Multifunctional Composite Sensor Support Structure with Integrated Cooling

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November 09, 2023
Outline

1. Motivation and Introduction
2. Hybrid composite design
3. Simulation results
4. First prototypes
5. Summary, conclusions and future work
Why is mechanics design important? - Future colliders (FCC-hh like)

High-luminosity phase of the LHC as example in this talk, but future colliders

- Momenta and angular ranges up by 10x and 2x
- Challenging for forward tracking/detectors
- Pile-up of a thousand results in very harsh conditions

HL-LHC upgrades as example:

- Support structures need to be optimized, light-weight → minimal mass possible, highly thermally conductive
- CMS HL-LHC upgrades as example

<table>
<thead>
<tr>
<th>Pixel Layer dose (3.7cm)</th>
<th>HL-LHC $3 ab^{-1}$</th>
<th>FCC $3 ab^{-1}$</th>
<th>FCC $30 ab^{-1}$</th>
<th>FCC (2.5cm) $30 ab^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\times 10^{16} n_{eq} cm^{-2}$</td>
<td>1.5</td>
<td>3</td>
<td>30</td>
<td>70</td>
</tr>
<tr>
<td>Dose (MGy)</td>
<td>5</td>
<td>10</td>
<td>100</td>
<td>220</td>
</tr>
</tbody>
</table>
Material budgets and mechanics

Substantial R&D on all fronts to make a FCC-hh detector a reality

- Support & Cooling constrains Tracker performance, e.g. thermal runaway
- Mechanics is significant fraction of the material budget
- Material testing standardization for irradiation response

- Can improve b-ID efficiencies by 2-3% per b-jet and high b-jet multiplicity ~10-15%
- Significant improvement by novel approach, b-ID relevant for di-Higgs (priority @FCC-hh)
Current Architecture of Support Systems

- State of the Art: Multilayer Structure
  - Integrates layers of different material systems with low thermal conductivity (e.g., epoxy interface)
  - Extensive multi-step fabrication process
  - Involves metallic cooling lines
  - Fabrication process poses additional challenges for non-planar geometries
  - Interfaces between layers involve thermal and thermomechanical considerations
Thermal Performance of Current Architecture of Support Systems

Multilayer Structure

Thermal FEA

Contribution of Each Layer to Thermal Response

- Silicon Module (Chip + pixel sensor)
- Thermal Interface Material, 100µm thick, $k_{th}=1.25$ W/mK
- Carbon Fiber Layer, 200µm thick, $k_{th}=0.03$ W/mK
- Epoxy Interface, 100µm thick, $k_{th}=1.1$ W/mK
- Carbon Foam Layer, 2.5mm thick, $k_{th}=35$ W/mK

- Cooling pipe, 50µm thick, $k_{th}=3.3$ W/mK

- Through-plane thermal conductivity of layer [W/mK]
- Nominal thermal conductivities of different layers

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Hybrid Composites for Support Structures with Integrated Services

Two-step manufacturing process to produce monolithic hybrid structures with integrated services

- Additive manufacturing of preforms to provide control of continuous fiber orientation
  - Fiber orientation is driven by thermal and thermomechanical performance requirements
- Compression molding to consolidate printed preforms and to integrate cooling lines
  - Remove voids and reduce effect of interfaces between dissimilar layered materials
Prototype Support Structure with Integrated Services

- Cooling lines molded in.
- Thermal pathways provided by continuous carbon fibers.
- Stiffness provided by ribbed structure and continuous carbon fiber (Weight 60% < sandwich structure).
- Strength provided by continuous carbon fiber
- Compression molding process included:
  - Preform of continuous fiber impregnated with PPS.
  - Printed continuous and discontinuous carbon fiber reinforced PPS.
Continuous Carbon Fiber Inclusion in 3D printed preforms

- Continuous carbon fiber filament produced by pultrusion process.
- 40% by volume of carbon fiber
- Average impregnated filament diameter of 1.5 mm
- Achieved high level of impregnation (>95%)
- Commercial grade of carbon fiber compounded with PPS was used for printing (50% wt. CF-PPS).
Characterization of Thermal Conductivity

- Laser flash technique (ASTM E1461) used for characterizing thermal conductivity of printed material (50% by wt. of carbon fiber reinforced PPS)
- Micromechanics models to predict thermal conductivity of filament with continuous carbon fiber.

Thermal conductivity in the three principal directions of printed short carbon fiber reinforced PPS.
Characterization of Thermal Conductivity

- Micromechanics predictions of thermal conductivity for 40% by volume of continuous carbon fiber reinforced PPS.
  - Two-step homogenization using Mori-Tanaka method.
  - Types of fiber considered: Hexcel AS4\(^1\) and Nippon CN-90
  - Polymer considered: Celanese Celstran 0203P6 PPS\(^2\)

<table>
<thead>
<tr>
<th>Hexcel AS4</th>
<th>Thermal Conductivity ((W/mK))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(K_{11})</td>
<td>2.918</td>
</tr>
<tr>
<td>(K_{22})</td>
<td>0.5</td>
</tr>
<tr>
<td>(K_{33})</td>
<td>0.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Nippon CN-90</th>
<th>Thermal Conductivity ((W/mK))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(K_{11})</td>
<td>200.2</td>
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<tr>
<td>(K_{22})</td>
<td>0.72</td>
</tr>
<tr>
<td>(K_{33})</td>
<td>0.72</td>
</tr>
</tbody>
</table>

\(^1\) Hexcel Corporation. HexTow\(^®\) AS4 Carbon Fiber Product Data Sheet. 2020.
Steady State FE Heat Transfer Analysis

- Heat transfer analysis used to drive design of continuous fiber and to investigate effects of fiber thermal conductivity
- Surface heat flux (0.1 - 1 W/cm²) applied over detector’s surface (heat flow of 2.5 – 25.85 W)
- Cooling line set to −35 °C
- Convection ($h = 7.5 \frac{W}{m^2°C}$) and radiation ($\epsilon = 0.92$) from exposed surfaces to ambient temperature of −20 °C
- Assumed ideal bonding between material systems (no thermal resistance)
Finite Element Mesh

Continuous Fibers Reinforcements:
- Hexahedron element mesh (DC3D8)
- Thermophysical properties of continuous carbon fiber reinforced PPS (investigated Hexcel AS41 and Nippon CN-90)
- Considered orthotropic elastic properties and thermal conductivity based on material orientation (Fibers oriented across cooling line)

Discontinuous Fibers Structure:
- Tetrahedral element mesh (DC3D4)
- Considered properties of short-carbon fiber reinforced PPS (measured experimentally)
- Neglects anisotropic thermal conductivity

Continuous Fiber System + Discontinuous Fiber System = Hybrid Compression Molded Structure
Temperature Field with Different Fiber Systems

Steady state temperature field at heat flow of 10.34 $W$

Hexcel AS4

Nippon CN-90

NOTE - Temp scale is different between the two plots
Temperature Fields at Different Heat Flows

- Fiber system considered: 40% vol. Nippon CN-90 reinforced PPS

Heat flow = 5.17 \( W \) 
\((0.2 \, W/cm^2)\)

Heat flow = 15.51 \( W \) 
\((0.6 \, W/cm^2)\)

Heat flow = 25.85 \( W \) 
\((1.0 \, W/cm^2)\)
Temperature Difference Between Detector and Coolant

- Temperature difference between detector and coolant varies between 4.2 °C and 15 °C across the detector.

Heat flow = 25.85 \( W \) (1.0 \( W/cm^2 \))

State of the art – CMS-Phase II Upgrade has \( \Delta T \sim 12 \text{ to } 17 \, ^\circ C \)
Stress Analysis of Hybrid Structure Under Pressure

- Cooling line pressurized at 68.9 Bar

**Stress in Fiber Direction**

\[ \sigma_{11} \ll X_1^T \sim 300 - 500 \text{ MPa} \]

**Stress Transverse to Fiber Direction**

\[ \sigma_{22} \ll X_2^T \sim 30 - 50 \text{ MPa} \]
Compression Molding Process

Positive Tool

Negative Tool

Printed discontinuous fiber reinforced thermoplastic

P = 35 Bar
T = 300 °C
Prototype Support Structures with Integrated Services – AS4 fiber

- Cross section of molded prototype demonstrates:
  - Feasibility of integrating cooling line with non-metallic liners
  - Hybrid continuous and discontinuous fiber architecture
  - Consolidation of multiple material systems through compression molding

- Printed carbon fiber reinforced PPS
- Cooling line (shown with liner before removal)
- Continuous fiber impregnated with PPS
Extended Multifunctional Test Structure – AS4 fiber

- Aim to show scale up capabilities of the manufacturing method
- Validate the structure with pressure and temperature testing
Part Performance Simulation for Pressure Test at 600 psi (41.3 bar)
Coolant Pressure – AS4 fiber

\[ \sigma_{11} \ll X_1^T \sim 300 - 500 \text{ MPa} \]
Deformation Scale Factor: 150x

\[ \sigma_{22} \ll X_2^T \sim 30 - 50 \text{ MPa} \]

\[ \sigma_{33} \ll X_3^T \sim 30 - 50 \text{ MPa} \]
Preliminary Results – Pressure Test – AS4 fiber

- Pressure test carried out at increments of 3.4 Bar up to 48.3 Bar
- N2 gas used for pressure test
- Sample held for 5 minutes at each pressure
Preliminary Results – Thermal Response – AS4 fiber

- Thermal response test carried out with room temperature coolant and film heaters to mimic sensors mounted on the surface of the structure
- Transient response recorded for $5 \, W/in^2$ and $7.5 \, W/in^2$ heating

Support structure prototype v2 with integrated cooling lines – $5 \, W/in^2$

Support structure prototype v2 with integrated cooling lines – $7.5 \, W/in^2$
Preliminary Results – Thermal Response – AS4 fiber

- Upcoming tests –

Thermal response with coolant at -20°C

Temperature difference between detector and coolant varies between 10 °C and 42.5 °C across the detector (-20 °C cooling line temperature)

Heat flow = 25.85 W
Convection Coefficient = 3000 [W/m²K]
Summary and Conclusions

1. The hybrid structures with integrated services offer the potential to reduce manufacturing time, cost, and to improve thermal performance.
   - Reduces the number of thermal interfaces
   - Provides engineered thermal paths through microstructures printed with highly thermally conductive fibers
   - Offers the potential to remove metallic liners used in traditional designs
   - Allows for complex non-planar designs

2. The heat transfer and structural analyses showed the potential to meet the thermal and structural requirements of support structures

3. The prototype demonstrated the feasibility of manufacturing support structures with integrated cooling
Future Work

1. Conduct experimental validation on prototype v2
   - Structural integrity of structure under cooling’s line pressure with scale up potential
   - Integrity of custom developed non-metallic cooling line connections
   - Thermal performance at sub-zero coolant temperatures
   - Verify simulation predictions for temperature fields in representative conditions

2. Apply technology to full size support structure
   - Potential for modular designs
   - High thermal conductivity fibers to improve thermal response
Acknowledgments

Award No.: DE-SC0022341
Thank You!