Parajuli, R., Shchukin, A., & Zhang, M. (2026). Novel composite reinforcement technique for HTS joints. IEEE Transactions on Applied Superconductivity, 1-5. https://doi.org/10.1109/tasc.2026.3657321. For the purpose of open access, a CC BY 4.0 licence has been applied

Novel Composite Reinforcement technique for HTS Joints

Roshan Parajuli, Alexander Shchukin, and Min Zhang

***Abstract*— Commercial high-temperature superconducting (HTS) tapes are limited in length, while large-scale applications such as high-field magnets require several kilometers of conductor. Joints between tapes are therefore unavoidable, and their electrical and mechanical reliability is a critical bottleneck. Soldered joints are attractive due to their relatively low resistance, but their mechanical strength is limited because of low adhesion between layers in the HTS tapes. In this work, a new mechanical reinforcement strategy was proposed and demonstrated. Anchor holes in joints allow the new composite structures, introducing different reinforcement components inside the joint, while the effect of the holes is negligible on joint resistance and critical current (I_c). Carbon fiber and epoxy fillings were used as reinforcement materials. This approach enhanced the shear strength of the joint from ~1.2 MPa to ~2.4 MPa, while the electrical resistivity did not increase significantly and had a very low level of ~30 nΩ·cm². The results demonstrated that the novel FIRM (Filling-Induced Reinforcement Matrix) approach for HTS joint can significantly improve the mechanical properties for use in high-field coils and magnets.**

***Index Terms*— Superconducting tapes, Superconducting joints, mechanical reinforcement, delamination**

I. Introduction

High-temperature superconducting (HTS) tapes based on REBCO (Rare-Earth Barium Copper Oxide) have become the leading material for next-generation high-field magnets due to their high critical current density and ability to operate in extreme magnetic fields. However, their limited manufacturing lengths (typically ~1 km) necessitate reliable joints for large-scale devices such as fusion magnets and NMR systems [1]. A key challenge in joint technology is achieving both low electrical resistance and high mechanical integrity under extreme temperature and mechanical stress. Soldered joints are widely used due to their low joint resistance, but their reliability is undermined by mechanical weaknesses, particularly delamination between the REBCO layer, buffer stack, and substrate [2]. Previous studies have reported that failure often initiates at the buffer–substrate interface under shear stress, making reinforcement strategies necessary. This delamination arises from the layered architecture of REBCO tapes, where adhesion between dissimilar materials is inherently weak, leading to failures under shear stress. Such issues are exacerbated in high-field environments where Lorentz forces impose significant mechanical loads [3], [4].

This work was supported by the Innovate UK project "Zero Emissions for Sustainable Transport" and UKRI project "Superconducting electrical machines for zero emission aviation." (Corresponding author: Roshan Parajuli).
Roshan Parajuli, Alexander Shchukin and Min Zhang are with the University of Strathclyde, Glasgow, UK (e-mail: roshan.parajuli@strath.ac.uk).

Prior studies have explored various joint reinforcement techniques, including over-banding and support structures to mitigate these problems. However, enhancing mechanical strength without degrading electrical properties remains a critical gap [3],[4],[5],[6]. This work investigates a novel Filling-Induced Reinforcement Matrix (FIRM) approach by introducing holes in HTS joints and filling them with different reinforcement materials. As a trial, we used carbon fiber threads and epoxy as fillers. The aim of this technique is to provide additional bonding between layers of HTS tape, transferring mechanical strains away from the weak REBCO interface and improve overall joint robustness without compromising electrical performance.

II. Joint Fabrication and Characterization

A. Joint fabrications

We prepared 50x12 mm^2 (6 cm^2) HTS joint samples made of Fujikura and Theva 12 mm HTS tapes. Initial step towards the robust joint fabrication was the optimization of the soldering conditions to achieve low resistance joints while maintaining the mechanical strength.

The soldering process was conducted in three steps:

Solder Application: Tapes were covered with Pb37Sn63 solder in a solder bath to achieve a uniform coating. This step ensures proper wetting and minimizes voids.

Cleaning and Preparation: Residues were removed, RF800 flux applied, and the joint area wrapped with Kapton tape to secure the tapes during pressing.

Heating and Pressing: Tapes were aligned in a face-to-face configuration in a mold and pressed under controlled heat and pressure via a heated press (Fig. 1). The process included heating plates up to required temperature, placement of mold with sample in between the heated plates, reaching required sample temperature with using temperature probe in the mold, pressing the heated plates using the hydraulic press. After reaching required pressure the joint was cooled using forced convection using fans on either side and cooled down to room temperature, then it was taken out of the press. Joints were held under the required temperature for less than 3 minutes in total.

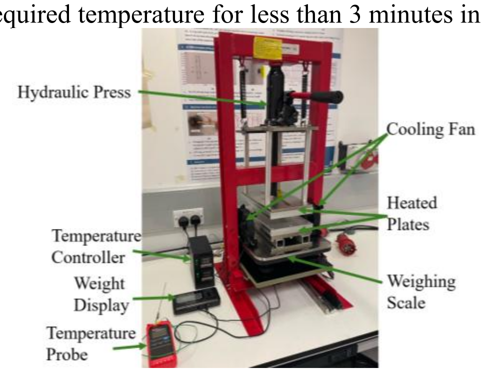

Fig. 1. Heating press setup with temperature-controlled dual heating pads and manual hydraulic press.

B. Electrical Characterization

The four-probe method was used to measure joint resistance, utilizing a TDK Lambda DC power supply, a DAQ system (NI 9238), and a Keithley 2182A nanovoltmeter. The critical current (I_c) was measured at 77 K under self-field conditions.

C. Mechanical Strength Characterization

Shear strength was evaluated using an Instron 5969 universal testing machine equipped with a 50 kN load cell. Samples were clamped over a 5 cm × 1.2 cm area, and strain was monitored using a video gauge. Shear tests were conducted at a displacement rate of 0.1 mm·min^{-1} until failure, producing stress–strain curves. Shear strength was calculated as the peak load divided by the overlap area.

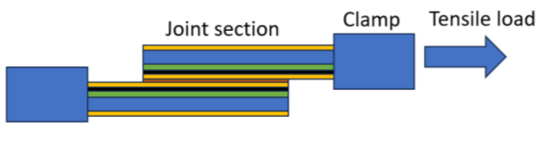

Fig. 2. Joint orientation in the universal testing machine showing the direction of tension.

D. Microscopic Characterization

Cross-sections were prepared by polishing the cut cross-section of the joint and imaged with JEOL JSM IT-100 Scanning Electron Microscope (SEM) to assess solder distribution, voids, and mechanical failure. SEM samples were analyzed to identify defects, pores, and failure modes. Comparisons between samples soldered at 220 °C and 260 °C highlighted microstructural influences on electrical performance.

III. Optimization of the Lap Joint Conditions

A. Resistance optimization

The main parameters for joint optimization were joint resistance and mechanical strength. In the first optimization step, we wanted to find the regions of temperature and pressure with low resistance using Theva tape joints, with temperature and pressure varied in the range of 200–260 °C and 1–3 MPa (Fig. 3).

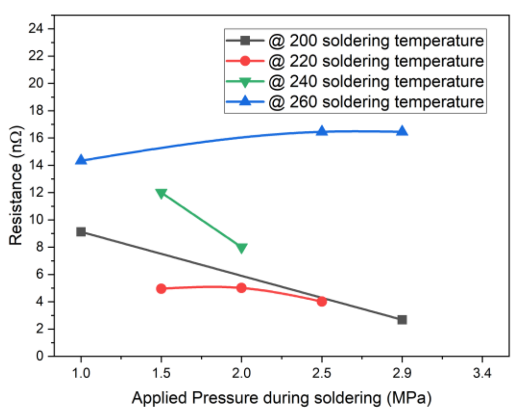

Fig. 3. Resistance of 6 cm^2 Theva joints at different pressures and temperatures.

During initial optimization, the minimum joint resistance of approximately 5 nΩ was achieved at 220 °C and 1.5–2.5 MPa, and at 200 °C and 2.9 MPa. The resistance decreased when the soldering temperature approached the melting point of the solder and further decreased with increasing pressure up to certain point, consistent with literature data [8].

For further optimization, 220 °C was selected as it provided low resistance across a wide pressure range. In the next step, pressure was varied from approximately 2 MPa to 5 MPa for both Fujikura and Theva joints. Fig. 4 shows the resistance of Fujikura and Theva joints at 220 °C under higher pressure conditions.

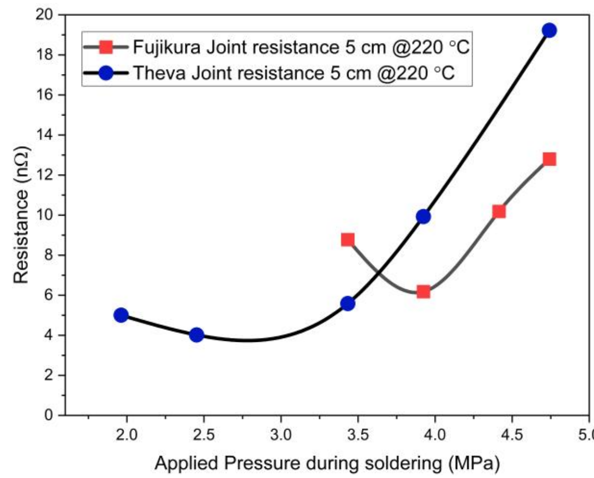

Fig. 4. Variation in joint resistance with respect to applied pressure during the soldering process for Theva and Fujikura tape joints.

B. Mechanical optimization

In Fig. 5 and Fig. 6, the trend in shear strength indicates that it increased with increasing pressure during the soldering process up to a certain pressure. Higher pressures (up to 3.9 MPa) enhanced mechanical strength after which the strength was reduced again in Theva tapes. Whereas in Fujikura the mechanical strength was seen to increase up to the range of applied pressure.

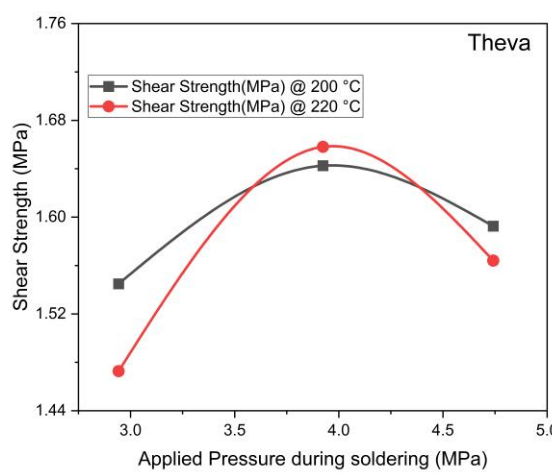

Fig. 5. Shear strength vs. soldering pressure for Theva joints.

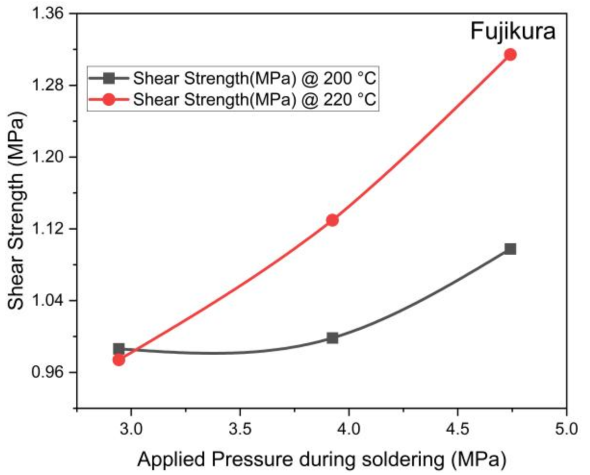

Fig. 6. Shear strength vs. soldering pressure for Fujikura joints.

C. SEM Results

The observed increase in resistance at higher pressures or temperatures can be attributed to uneven pressure distribution along the solder layer and the formation of voids or defects, as reported in [9] (e.g., pores visible in Fig. 7). At 260 °C, porosity in the solder layer was more pronounced, as observed by SEM, correlating with higher resistance. As seen in Fig. 8, fracture surfaces showed crack initiation at the REBCO–substrate interface, which can be mitigated using reinforcement, thus altering crack propagation paths.

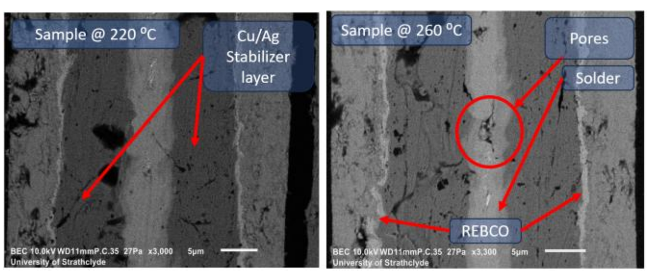

Fig. 7. Fujikura Tape cross-section at different soldering temperatures before mechanical test.

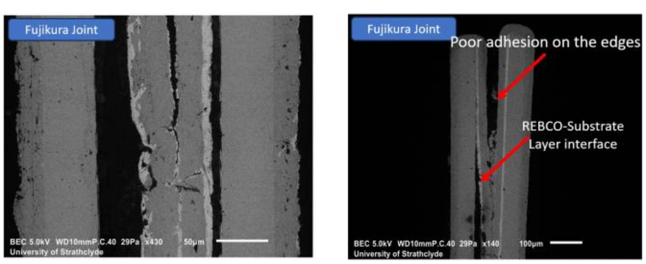

Fig. 8. Fujikura Tape cross-section after mechanical test.

IV. New FIRM Joint Approach

A. Mechanical Reinforcement

After mechanical testing, the samples were inspected, and in most cases, delamination was observed at the REBCO–buffer/substrate interface. This is consistent with literature reports identifying REBCO tape interfaces as the "weak link" [9]. Finite-element models by Liao et al. [10] indicate tensile loading generates high stress concentrations at the joint overlap edge, where the REBCO layer reaches its maximum strain (≈0.73% at a global strain of 0.45%), triggering irreversible degradation. In such cases, the solder and substrate often remain intact, while the REBCO/buffer layer tears. Mechanical strength of the tape is heavily dependent on the strengthening material and determines the strength of the tape [11]. In case of joints there is a discontinuity of strengthening material which makes the joint a weak spot. To address this issue, a post-soldering reinforcement technique was developed to mitigate delamination.

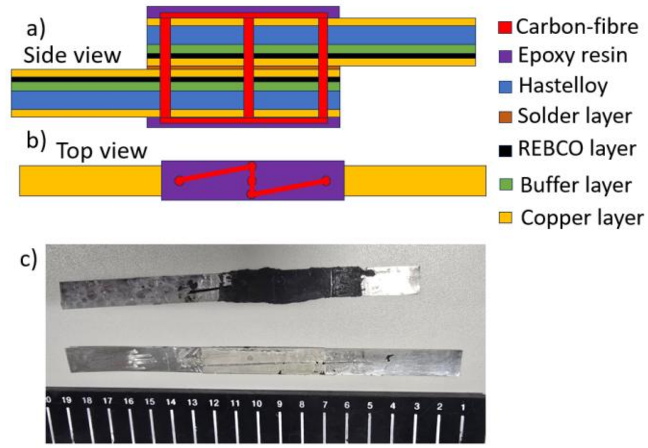

Fig. 9. a) and b) Schematic for carbon fiber positioning (shown in red). c) Fujikura Tape before (bottom) and after (top) epoxy/carbon fiber impregnation.

Step 1: Drilling Holes: Precision holes (0.6mm) were drilled through the Hastelloy substrates along the joint.
Step 2: Threading Carbon Fiber: Carbon fiber threads were inserted through the holes, mechanically linking the substrates and redistributing stress.
Step 3: Epoxy Application and Compression: Epoxy resin (Stycast 2850FT) was applied, and the assembly was compressed under heat to cure, forming a composite reinforcement. The assembly was heated at 50 ºC for 2 hours under pressure of 0.8 MPa and the heat was turned off, and it was further kept under the same pressure for 24 hours.

B. Mechanical Shear Strength

To address delamination, a carbon-fiber/epoxy tie was introduced, passing through precision holes drilled in the Hastelloy substrate layers. In this reinforced design, axial and shear loads are redistributed: the high-stiffness fiber rods carry a portion of the load, bypassing the weak REBCO interface. Conceptually, the joint becomes a hybrid composite, where the total applied force F is shared between the soldered lap and the fiber-reinforced composite. In practice, this load sharing significantly increased strength: the average lap-shear strength rose from approximately 1.2 MPa for unreinforced joints to 2.4 MPa for reinforced joints measured at room temperature (Fig. 10). The reinforcement effectively stiffened the joint, increasing shear yield by ~100%.

However, reinforcement altered the failure mode. Reinforced samples failed in a brittle manner (sudden fracture of the tape layer) instead of the more ductile tearing observed in unreinforced joints. This brittle behavior is a known tradeoff in composite joints: stiff fiber ties or adhesives can increase strength while reducing ductility. In practical terms, the reinforced joint can sustain higher peak loads but provides less warning before failure.

These observations align with classical fracture mechanics: introducing an alternative load path shifts the location of maximum stress intensity factor. While beneficial in suppressing delamination, stress concentrators are introduced at the hole boundaries. Optimizing hole geometry, spacing, and filler distribution could reduce brittleness while maintaining enhanced strength.

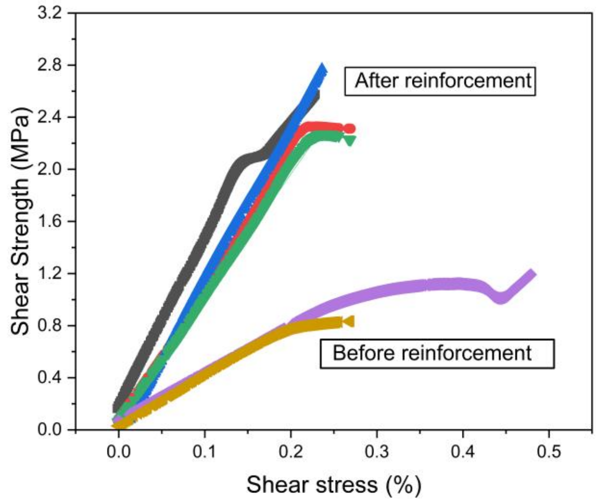

Fig. 10. Shear strength versus shear stress of Fujikura tape before and after reinforcement.

Using this new FIRM approach, it was found that drilling of the holes in the joint can be done without significant degradation in I_C as shown in Fig.11.

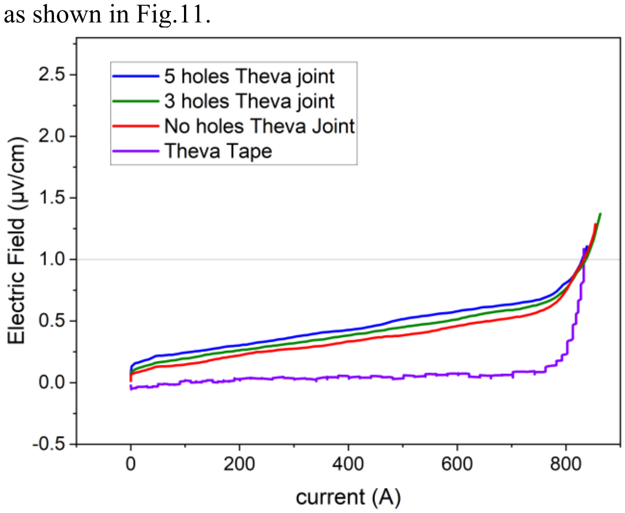

Fig. 11. I_C Plot for Theva tape and joint made at 220 °C and 3.5 MPa pressure before and after drilling holes.

It can be seen in Fig 12, the reinforcement in our approach achieves minor trade-offs in resistance for substantial mechanical strength: two samples maintained their initial resistance, while a third showed a minor increase.

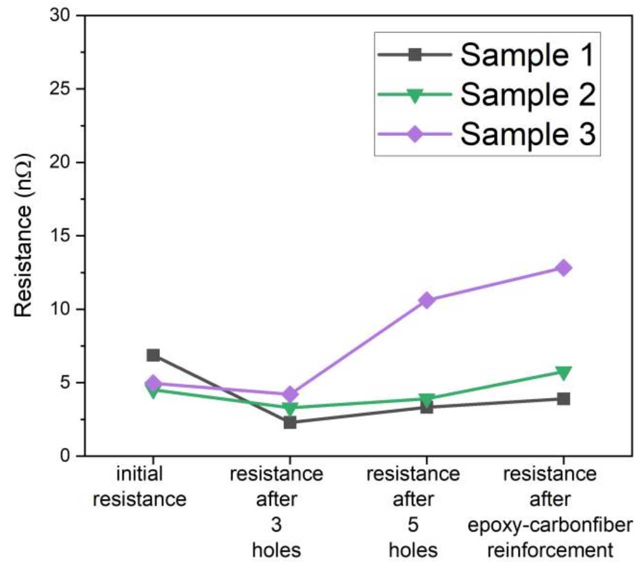

Fig. 12. Resistance value of the Fujikura sample after each step of reinforcement.

Several approaches have been explored to enhance joint reliability. Ultrasonic welding of REBCO tapes, with or without solder, can reduce joint resistance but often introduces new interface defects[12]. Mechanical lap joints using indium foil or bolted clamps avoid solder altogether, however achieving low electrical resistance remains challenging and delamination under shear can still occur [13].

Filling-Induced Reinforcement Matrix (FIRM) approach for HTS joint is novel in REBCO technology: by drilling holes and anchoring the substrate layers directly, a portion of the stress in joint is relieved from the REBCO interface. The observed doubling of strength represents a significant improvement. This approach is unique in explicitly addressing mechanical reinforcement while complementing electrical optimization strategies.

V. Conclusion

Using new FIRM approach, it was shown that the joint strength can be significantly improved while incurring only a modest resistance penalty and almost no degradation of Ic even after drilling 5 holes in a joint. This method enhances robustness against delamination, the primary failure mode of unreinforced joints. Although reinforcement increases brittleness, the approach is promising for high-field coil applications. While the brittle failure mode requires careful consideration, the method provides a viable route to more robust REBCO splices. Parameters such as solder alloy composition, fiber type, epoxy viscosity, and curing temperature offer opportunities for further optimization. The specific contribution of each component to the improvement in mechanical strength remains unclear. Future work will focus on optimizing matrix geometry and materials to recover ductility and on integrating this reinforcement into coil-winding prototypes.

VI. References

[1] J. B. Song, Y. H. Choi, D. G. Yang, Y. G. Kim, K. L. Kim, and H. G. Lee, 'Review of core technologies for development of 2G HTS NMR/MRI magnet: A status report of progress in Korea University', *Results Phys.*, vol. 7, pp. 3264–3276, 2017, doi: 10.1016/j.rinp.2017.08.046.

[2] Y.-H. Zhou, D. Park, and Y. Iwasa, 'Review of progress and challenges of key mechanical issues in high-field superconducting magnets', *Natl. Sci. Rev.*, vol. 10, no. 3, p. nwad001, Feb. 2023, doi: 10.1093/nsr/nwad001.

[3] L. E. Aparicio, S. Ito, and H. Hashizume, 'Comparison of shear strength and failure mechanisms of lap joint between REBCO tapes bonded by different joining techniques', *Fusion Eng. Des.*, vol. 136, pp. 1196–1201, Nov. 2018, doi: 10.1016/j.fusengdes.2018.04.101.

[4] M. Takayasu, 'Width-bending characteristic of REBCO HTS tape and flat-tape Rutherford-type cabling', *Supercond. Sci. Technol.*, vol. 34, no. 12, p. 125020, Dec. 2021, doi: 10.1088/1361-6668/ac30eb.

[5] X. Wu *et al.*, 'Electromechanical Performance Study on Silver Diffusion Joints of REBCO Coated Conductors under Axial Tensile Stress', *IEEE Trans. Appl. Supercond.*, pp. 1–1, 2016, doi: 10.1109/TASC.2016.2631722.

[6] S. Ito, H. T. Fujii, R. Hayasaka, Y. S. Sato, and H. Hashizume, 'Comparison of Heat Assisted Lap Joints of High-Temperature Superconducting Tapes With Inserted Indium Foils', *IEEE Trans. Appl. Supercond.*, vol. 29, no. 5, pp. 1–5, Aug. 2019, doi: 10.1109/TASC.2019.2892050.

[7] A. R. Nisay and H.-S. Shin, 'Performance characteristics of REBCO coated conductor joints fabricated by flux-free hybrid welding', *Supercond. Sci. Technol.*, vol. 36, no. 12, p. 125013, Dec. 2023, doi: 10.1088/1361-6668/ad0793.

[8] X. Pan, W. Wu, X. Yu, L. Lu, C. Guo, and Y. Zhao, 'Typical electrical, mechanical, electromechanical characteristics of copper-encapsulated REBCO tapes after processing in temperature under 250 °C', *Supercond. Sci. Technol.*, vol. 36, no. 3, p. 034004, Mar. 2023, doi: 10.1088/1361-6668/acb740.

[9] P. Gao, Y. Zhang, X. Wang, and Y. Zhou, 'Interface properties and failures of REBCO coated conductor tapes: Research progress and challenges', *Superconductivity*, vol. 8, p. 100068, Dec. 2023, doi: 10.1016/j.supcon.2023.100068.

[10] T. Liao, W. Wang, Z. Chen, and M. Guan, 'Numerical Study on Mechanical Behavior and Electromechanical Properties of Solder-Jointed REBCO-Coated Conductors', *Materials*, vol. 17, no. 11, p. 2517, May 2024, doi: 10.3390/ma17112517.

[11] K. Han, J. Chen, R. E. Goddard, W. D. Markiewicz, V. J. Toplosky, and R. P. Walsh, 'Mechanical Properties of Non-Superconducting Components in YBCO and Nb_3Sn Composites', *IEEE Trans. Appl. Supercond.*, vol. 21, no. 3, pp. 3119–3122, June 2011, doi: 10.1109/TASC.2010.2090444.

[12] H.-S. Shin and J.-M. Kim, 'Development of Low-Resistance Splice Joint for Long GdBCO Coated Conductor Tapes Using Ultrasonic Welding Method', *IEEE Trans. Appl. Supercond.*, vol. 26, no. 4, pp. 1–4, June 2016, doi: 10.1109/TASC.2016.2532741.

[13] Y. Zhu, H. Li, L. Liu, W. Huang, X. Yang, and Y. Zhao, 'Tensile Characteristics of Mechanical Lap Joints Between Commercial ReBCO Tapes With Various Interlayer Materials', *IEEE Trans. Appl. Supercond.*, vol. 31, no. 8, pp. 1–4, Nov. 2021, doi: 10.1109/TASC.2021.3110467.