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Andong National University

Characterization of electrical delamination behaviors in REBCO coated conductor tapes under transverse loading

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Introduction

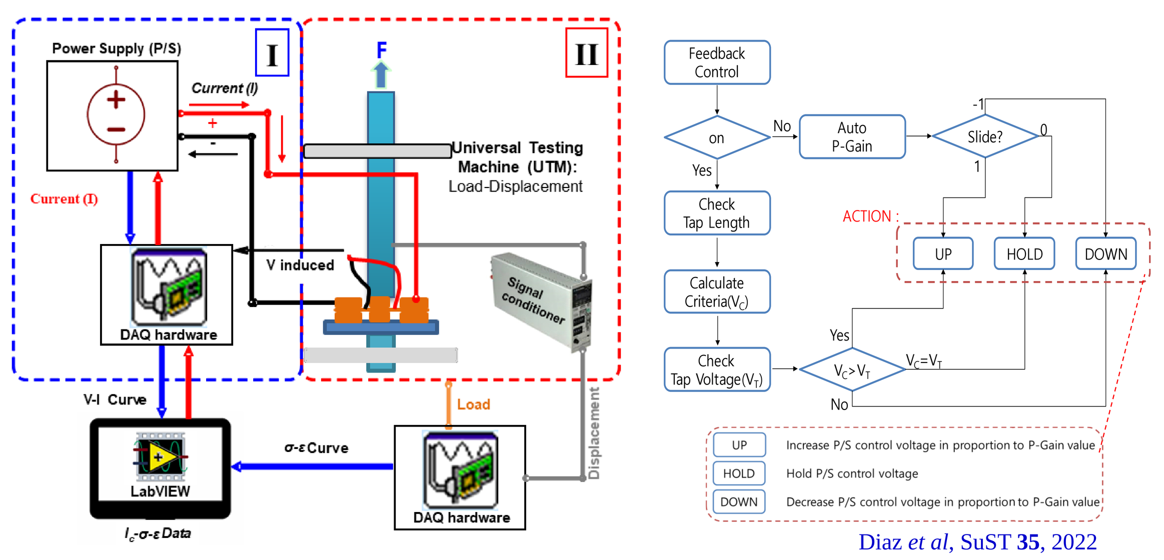
- In the practical application of high temperature (HTS) REBCO coated conductor (CC) tapes, such as epoxy-impregnated or no-insulation (NI) coils.
- These CC tapes experience stress from Lorentz forces and thermal expansion, leading to delamination and degradation of critical current (I_c).
- This study focuses on analyzing REBCO CC tapes subjected to transverse tension at 77 K and self-field to understand the mechanisms behind delamination failure and identify the electromechanically weak points in the multilayered architecture of the practical REBCO tapes.
- The electromechanical delamination strength of three REBCO CC tape samples was determined using a wide Cu anvil and a continuous I_c measurement system, which precisely observes the I_c degradation behavior of the CC tapes.
- Moreover, simulation analysis was used to distinguish the intrinsic strength of each constituent layers of the CC tapes. Stress concentration region were identified and discussed. Delamination schematics were also generated based on the simulation, which further explains the rapid drop in I_c of each tape. It is crucial to prioritize the prevention of delamination in HTS REBCO CC tapes as it negatively impacts their performance during operation.

Experimental procedure

❖ Sample specifications

Fabrication process	IBAD/RCE-DR	IBAD/MOCVD	IBAD/PLD[1]	IBAD/PLD[2]
Structure	Ag/GdBCO/ LMO/IBAD-MgO/Y_2O_3/Al_2O_3/ Stainless steel	Ag/YBCO/LaMO Homo-epi MgO/ IBAD-MgO/ Hastelloy C-276	Ag/YBCO/CeO_2/ $LaMO_3$/MgO/ Y_2O_3/Al_2O_3/ Hastelloy C-276	Ag/GdBCO/$LaMO_3$/IBAD-MgO/Y_2O_3/Al_2O_3/ Hastelloy C-276
REBCO thickness (µm)	~ 1.5 µm	~ 1.6 µm	~ 1 µm	~ 1 µm
Critical current, I_c (A)	~250	~109	~250	~180
Dimension, t x w (mm)	0.122 × 4.06	0.088 × 4.01	0.087 × 4.01	0.047 × 3.98
Substrate thickness (µm)	~100	~ 50	~ 50	~ 35
Stabilizer/lamination techniques	Cu electroplated, surround (~15 µm)	Cu electroplated, surround (~20 µm)	Cu electroplated, surround (~20 µm)	Cu electroplated, surround (~5 µm)
Manufacturer	SuNAM.	SuperPower	SST	SuperOx

❖ System configuration for continuous measurement of I_c in REBCO tapes under transverse tension



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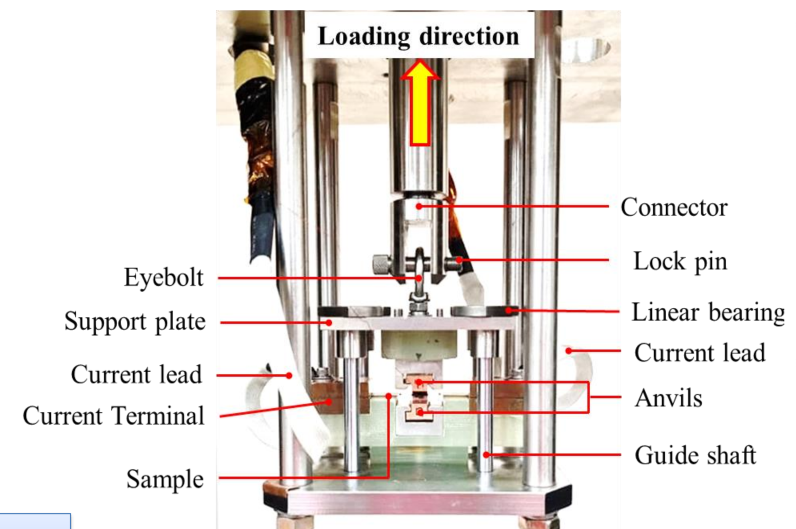
- Monitored tap voltage (V_T) reaching criteria voltage (V_C) determines initial critical current (I_{c0})
- Slide control in block diagram is core function of feedback system
- Pushing up slide increases current to CC sample, while pushing down decreases current
- If monitored V_T differs from V_C, command given to raise or lower P/S control voltage
- P/S control voltage changes via auto P-gain value times slide number (1, 0, or -1)

❖ Electromechanical test setup under transverse tension at 77 K



Conditions on anvil test method:

- ✓ *Anvil dimensions:*
  → 4.5 mm × 8 mm
- ✓ *Displacement rate:*
  → 0.5 mm/min
  → Continuous loading
- ✓ *Test temperature:*
  → 77 K

Condition on EMP measurement:

- ✓ *I_c measurement technique:*
  → Continuous I_c measurement

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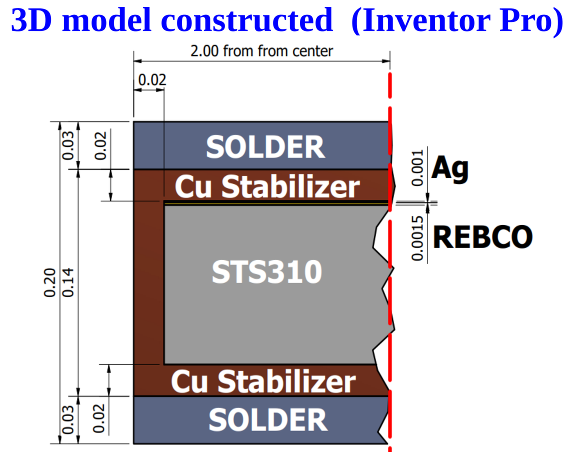
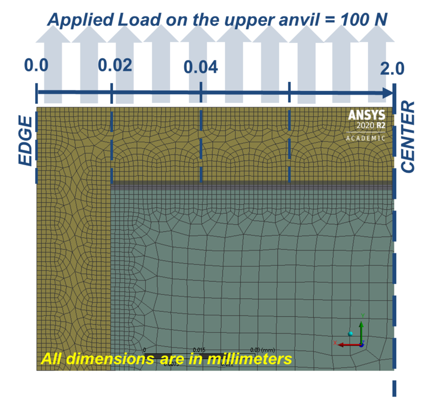
❖ Simulation model and parameters

3D model constructed (Inventor Pro)



Imported model on ANSYS 2020 R2



Material properties used for FEA

Constituent layer	E (GPa)	Poisson's ratio	Yield Strength (MPa)
Ag	76	0.3	13
REBCO	178	0.3	56
STS	200	0.275	600
Hastelloy	200	0.30	700
Cu Stabilizer	117	0.35	100
Solder	30	0.3	60

Modelling Conditions:

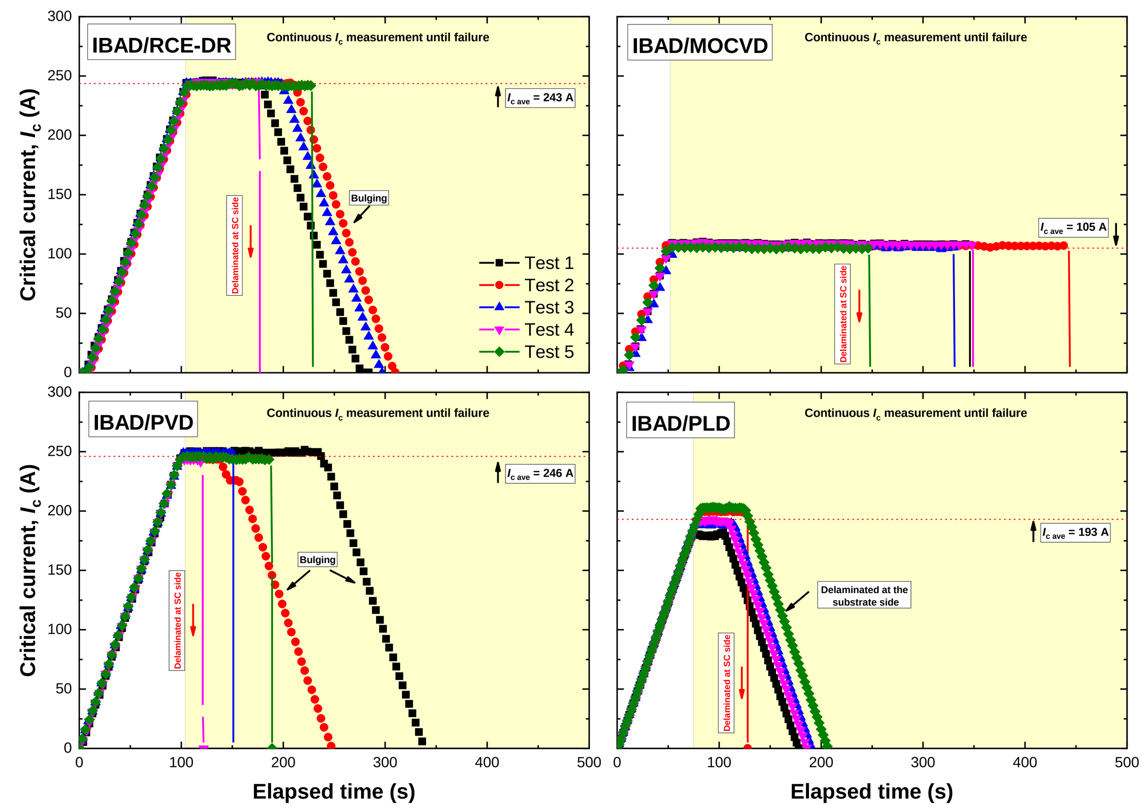
- ✓ The model: **Linear elastic boundary condition.**
- ✓ *Mesh size and shape:*
  → Quadratic element order
  → Node No.: 28,261
  → Element No.:70,819

- Local adaptive mesh refinement was used in the surface contact of Cu Stabilizer to its upper solder, Ag, REBCO, and STS310S, such that stresses at the boundary contacts are more **accurately resolved**.

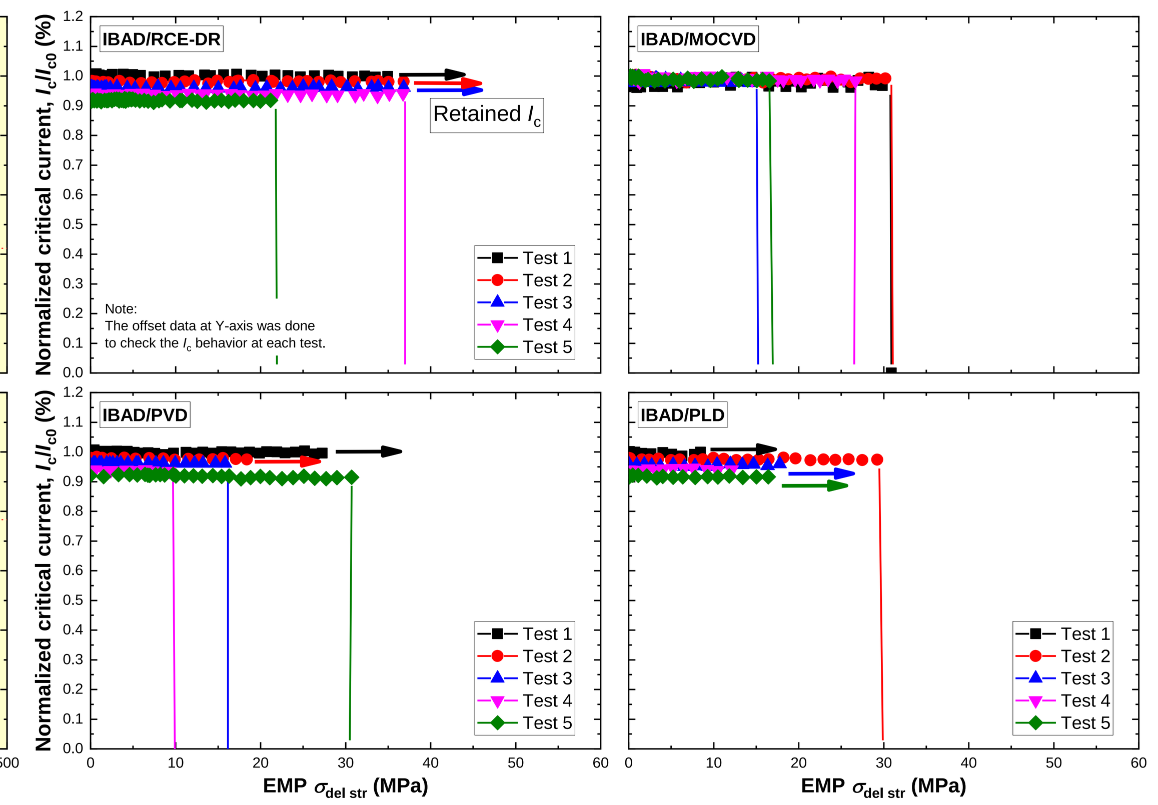
Results and Discussion

❖ Electromechanical properties of commercially available REBCO CC tapes under transverse tensile load

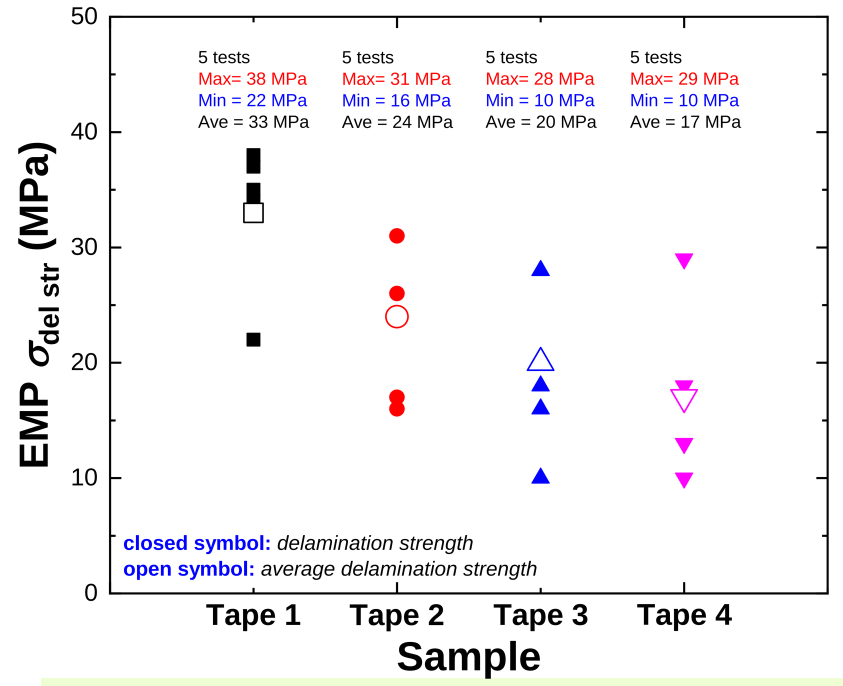
Histories of transport current during loading



I_c/I_{c0} behaviors under transverse tensile load



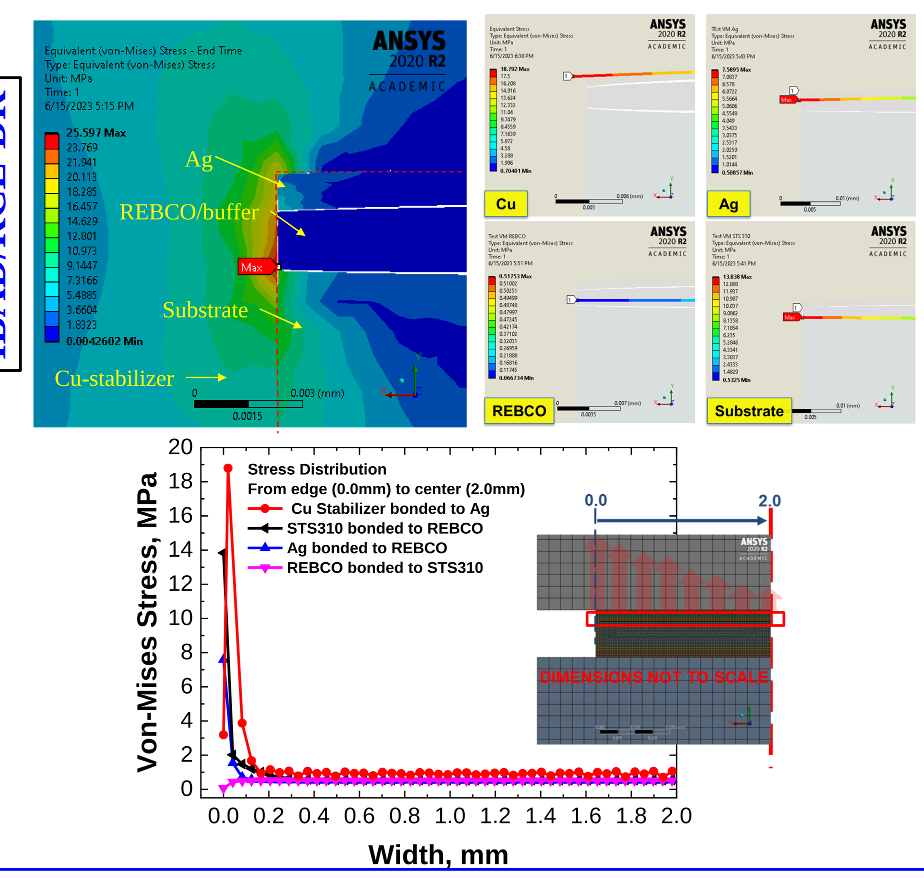
❖ Electromechanical delamination strength distribution



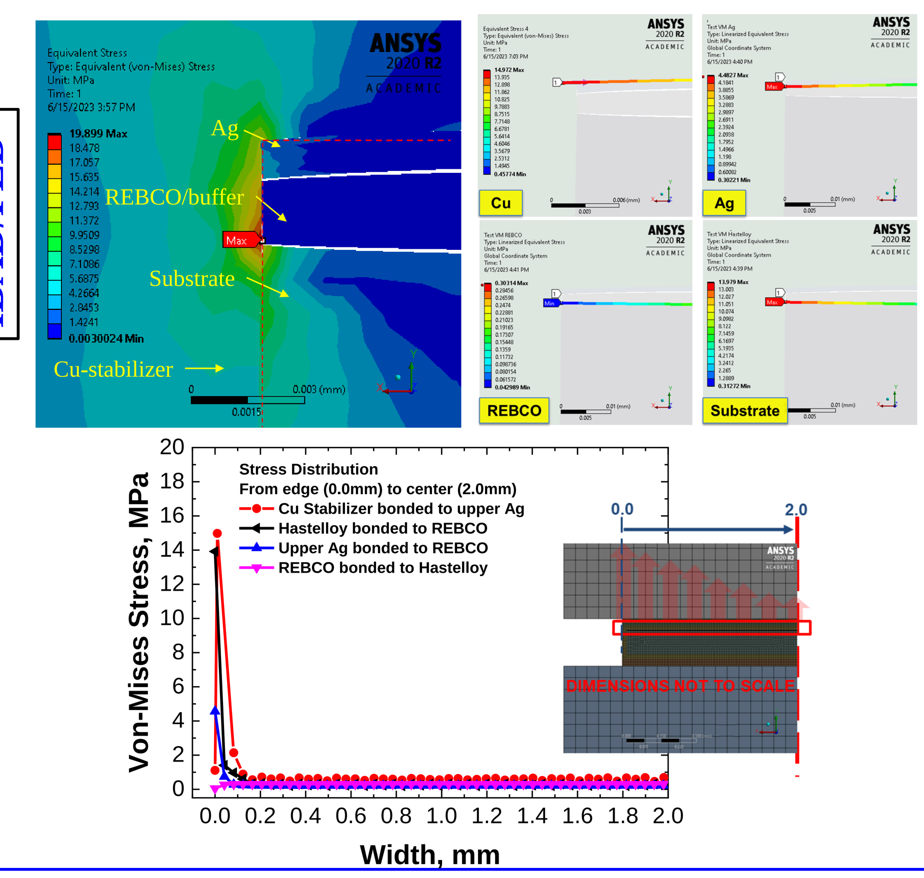
- **Abrupt degradation of I_c** observed in the majority of the samples, a common occurrence in delamination tests.
- IBAD/RCE-DR CC showed the highest delamination strength, an average of approximately 33 MPa at 77 K.
- Scattering extent of strength among samples was similar, with standard uncertainty of ~3.
- Tests involving inclined drops in I_c at the end of the experiment indicate that the REBCO film remained intact without any noticeable damage.

❖ Numerical analysis of stress distribution in two representative Cu-stabilized CC tapes

IBAD/RCE-DR



IBAD/PLD[1]



Stress distribution along the constituent layers of the CC tapes

- **Cu stabilizer** supports all the transverse tensile stress applied to CC tapes. Cu edges effect significantly on the delamination strength of the CC tape.
  - ✓ IBAD/RCE-DR sample, the maximum stress is ~25 MPa
  - ✓ IBAD/PVD[1] sample, the maximum stress is ~20 MPa.
- **Stress concentration** is evident at the **edge of the substrate-REBCO** interface, observable in both samples.
  - ✓ Anticipatedly, the cracking or opening of the CC tape initiates precisely between the substrate-ReBCO interface.
- **Experimental results consistently** demonstrate delamination at the **REBCO film.**
- The **REBCO film** exhibits the lowest transverse tensile stress compared to other layers in the multilayered CC tape.
  - ✓ The **substrate-REBCO interface** is identified as the **weakest interface** among the layers.

Conclusions

- In this study, an investigation of the electromechanical delamination strength of commercially available REBCO CC tapes under transverse tensile load at 77 K. We utilized the anvil test method with a wider upper Cu anvil (4.5 mm x 8 mm) in conjunction with our recently developed continuous I_c measurement system.
- The numerical simulations confirmed that the **weakest interface** among the constituent layers of the REBCO CC tape exists between the **substrate and the REBCO** film. **Stress concentration** was observed at the **bottom edge** of the REBCO film, leading to the initiation of cracks and subsequent delamination fractures.
- The **significance of the Cu edges** in resisting the transversely applied tensile load to the multilayered structure of the CC tape was evident. However, despite the minimal scattering or spread of data, it is still necessary to make efforts to reduce this variability. Enhancing the interfacial adhesion of the substrate layer has the potential to increase the transverse EMP and narrow the scattering of delamination strength.
- Overall, these findings shed light on the delamination behaviors of REBCO CC tapes and provide valuable insights for improving its performance in practical applications.

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