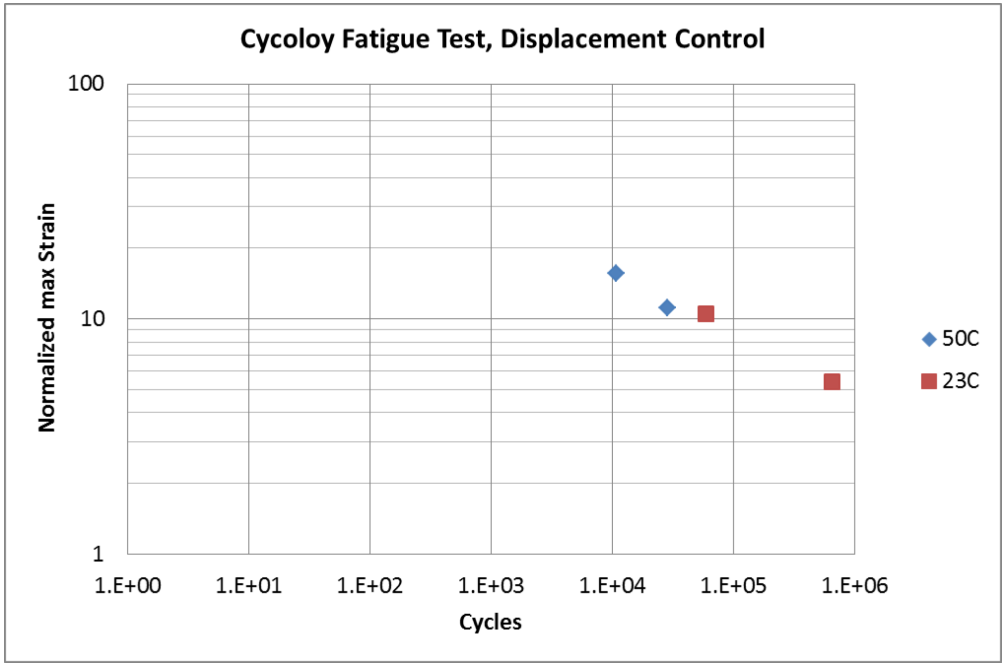
PC/ABS Blend Fatigue Test

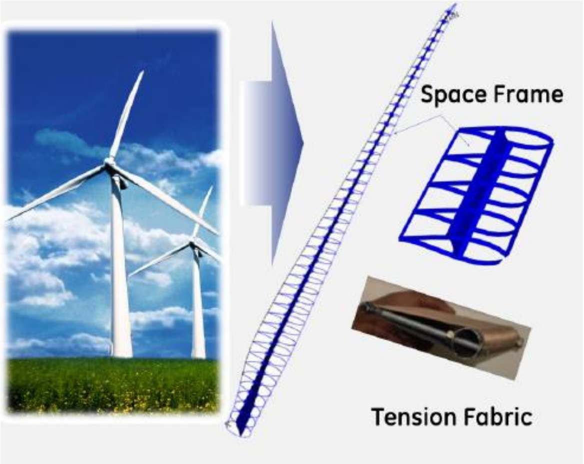




- Fatigue test data indicated the life of PC/ABS blend was significantly lower than LE panel design life.
- Unlikely to find alternate material which meets both structural and cost requirement.

Summary - TFB Strategic Walk

1. Project focused on structure design & manufacturing process – new blade architecture to enable new manufacturing methods for lifecycle cost & LCoE reduction
2. 3 truss structures with fabric cover studied. Various issues & risks encountered: complex fabric tension mechanism, < 3% weight saving, unlikely to meet cost target, etc.
3. Switched to D-beam with non-structural TE. Further study showed 2/3 surface area was composite structure, 4% DM & DL saving vs baseline.



4. Pursued more radical change in blade architecture for more cost saving. Down selected concept to box beam w non-structure LE & TE.
5. Identified thermo-plastic manufacturing process for LE & TE panels to reduce manufacturing cost: high through-put, low labor cost, low mold cost. Replaced fabric with thermoplastic for labor saving.
6. Candidate thermoplastic materials have reasonable static testing results, but poor fatigue testing results, not meeting design life.
7. Unlikely to find alternate material which meets both structural and cost requirement, not pursue further.
8. Program met ARPA-e's charter: high risk developments, success is measured by taking the project as far as necessary, but also knowing when to stop.