U.S. MAGNET DEVELOPMENT PROGRAM

Modeling of the Interface Debonding Status and Future Plans

G. Vallone[1], E. Anderssen[1], D. Arbelaez[1], L. Brower[1], P. Ferracin[1], J. L. Rudeiros[1], S. Prestemon[1], T. Shen[1], S. Yin[1]

[1]Lawrence Berkeley National Laboratory

US-MDP Collaboration Meeting 2021

05 March 2021

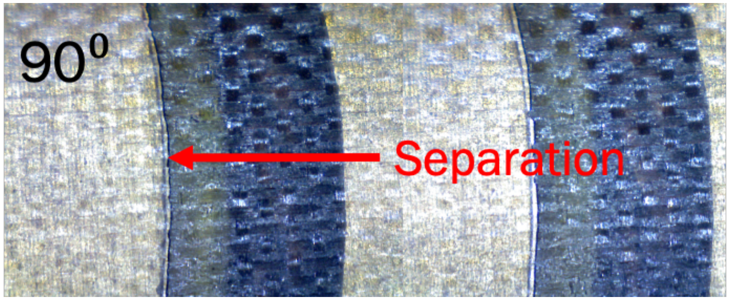
Outline

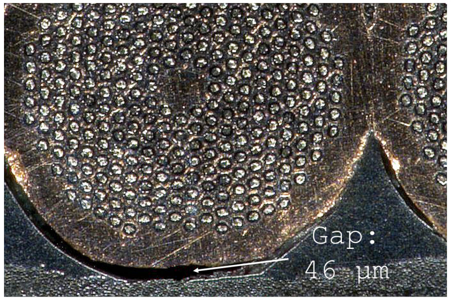
- Introduction
- Interface strength: measurements and models
- CCT debonding model
- Conclusion

Outline

- Introduction
- Interface strength: measurements and models
- CCT debonding model
- Conclusion

Introduction



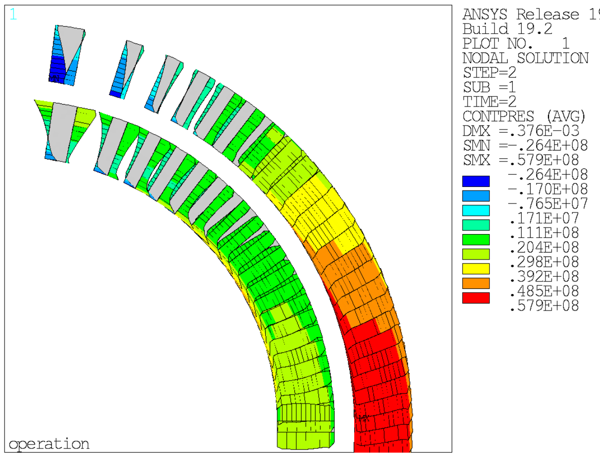


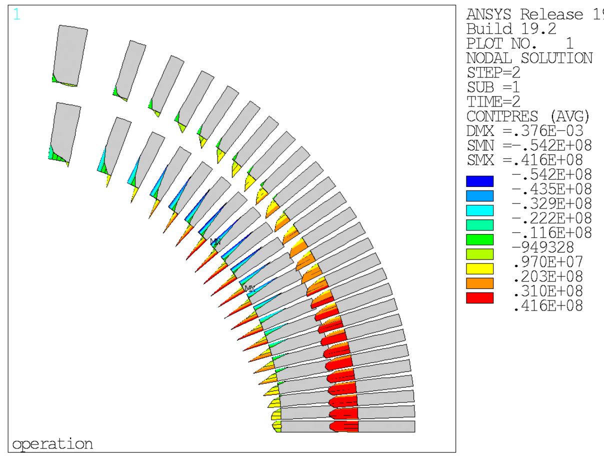
- **Bonded joints** (interfaces) are **commonly used** in superconducting magnets coils
  - Pole/coil, pole/wedges in cos(ϑ) designs
  - Pole/coil in block coils
  - **Even more** used in certain '**stress-managed**' designs: e.g. spar/cable and rib/cable in CCT magnets

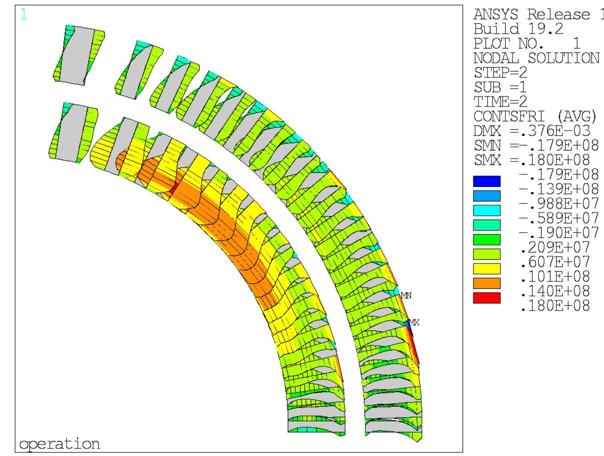
- These interfaces **can fail**:
  - Their failure is considered one of the possible cause of **training**
  - **Our failure criteria** are often **empiric** (e.g. 20 MPa on the max/avg. tension)
  - **Shear stress** rarely considered as possible source of failure

- In FE models we often consider only 2 cases: perfectly **bonded**, and completely **debonded** (with or without friction)
  - Reality can be in between… The **interface** may be **failed** only **partially**
  - As often happens on supercond. magnets, almost impossible to **measure** during a magnet test…

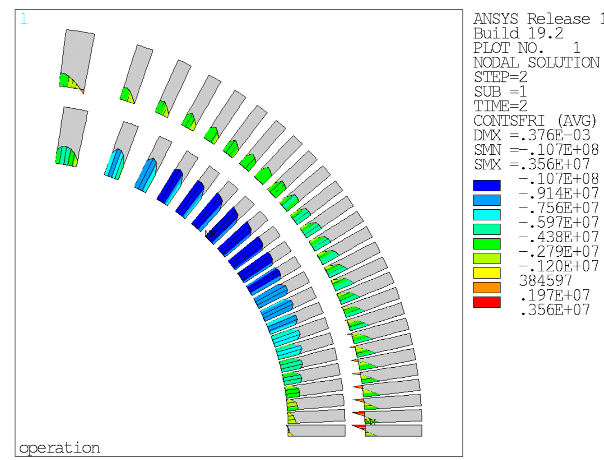
CCT5 FE Model - Tension







- FE 2D numerical model of CCT5 – **bonded** contacts
- **Normal** contact status during powering:
  - Conductor/rib: 26 MPa max **tension** on the first turn
  - Conductor/spar: worst condition at ~45°with 54 MPa of tension
- **Shear** contact status:
  - Conductor/rib: 18 MPa max shear stress on the outer layer
  - Conductor/spar: worst condition at ~45°with 10 MPa of shear stress at the interface
- **After 'partial' detachment** the situation could **change**: increase of tension on other interfaces?



The Plan

- Our FE models are often neglecting significant mechanical phenomena – would be acceptable only if the bonded joints were strong enough (design?)
- Preliminary **plan**:
  1. Measure interface behavior with ad-hoc **experiments**
  2. Develop a **FE** model of the **experiments**
  3. **Calibrate** the **interface** models on the **measurements**
  4. Use the calibrated model on a **2D** model of a CCT magnet (CCT5) / subscale
  5. Develop **3D** models (probably need to re-calibrate the interface models)

- **Goals**:
  - Understand better the debonding process at the coil/mandrel (pole…) interface
  - Reproduce and understand CCT4/5 training
  - Propose improvements (that might be tested on the subscale)

- **Disclaimer**:
  - The results presented hereafter, especially in absence of more measurements, can provide only a qualitative reproduction of the real magnet behavior.

Outline

- Introduction
- Interface strength: measurements and models
- CCT debonding model
- Conclusion

Interface Properties Measurements

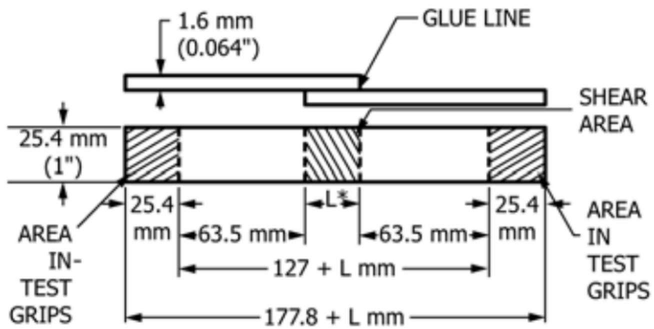
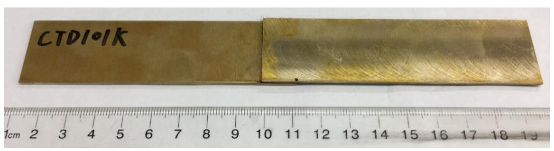
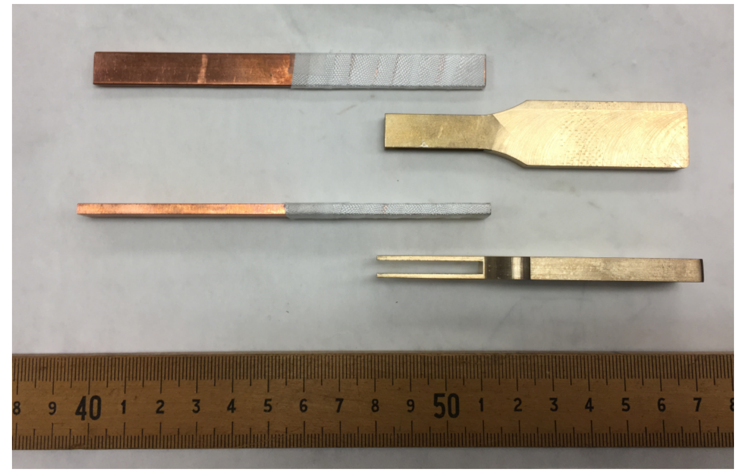


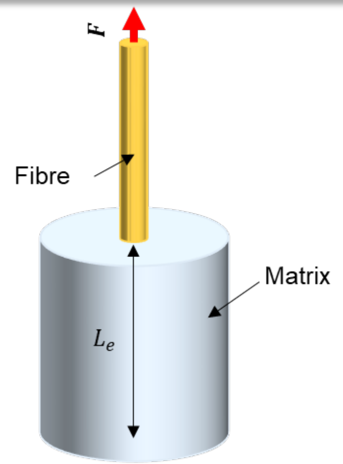
FIG. 1 Form and Dimensions of Test Specimen

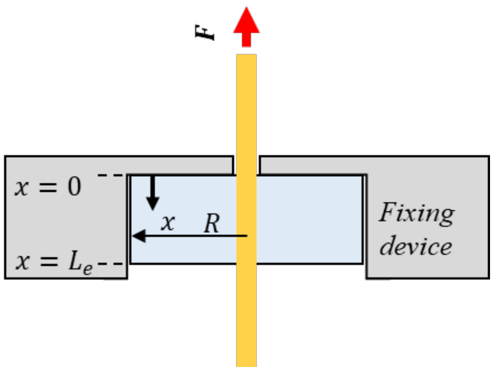


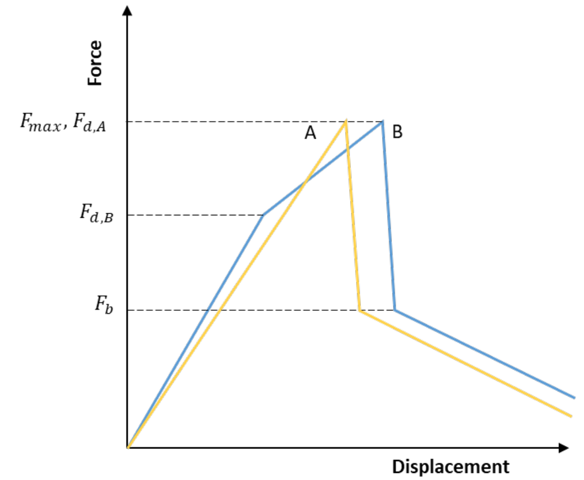


- **Preliminary** measurements on **single lap** and **double lap** shear samples
  - Single lap useful for **mixed mode** (tension+shear) failure (likely to occur in magnets)
  - Double lap useful for verification of **shear** failure
- These tests tried to **reproduce** as close as possible the **coil/structure** interfaces
  - Copper/copper (single-lap), impregnated insulation/Aluminum bronze (double-lap)
- Still **missing** some effects:
  - **Reaction** impact on bonding
  - Effect of **temperature**, insulation **thickness**, etc.
- **Released energy** during crack propagation?

Interfacial Shear Strength Characterization – Pull-out Technique





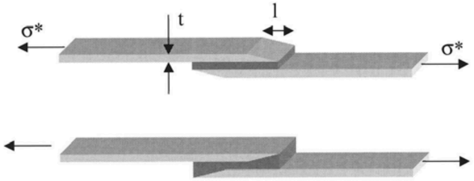


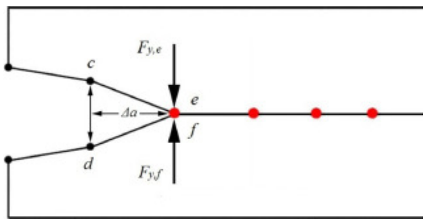
- **Experiments planned**, using the **pull-out** technique:
  - Quick and versatile sample preparation, allowing for the characterization of the main three types of interfaces present in the Nb3Sn based CCT coil:
    1. Nb_3Sn strands – Resin 2. S-2 glass insulation – Resin 3. Mandrel - Resin
  - Direct estimation of both interfacial **shear strength** (IFSS) and **friction** coefficient between constituents.
- **Proposed measurements**:
  - Different resins at room temperature, including CTD-101K as a benchmark, with at least 10 samples per system.
  - Further studies might include thermal analysis, 77 K testing, SEM examination of debonded surfaces.

Proposal by J. L. Rudeiros

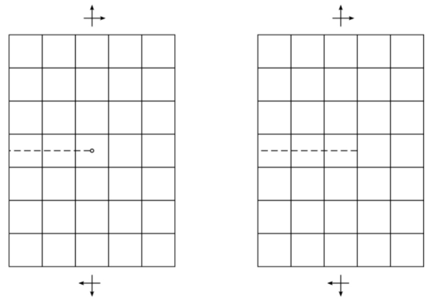
Debonding Material Models

- Many **methodologies** available to simulate debonding:
  - 'Manually' **kill contact** elements – needs a failure criteria (e.g. max tension/shear, VCCT). Does not allow to 'degrade' the contact stiffness during failure.
  - **VCCT** (Virtual Crack Closure Technique, used as fracture criteria)
  - **Plastic glue** models – with/without killing the underlying contact
  - Cohesive zone model (**CZM**)
  - **SMART** crack growth (K_I/J-integral + adaptive re-meshing)
  - **XFEM** – special elements that allow the crack propagation inside. More useful when the crack propagation path is unknown.



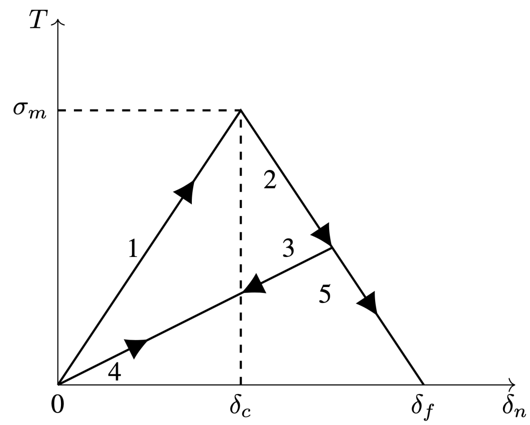


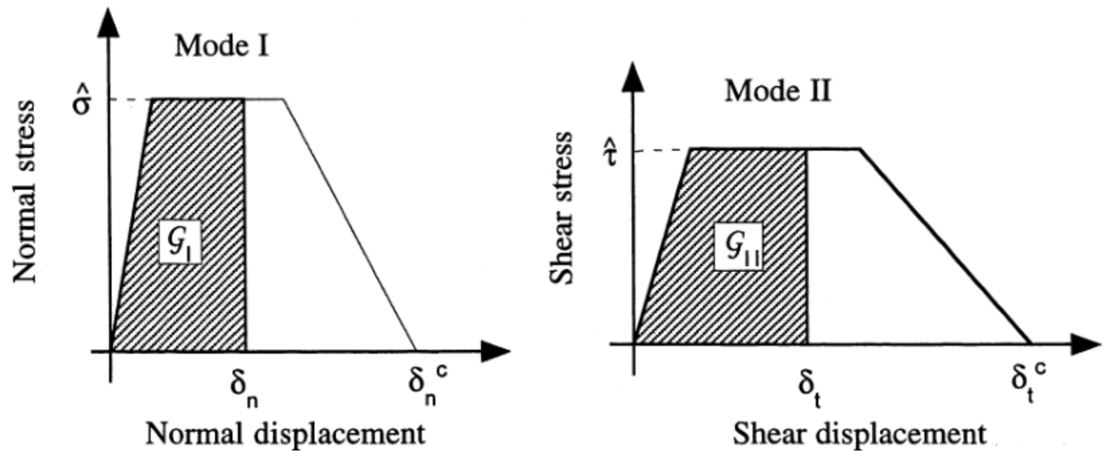
- Here after we use **CZM**, particularly suited to our scope:
  - We already know the potential failure locations (interfaces…)
  - Allows to simulate **mixed** mode failure, glue plasticity
  - **No** need for:
    - **Special meshes** near the crack (**no remesh** after propagation)
    - Explicitly **model** the **glue** – easy to extend available models



- Material properties required:
  - Glue elastic properties (E, nu) and thickness (difficult to know in our case…)
  - Elastic and shear **strength**
  - **Fracture** release energy for both modes (G_{Ic}, G_{IIc})

Cohesive Zone Material Model





- Cohesive zone model for **single-mode** failure:
  - Initial slope dictated by the **glue modulus** and **thickness** → Glue thickness can change the joint strength…
  - δ_c is the displacement at the **damage** '**start**'
    - **Degraded stiffness** for damaged interfaces
  - δ_f is the displacement at the **debonding completion**
  - Damage defined as: $\lambda = \frac{\delta - \delta_c}{\delta_f}$ for $\delta > \delta_c$, 0 otherwise
  - Total area below the curve equal to the **energy release rate** G

$$\lambda = \sqrt{\left(\frac{\delta_n}{\delta_n^c}\right)^2 + \beta^2\left(\frac{\delta_t}{\delta_t^c}\right)^2}$$

- **Mixed-mode** failure:
  - **Quadratic** sum for mixed mode debonding (beta assumed equal to 1 here)

- **Some issues**:
  - Standard ANSYS allows only for **bilinear** laws with mixed mode failure(more can be added with subroutines)
  - **Post-debonding friction** does not work (should work, seems a bug. Can still activated manually during solution)

How strong can adhesive joints be?

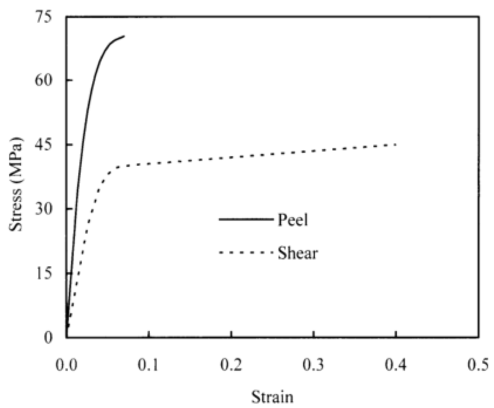
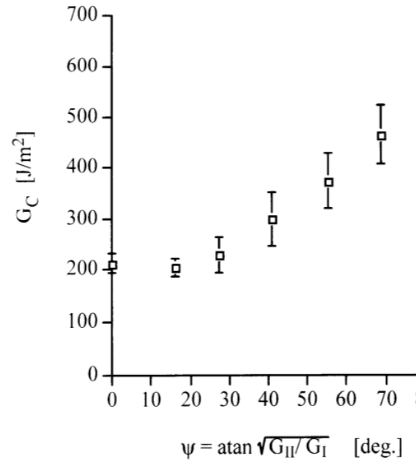
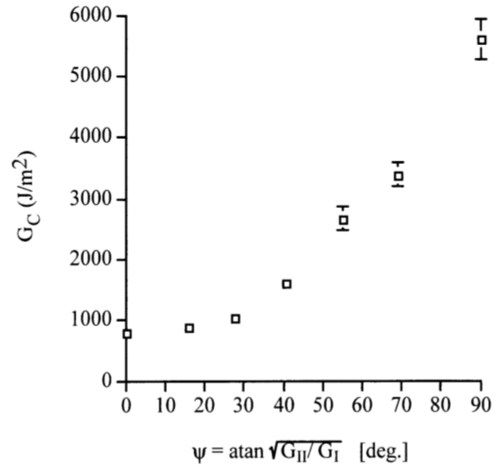


Figure 2.16 Stress-strain curves for FM300-K film adhesive [53]





- Tensile **strength** of bonded joints is usually lower than 100 MPa (50 MPa for Shear)
- **Common** values around 70 MPa tensile, 35 MPa shear
  - **Tresca** criterion seems to apply on most adhesives (shear = ½ tensile)
  - A reliable 70 MPa bonding strength would allow to significantly decrease stresses on the conductor in many designs…
  - This would also require a glue layer 'thicker' than what we normally consider (0??)

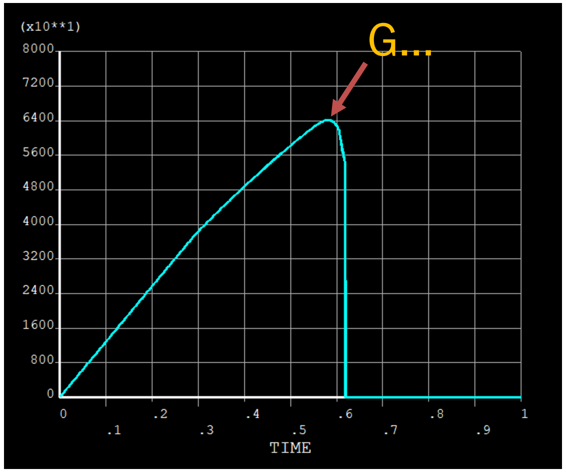
- $G_C(\Psi)$ curves measured on different adhesive systems (Cybond 4523GB, Permabond ESP 310) suggest that roughly: $\mathbf{G_{IIc} \sim 3G_{Ic}}$

Material Model Calibration

DOUBLE LAP JOINT TEST					
smax	Gcn	tmax	Gct	Fmax	Stress
MPa	J/m2	MPa	J/m2	N/m	N/mm2
10	200	10	600	97612	9.76
20	200	10	600	98746	9.87
20	200	20	600	193175	19.32
20	200000	10	600000	99584	9.96
70	200	35	600	312706	31.27

SINGLE LAP JOINT TEST					
smax	Gcn	tmax	Gct	Fmax	Stress
MPa	J/m2	MPa	J/m2	N/m	N/mm2
20	200	10	600	92750	9.28
20	100	10	300	90749	9.07
20	50	20	150	87933	8.79
20	25	10	75	73215	7.32
24	50	12	150	100081	10.01
24	25	12	75	74081	7.41
24	30	12	90	81397	8.14

- **Assumptions**: $1.\ \tau_R = \frac{1}{2}\sigma_R$ $2.\ G_{n_c} = \frac{1}{3}G_{t_c}$ $3.\ E = 5\ GPa$

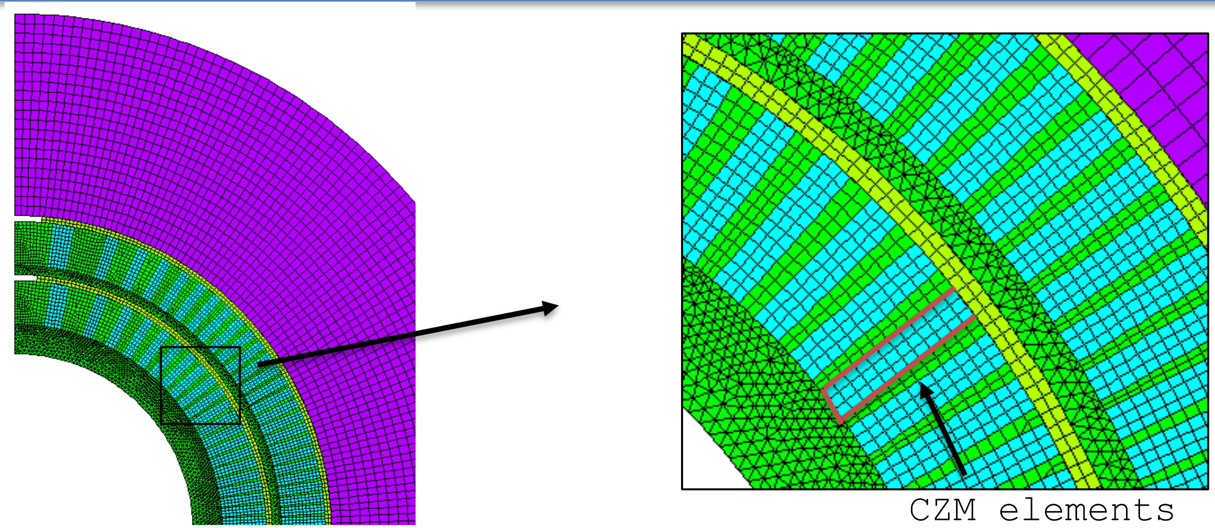


- **Double lap** joint used to calibrate the material **strength**
  - tensile strength: 24 MPa, shear strength: 12 MPa
- **Single lap** joint results used to calibrate the **fracture toughness**
  - Fracture toughness, mode I: 30 J/m^2 mode II: 90 J/m^2
- Preliminary values, more exp. data needed
  - E.g. the **disp./force curve** might allow for a better **toughness** calibration
    - Available data not clean enough
  - Measurements at **room temperature** - no data at cold

Outline

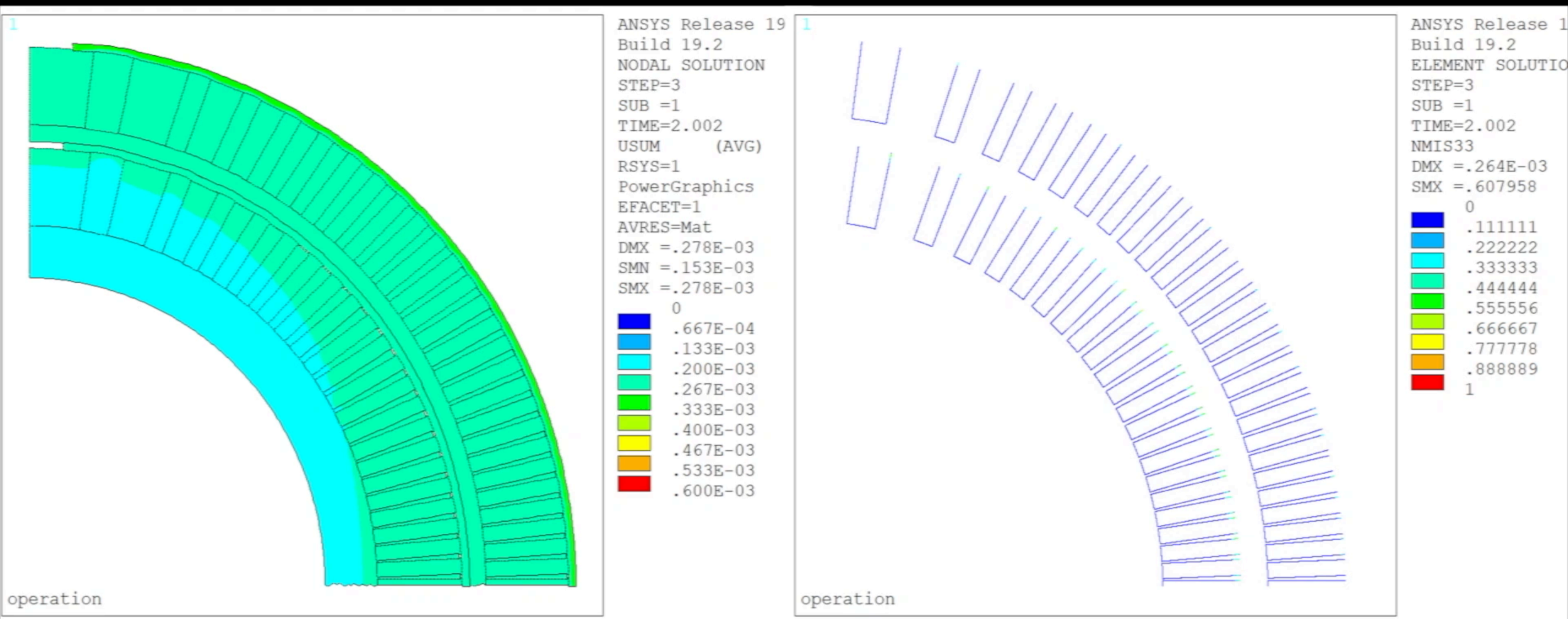
- Introduction
- Interface strength: measurements and models
- CCT debonding model
- Conclusion

CCT Model Description

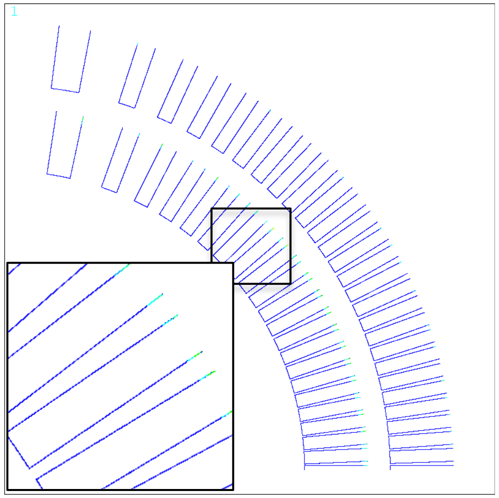


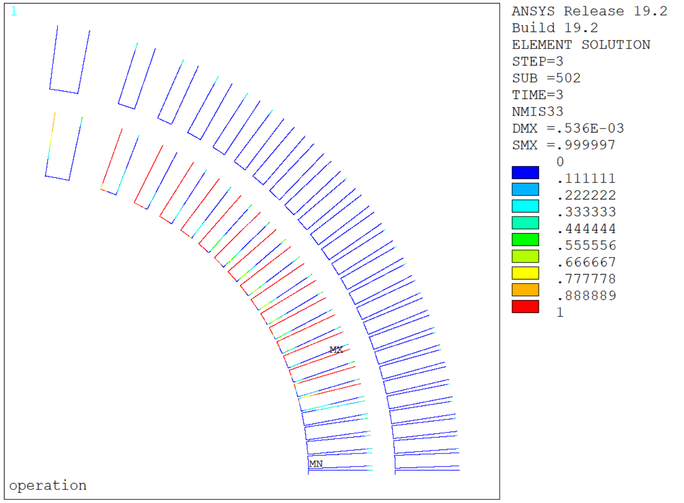
- **Contact** elements with **CZM properties** around the cable (**cable/spar**, **cable/rib**)
- Shim ‘angle’ increased w.r.t reality – otherwise some of the conductor ‘blocks’ fly away after detachment
  - This region is not realistic in 2D anyway
- **Elasto-plastic material** model for the **conductor**
  - Extracted from RVE models of the cable
- ‘**Single ramp**’ simulation – cooldown, then current is increased - no powering/quench/powering simulation

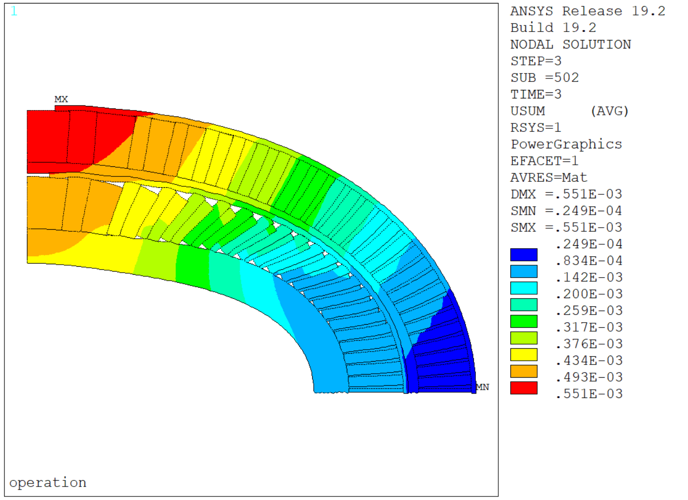
Failure during powering



Failure during powering

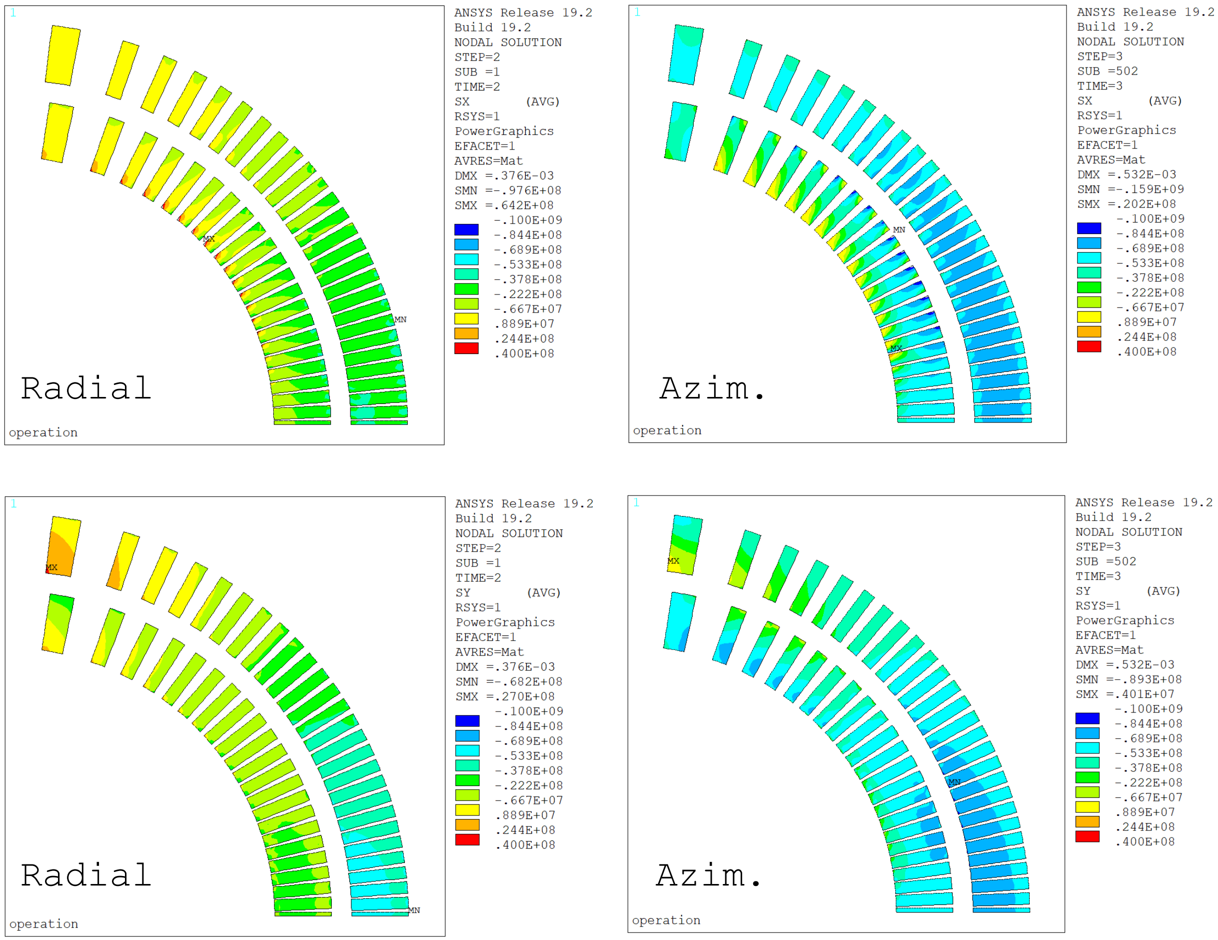






- Some ‘small’ **detachment** after **cooldown** at the outer radius
  - This is what you might **see** looking at the coil after a test…
  - Almost **no damage inside**!
- Significant damage on the **inner layer** – negligible on the **outer layer**
  - Most of the spar/cable interface failed (from ~20 to 75 deg approx.)
  - The rib/cable interface fails on both sides (completely on the side in tension)
- **Failure propagates slowly** from the outer edge, **then suddenly** propagates at around 12 kA
  - Impossible to say if this would be one or multiple **events** in a real magnet
  - This is quite close to where most CCT5 quenches were… (more later)

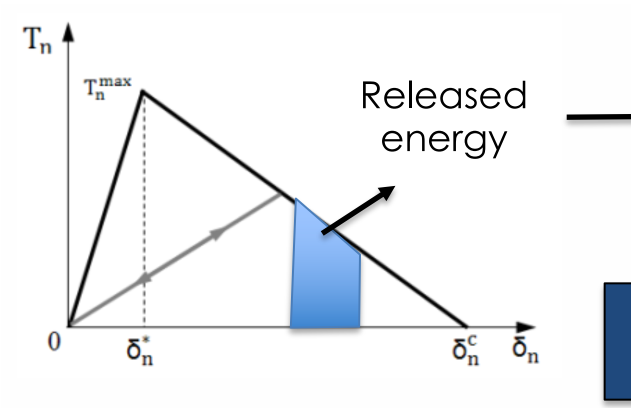
Powering - Stresses



Bonded CZM

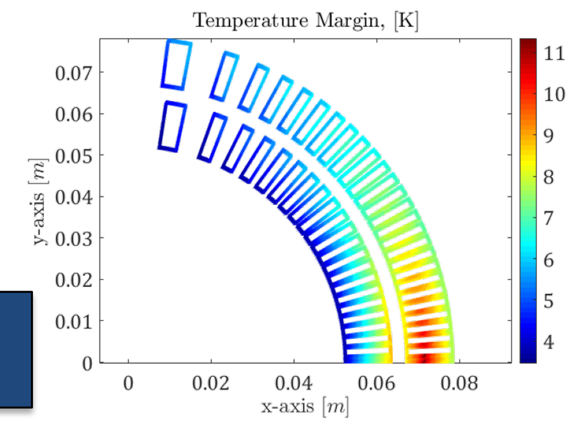
- Does the stress distribution change because of the interface failure?
- **Yes, higher stresses** – neglecting the corner spikes:
  - Radial: 100 MPa vs ~60 MPa
  - Azim.: 90 MPa vs 70 MPa
- The CZM model shows significant **stress gradients**
- Note: stresses on an elasto-plastic model are not ‘what we are used to’ and should not be compared with the empirical limit of 150/200 MPa.

Quench Simulation



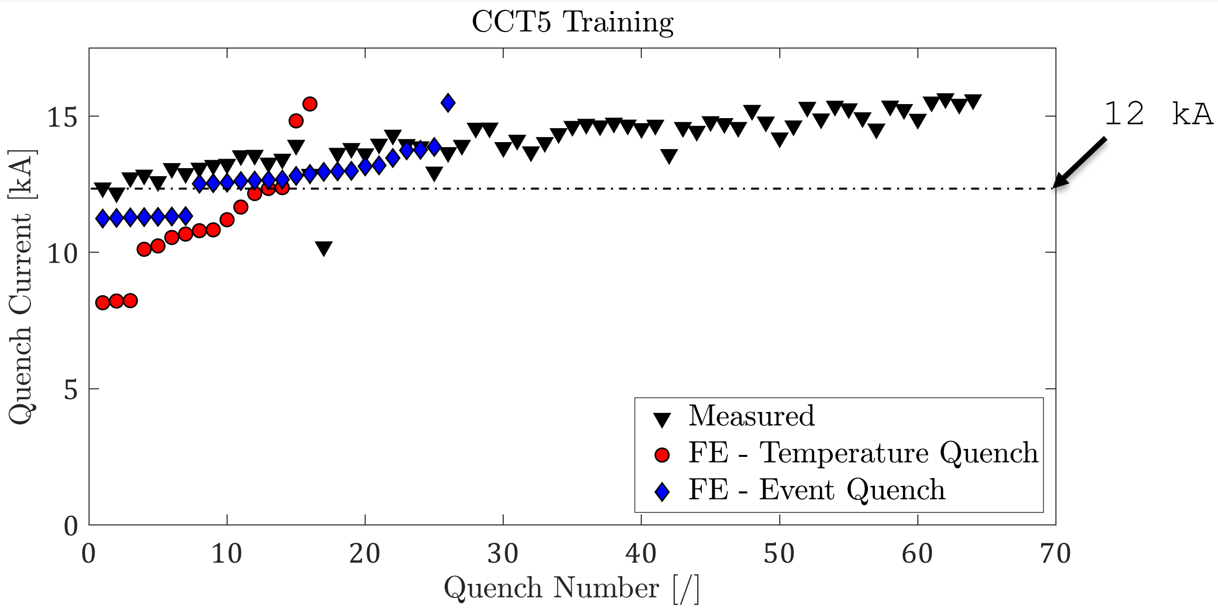
$$dE \propto d\omega(1 - d\omega)$$
$$d\omega \propto d(\delta_n - \delta_n^*)$$

Compare to fixed threshold | Compare to local T margin



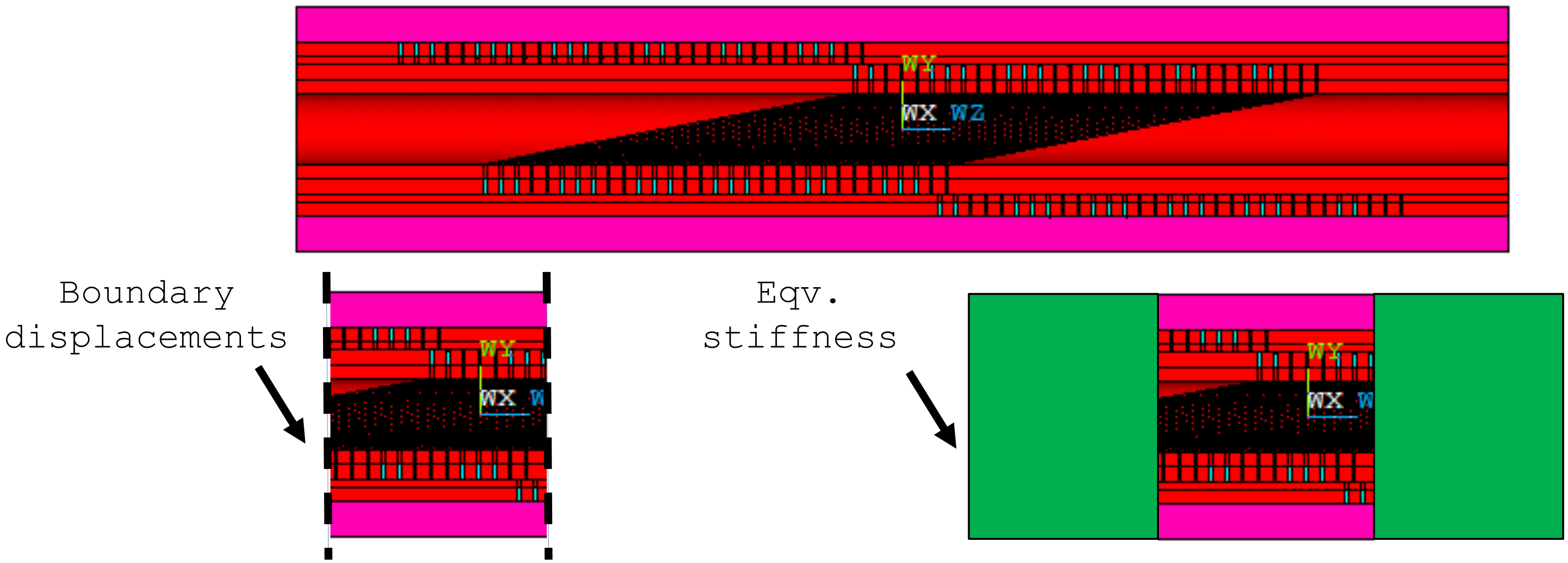
- Can we **correlate** the **crack propagation** to **energy releases**?
  - **Crack energy** released should be related (proportional) to the **heat released** (minus elastic waves…)
    - Difficult to say how much heat goes trough the conductor and how much trough the mandrel
    - Add temperature measurements in the future? Challenging at cryogenic temperature
- A couple of **simplified approaches**:
  1. **Derivative** of **damage** vs time proportional to the released energy?
     - Compute the **local temperature** margin
     - Compute the contact element energy change
     - Assume that the change in temperature is proportional (ok this would have been better with the enthalpy margin)
  2. **Event magnitude** approach
     - The energy released by the crack is propagating to every location in the magnet (shocks?)
     - The limit should not be constant but decrease with the margin…
- This study is **only qualitative**, and useful for **comparison** purposes

Training



- CCT5 **training** curve comparison (threshold calibrated). Results suggest that the 'event quench' mechanism might be predominant. Notes:
  - I am assuming that these events cause quenches, but this result does not prove it
  - We should **compare** the 'crack propagation currents' with **measured AE events**
  - Quenches could be distributed along the **length** – we need a **3D** model!
  - Difficult to say if one '**quench**' does not represent '**multiple quenches**' in reality
- **Prestress** model: apply ~250 MPa of azimuthal stress on the shell
  - **Interface** is **still cracking**, but the **propagation** is **slower,** and the released energy is below the threshold (**no quenches**…)

Scaling to 3D



- Can we run a 3D model of the whole magnet with cohesive elements?
  - Unreasonable, and parallel computation (clusters) would not help a lot (many time steps)
- We need to 'divide' (et impera…) the problem. Possible approaches:
  1. **Submodel** – rough simulation of the whole assembly and refined analysis of the region of interest
  2. **Superelements** – attach equivalent stiffness around the region of interest
     - Not clear how both these approaches would be during **powering**
  3. Single cable along the length with **cut-boundary** conditions (periodic/superel.)
     - Concept similar to Brower's CCT slice model

Outline

- Introduction
- Interface strength: measurements and models
- CCT debonding model
- Conclusion

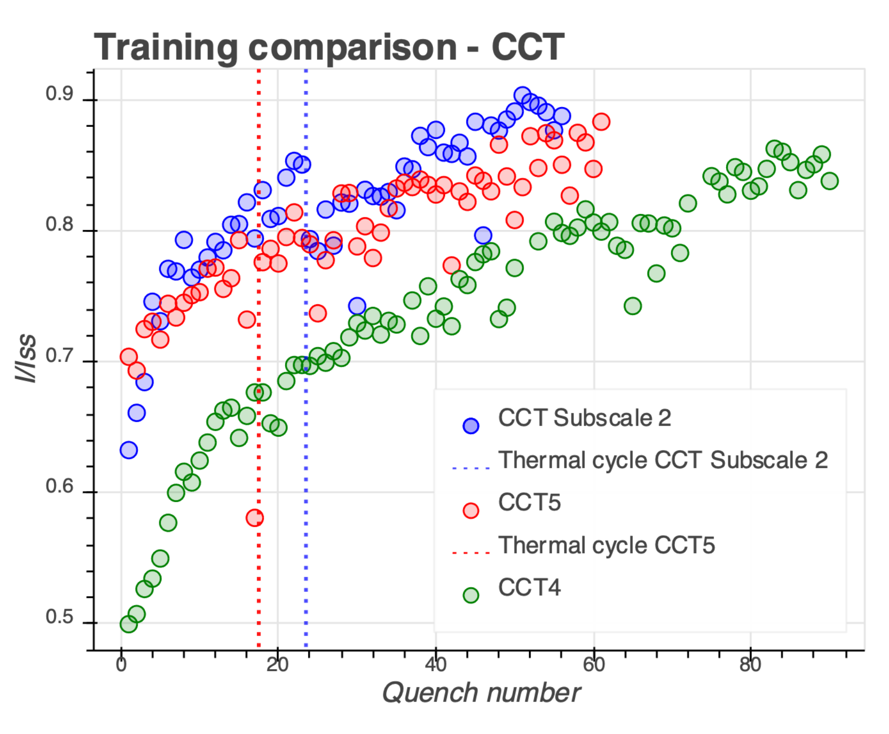
Conclusion

- **Key points**:
  - We developed capabilities to simulate **mixed-mode debonding** of superconducting **magnets interfaces** and applied it to a **CCT model**
  - Results suggest that:
    - Conductor **stresses change** because of the interface failure
    - Debonding might cause quenches via the release of **elastic waves** and not via local heat generation
    - Applying some **prestress** to CCT magnets could reduce training

- **Future plans:**
  - Updated plan for interface properties **measurements**
  - **Comparative** studies (2D model):
    - Stiffer spar study (Is the debonding due to the deformability (bending) or to the applied stress?)
    - Thermal/powering cycles effect on interfaces
    - Different epoxy properties… and more
  - Apply this modeling strategy to the **BOX samples** developed at **PSI**
  - **3D** model

- Questions?

Extra


Training comparison - CCT
0.9
0.8
0.7
0.6
0.5
I/Iss
0
20
40
60
80
Quench number
CCT Subscale 2
Thermal cycle CCT Subscale 2
CCT5
Thermal cycle CCT5
CCT4