Simulation of Fatigue in High-Temperature Superconductor using Findley criterion

Justin Robert
Department of Mechanical Engineering
TKM College of Engineering
Kollam, Kerala, India
justinrobert95@gmail.com

Ashok K.B.
Department of Mechanical Engineering
TKM College of Engineering
Kollam, Kerala, India
ashokkb189@gmail.com

Rijo Jacob Thomas
Department of Mechanical Engineering
TKM College of Engineering
Kollam, Kerala, India
rijojthomas@tkmce.ac.in

A. Nijhuis
University of Twente
Faculty of Science & Technology,
The Netherlands
a.nijhuis@utwente.nl

***Abstract*— Fatigue is the weakening of a material caused by cyclic loading that results in progressive and localized structural damage and the growth of cracks. Once a fatigue crack has been initiated, each loading cycle will grow the crack a small amount. To predict the fatigue life of a component, fatigue tests are carried out to measure the rate of crack growth by applying constant amplitude cyclic loading and averaging the measured growth of a crack over thousands of cycles.**

In the case of High-temperature superconducting (HTS) tapes such as repeated thermal cycles, periodic electromagnetic force, etc., affect the performance of superconductors. This may degrade the superconductor properties and in turn affects the performance of superconducting magnets and power systems. Therefore, it is important to understand the mechanical and electrical fatigue strengths or limits while designing superconducting devices.

High-cycle uniaxial fatigue tests are difficult and time-intensive, but these challenges must be faced to determine the electrical and mechanical fatigue limits at cryogenic temperatures. The fatigue tests will be terminated till there are any mechanical failures. In a practical fatigue loading test, it is difficult to test each sample with different maximum stress values of cables and their critical current variation with the number of cycles (minimum $1x10^5$ cycles).

This study focuses on developing Stress based models of fatigue (Findley criterion) using FEA software. The experiment results from the open literature support the predicted fatigue strength of the HTS tape. The fatigue effect is modelled for various stress ratios and applied forces. It is found that with increasing stress ratio, fatigue strength also increases. The results also showed that the Findley criterion is a more appropriate approach than the Matake criterion from the literature, especially when considering the variation in stress ratio. For REBCO tape, the endurance limit is 207.12 MPa.

The findings of this study will help in assessing the rate of crack growth in HTS under different conditions for thousands of fatigue cycles which experimentally otherwise to would be cumbersome and time taking. The data generated would help in designing HTS based superconducting cables and wires for the future.

Keywords*— *High-Temperature Superconductor, Fatigue Failure, Cyclic Loading, Findley criterion, Cryogenic Temperatures, Superconducting Cables

I. INTRODUCTION

The second-generation high-temperature superconducting (HTS) $(RE)Ba_2Cu_3O_{7x}$ (REBCO) coated conductor tapes have wide application owing to their current transmitting capacity and also because they are not susceptible to high magnetic fields. They are used in 45-T superconducting magnets [1].

The strengths or limits of mechanical and electrical fatigue are crucial for designing superconducting devices in real-world applications when fatigue loading conditions are known. However, research on the 2G CC tapes at or below 77 K using the high-cycle uniaxial fatigue test is still limited, and the irreversible I_c degradation limit for electric fatigue has yet to be established. High-cycle Uniaxial Fatigue Tests are difficult and time-consuming, but they must be required to evaluate the electrical and mechanical fatigue limits at cryogenic temperatures. Electrical and mechanical fatigue strengths and limits, on the other hand, should be determined in conditions that are reflective of real-world scenarios. For example, fatigue cracks often begin near the slit edges of 4 mm wide CC tapes, regardless of the CC tape process; to elucidate the fatigue fracture mechanisms of multilayered REBCO CC tapes under cyclic loading, comparison tests with 12 mm wide tapes without slit edges should be done [2][3]. The mechanical fatigue limit can be defined as the fatigue strength at $1 \text{ x } 10^6$ cycles. 609 MPa is the limit for 4 mm wide tape, and 679 MPa is the limit for 12 mm wide tape. Through fractographic studies, the electrical fatigue strength of a CC tape is discovered to be considerably influenced by the fracture behaviour in the SC layer, whereas the mechanical fatigue strength is mainly driven by the substrate [3]. At room temperature and 77 degrees Celsius, the monotonic tensile stress-strain curve for YBCO coated conductors were measured. The 0.2 % offset line reported yield strengths of 549 MPa and 667 MPa at RT and 77 K, respectively, corresponding to tension loads of 238 N and 267 N [4].

II. MODELING

Engineering and design have embraced modeling as a necessary component. In numerous sectors of engineering,

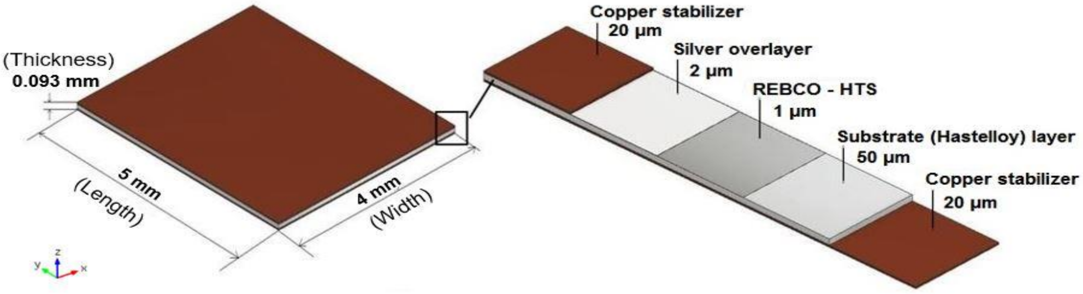

Fig. 1. Modelled geometry of HTS tapes.

modeling is used for analysis, optimization, virtual production, and so on. Computer simulations have the ability to lower total production costs while also shortening product development time. One of the most important features of analysis software is the parametric analysis of variables that affect the performance of a device or system that must be explored.

High-temperature superconducting tapes have a multi-layered structure, as seen in fig. 1. REBCO tape is made by layering a thin buffer layer and REBCO film over a substrate material (Hastelloy), then layering a silver layer and a copper layer on top. There are three steps to the modelling process. Using the metal-organic vapour deposition (MOCVD) process, the REBCO layer is first formed on the substrate at 1020 K.

Second, the tape is electroplated with copper and silver at 333 K to provide electrical stability. Finally, it's brought up to operating temperature (77 K). The buffer layer is ignored because of its short thickness. The effect of change in residual compressive strain, which is thermally caused when cooling down from 1020 K to 77 K, is computed for various examples of Hastelloy, silver, and copper thickness. At room and liquid nitrogen temperatures, a parametric study is also carried out to better understand the effect of REBCO tape thickness on the thermally induced residual strain. A piece of tape with dimensions of 4 mm width by 5 mm long and a thickness of 0.093 mm is the model under consideration.

Linear temperature dependence of material properties, plastic deformation of copper, silver, and Hastelloy, stress contribution from buffer layer is negligible due to their very small thickness, and REBCO is elastic over the entire range of applied load are some of the assumptions used in the model's development [5].

A. *Mesh and boundary conditions*

To determine the optimum mesh for fatigue simulation, a mesh-independent analysis is carried out. Fig. 2 depicts the optimal mesh, which consists of 30 elements along the width, 40 elements along the length, and 6 elements along the thickness of the REBCO tape. Table 1 lists the material properties used in the simulation [6]. The boundary condition is set up so that one side of the tape is fixed while the other is subjected to a tensile load. The applied load varies between 248.86N (669 MPa) and 24.886 N (66.9 MPa) [5].

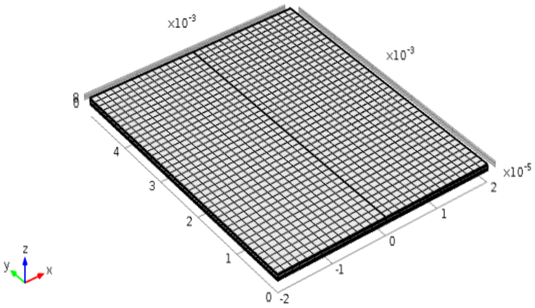

Fig. 2. Meshed geometry of HTS tape

III. THEORY

The stress-based Findley criterion is chosen for fatigue simulation. Fatigue evaluations are performed on the plane with both normal stress and shear stress are maximum, which is considered as the critical plane. The Findley criterion is based on equations 1 and 2.

$$\left(\frac{\Delta\tau}{2}+k\sigma_n\right)_{max}=f \qquad (1)$$

$$\sqrt{\left(\frac{\sigma_{max}-\sigma_{min}}{2}\right)^2+(k\sigma_{max})^2}+k\sigma_{max}=2f \qquad (2)$$

The normal stress sensitivity coefficient and limit factor are k and f, respectively. By setting σ_{max} = 669 MPa, σ_{min} = 66.9 MPa, and R (stress ratio) = 0.1, these values can be calculated [3]. It may be observed that, fig. 3 depicted a linearly dependent relation between the Limit factor and normal stress sensitivity coefficient.

TABLE I. PROPERTIES OF LAYERS USED IN THE SIMULATION. [6]

Material	Young's modulus (GPa)	Yield stress (MPa)	Poisson's ratio	Thermal expansion coefficient (K^{-1})
Hastelloy (RT)	223	891	0.307	1.34×10^{-5}
Hastelloy (77 K)	228	1141	0.307	1.34×10^{-5}
Copper (RT)	80	120	0.34	1.77×10^{-5}
Copper (77 K)	98	146	0.34	1.77×10^{-5}
Silver	87	225	0.37	3.9×10^{-5}
REBCO	157	--	0.3	1.1×10^{-5}

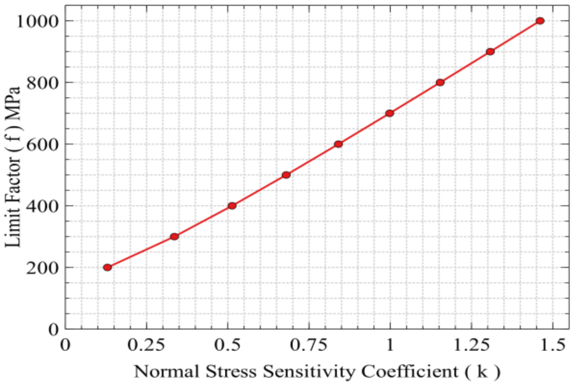

Fig. 3. Normal stress sensitivity coefficient and Limit factor function of Findley criterion.

The Stress-Based Findley Fatigue Model aids in determining whether or not the tape is safe or damaged. The results of this model are expressed in terms of the fatigue usage factor (FUS), which is defined as the ratio of applied stress to fatigue strength [5].

$$\text{Fatigue Usage Factor (FUS)} = \frac{\text{Applied stress}}{\text{Fatigue Strength}} \qquad (3)$$

IV. VALIDATION OF THE NUMERICAL MODEL

The numerical simulation model is validated by comparing the results to those published in the literature [3], as shown in fig. 4. Both results are in good agreement, with a 0.50 % deviation between the present study and the experimental results published in the literature.

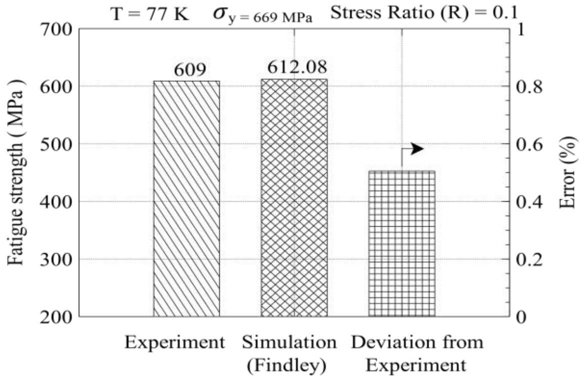

Fig. 4. Validation of simulation with experiment [3].

V. RESULTS AND DISCUSSIONS

Fig. 5 depicts the FUS distribution after the fatigue simulation. It should be noticed that each layer has a different colour distribution due to differences in fatigue strength. The fatigue strength of different layers with the changes in the applied stress is depicted in fig. 6. It may be noted that Hastelloy has a greater value of FUS and hence Hastelloy undergoes the first failure followed by REBCO, copper bottom, silver and copper top. The top and bottom copper layers have differing FUS values, and the bottom copper layer fails first when compared to the top copper layer. It may be due to the effect of the adjacent Hastelloy layer. Also observed that the fatigue usage factor increases with increasing the applied stress. If the applied stress is above 770 MPa, both REBCO and Hastelloy layers will fail together. Each layer's FUS value is influenced by the FUS values of adjacent layers.

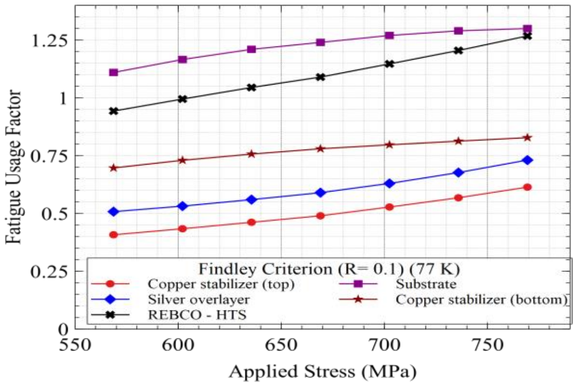

Fig. 6:- FUS variations of different layers with Applied stress.

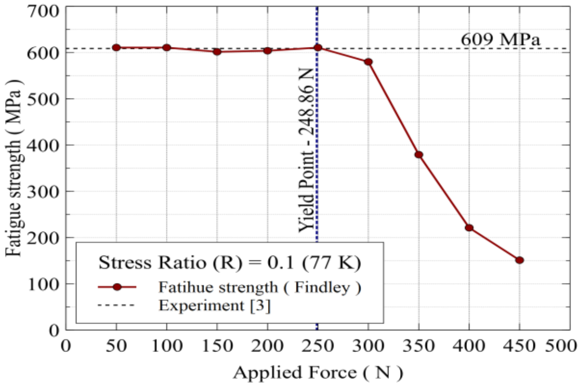

Fig. 7. Nature of fatigue strength with various Applied forces.

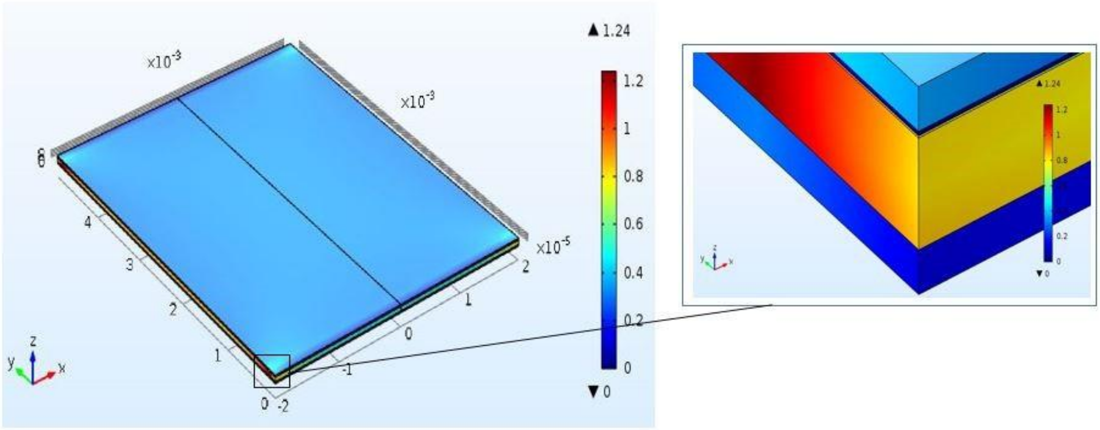

Fig. 5. Distribution of FUS value in HTS tape (Findley criterion).

A. *Fatigue effect on different applied forces*

Fig. 7 shows the variation of fatigue strength with applied force. Up to the yield point, the value of fatigue strength is almost constant and the value at the yield point is equal to 612.08 MPa. Generally, the fatigue strength is determined below the yield point. In order to get a better understanding the force is applied above the yield point, and it is discovered that after the yield point, the fatigue strength drops sharply.

B. *Fatigue effect on different stress ratios*

At cryogenic temperatures, fig. 8 depicts how fatigue strength fluctuates with variations in the value of the stress ratio. Where the maximum stress value is taken as constant (669MPa) and the stress ratio varies from -1 to 0.7. It may be noted that fatigue strength increases with an increase in the stress ratio or when it is moved from compression to tension. The endurance limit of the REBCO tape is found to be 207.12 MPa, corresponding to the stress ratio of -1.

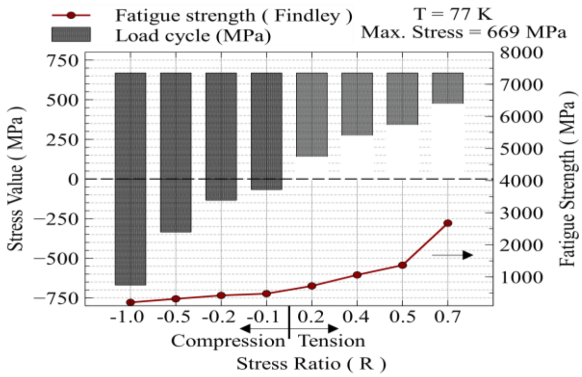

Fig. 8:- Variation of fatigue strength with various R values.

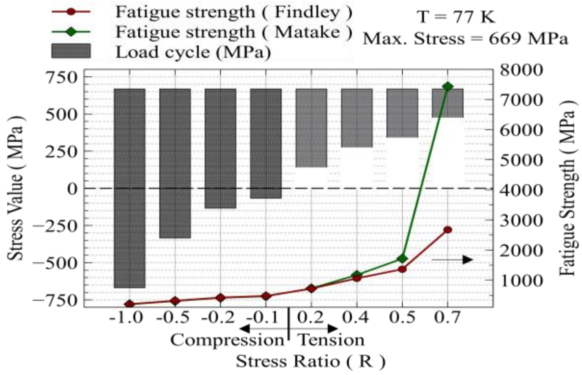

Fig. 9. Variation of fatigue strength with different R values on Findley and Matake [5] criteria.

C. *Comparison between Findley and Matake criteria*

The criteria used for fatigue simulation of HTS tape are compared, and a parametric analysis is performed with the tensile fatigue simulation on different applied forces and stress ratios. Based on these results, it is found that the Findley criterion is a more appropriate approach than the Matake criterion [5], especially when considering the variation in stress ratio. In fig. 9 shows that how the fatigue strength varies with changes in the value of stress ratio at cryogenic temperature. The maximum stress value is taken as constant (669MPa) and the stress ratio varies from -1 to 0.7. From the graph, it may be noted that fatigue strength increases with an increase in the stress ratio or when it is moved from compression to tension. But Matake criterion shows a drastic change in fatigue strength from a stress ratio of 0.5. This is mainly due to the selection of a critical plane for the calculation of the fatigue usage factor, i.e., in the Matake criterion, the critical plane is selected based on the plane with maximum shear stress, but in the Findley criterion, the critical plane is selected based on the plane where both normal stress and shear stress are maximum. The fatigue strength at R=-1.0 (endurance limit) for both the Findley and Matake criteria is calculated to be 207.12 MPa and 200.9 MPa [5], respectively.

VI. CONCLUSION

Fatigue simulation (Findley criterion) is carried out by using FEA software and the following are the conclusions. Different layers of REBCO tape show various fatigue strengths and Hastelloy undergoes the first failure followed by REBCO, copper bottom, silver and copper top. The fatigue strength of REBCO tape is found to be 612.08 MPa. It may be recognized that fatigue strength increases with increasing the stress ratio. Findley criterion is a more appropriate approach than the Matake criterion, especially when considering the variation in stress ratio. The endurance limit of the REBCO tape is found to be 207.12 MPa.

VII. ACKNOWLEDGEMENT

We are also thankful to the Department of Mechanical Engineering, TKM College of Engineering and the EMS Group, University of Twente, the Netherlands for providing the facilities to carry out the work.

REFERENCES

[1] S. Hahn *et al.*, “45.5-Tesla Direct-Current Magnetic Field Generated With a High-Temperature Superconducting Magnet,” *Nature*, vol. 570, no. 7762, pp. 496–499, 2019, doi: 10.1038/s41586-019-1293-1.

[2] H. S. Shin, A. Gorospe, Z. Bautista, and M. J. Dedicatoria, “Evaluation of the electromechanical properties in GdBCO coated conductor tapes under low cyclic loading and bending,” *Supercond. Sci. Technol.*, vol. 29, no. 1, p. 14001, 2016, doi: 10.1088/0953-2048/29/1/014001.

[3] H. S. Shin, M. B. De Leon, and M. A. E. Diaz, “Investigation of the electromechanical behaviors in Cu-stabilized GdBCO coated conductor tapes using high-cycle fatigue tests at 77 K and related fractographic observations,” *Supercond. Sci. Technol.*, vol. 33, no. 2, p. 25012, 2020, doi: 10.1088/1361-6668/ab617b.

[4] W. Chen *et al.*, “Fatigue Behavior of Critical Current Degradation for YBCO Tapes at 77 K,” *IEEE Trans. Appl. Supercond.*, vol. 28, no. 3, 2018, doi: 10.1109/TASC.2018.2806912.

[5] R. Justin, K. . Ashok, and J. T. Rijo, “Simulation of Fatigue in High-Temperature Superconductor using Matake criterion,” in *Recent Innovations in Mechanical Engineering*, 2021, pp. 42–47, [Online]. Available: https://online.pubhtml5.com/fmlo/ffaw/#p=1.

[6] K. Ilin *et al.*, “Experiments and FE modeling of stress-strain state in ReBCO tape under tensile, torsional and transverse load,” *Supercond. Sci. Technol.*, vol. 28, no. 5, p. 55006, 2015, doi: 10.1088/0953-2048/28/5/055006.