Finite element investigation of the mechanical behaviour of a Twisted Stacked-Tape Cable exposed to large Lorentz loads

Federica Pierro¹, Zijia Zhao¹, Luisa Chiesa¹, Makoto Takayasu²

1 Tufts University, Mechanical Engineering Department, Medford, MA 02155, USA
2 MIT, PSFC, Cambridge, MA 02139, USA

Email: federica.pierro@tufts.edu

Abstract. The mechanical response of Twisted Stacked-Tape Cables (TSTC) experiencing large Lorentz loads generated during its operation in high-current, high-field magnets was investigated using finite element analysis. Two conductor configurations were investigated: a stack of 40 REBCO tapes inside a solid cylindrical copper rod (former) and a solder filled copper tube. Several simulations were conducted to highlight the effect of different parameters in the cable and the differences between the two configurations. A parametric study on the geometrical parameters of the solder filled tube configuration was performed. It was found that increasing the ratio between the thickness of the copper tube and the amount of solder in the cross section lowers the maximum stress experienced by the stack of tapes. Another simulation explored the effect of using different width tapes in the stack and it was found that, for a given Lorentz load, a wider tape reduces the maximum stress experienced by the stack. In certain applications, the cable requires the addition of material for structural support or stability reasons therefore a simulation was performed to understand the effect of copper surroundings. It was found that surrounding the cable with copper as well as using a thick copper tube lowers the stress experienced by the stack and makes the behaviour of the copper core and the solder filled tube configurations almost identical. Finally, the critical current performance of the TSTC conductors as a function of Lorentz load was estimated. A minimal degradation below 2% was predicted for the copper core configuration up to 1000 kN/m and up to 600 kN/m for the solder filled tube configuration.

1. Introduction
Second generation (2G) REBCO (rare-earth-barium-copper-oxide) high temperature superconductors (HTS) have excellent mechanical properties as well as high field and high current capabilities, which make them attractive conductors for high field applications such as fusion reactors and particle accelerators. Due to the flat geometry of HTS tapes, the design and fabrication of multi-tape high current density cables is extremely challenging. Several cabling methods are currently under development such as Roebel assembled coated conductor (RACC) [1], the twisted stacked-tape cable (TSTC) [2], the conductor in round core (CORC) [3] and other cable configurations using stack of tapes [4-5].

In high current and high field applications, the natural occurring Lorentz load can be large enough to cause degradation of the electrical performance of the tapes used in the cables. This large, accumulating transverse electromagnetic compression is due to the interaction between the high currents and the large magnetic field generated in the magnets utilizing those cables.
In previous work [6], the effect of electromagnetic transverse compression on an untwisted 40-tape TSTC was investigated using numerical finite element analysis. Two support methods were investigated: a solid cylindrical copper core and a solder filled copper tube (figure 1). The stress/strain states caused by the accumulating Lorentz load were analyzed in both conditions investigating the influence of the stack orientation and the friction between tapes.

The scope of this work was to provide insights for cable design by investigating how the stress experienced in the stack changes in function of the geometrical parameters of the cable. Therefore, the stress values reported in the result sections should not be interpreted as absolute value for a specific solution, but as a tool to guide the design process and avoid critical situations. The studies on the conductor originally presented in [6] for the solder filled tube configuration and covering electromagnetic loads up to 300 kN/m, were expanded to consider loads up to 1000 kN/m. The effect on the stress distribution in the stack was investigated as a function of the following parameters: thickness and outer diameter dimensions of the copper tube (solder filled configuration), conductor width and structural surrounding material (solid copper core and solder filled configurations). The stress distribution in the stack of tapes as a function of the tape width was investigated to highlight the advantages and disadvantages of different tape widths on the cable design. Furthermore, the effect of having copper structural material surrounding the cable was examined for both solid copper core and solder filled configurations. Finally, the evaluation of the critical current performance of the TSTC is discussed combining literature data of critical current as a function of strain at 4.2 K and 19 T [19] and strain results from the finite element simulations.

2. Finite Element Analysis
Structural finite element analysis was performed using ANSYS® to investigate a full scale three dimensional stacked-tape cable under transverse compression. The cable is studied in the untwisted configuration but the stack was oriented at 45 degrees, which was shown to be the most critical orientation for the tapes in the stack when they experience accumulating electromagnetic loads [6].

A 40-tape stacked-tape cable made with 4 mm wide Superpower tapes [7] was modeled with two cabling support structures. Both configurations are shown in figure 1. In the first case, the stack is completely surrounded by solid copper (figure 1(a)) while in the second method the superconducting stack is enclosed by a copper tube filled with solder (figure 1(b)). Both configurations have the same external diameter of 8.4 mm, and the copper tube of the second method has a thickness of 0.8 mm.

![Figure 1](image1.png)

**Figure 1.** A 40-tape stacked-tape cable with two supports methods: solid copper core (a) and solder filled tube (b) [6].

![Figure 2](image2.png)

**Figure 2.** Nodal distribution of the applied electromagnetic Lorentz load for the TSTC solder filled tube model [6].

2.1. Element Type and Mesh Density
HTS tapes were modeled as a uniform volume using SOLSH190 structural solid-shell elements using a novel technique developed in [8]. Each tape was modelled with a uniform thickness along the width, neglecting the thickness variation in the copper layers typically observed in real tapes. Details of the
modeling of the multi-layer tape as uniform volume are listed in [8]-[9]. The support structure was meshed using SOLID185 homogeneous structural solid elements.

A mesh study was performed in [6] and the optimal mesh was determined to be such that the element size for the HTS tapes was 0.1 mm along its width, resulting in 40 elements for a 4-mm wide tape. Each tape was meshed with only one element through the thickness and with an element size of 0.2 mm along its length, resulting in 50 elements for a 10-mm long stack. The optimal final mesh for the entire cable consisted of about 200,000 elements. 80,000 of those elements are used to mesh the 40-tape stack.

2.2. Material Properties
The materials in the FEA were modeled as bilinear isotropic to capture the nonlinear elastic-plastic deformations that occurs in the HTS tapes when experiencing large deformations. Three parameters describe the bilinear model: the Young modulus, the yield stress, and the tangent modulus. HTS tapes were modelled as a homogeneous material with an average Young modulus of 140 GPa, a yield stress of 825 MPa and a tangent modulus of 13 MPa, obtained experimentally in [9]. Material properties for the support structures were collected from published literature [10]-[16]. Young modulus of 30 GPa and 120 GPa, yield stress of 100 MPa and 400 MPa and tangent modulus of 1 GPa and 4.5 GPa were defined for the solder (Sn60/Pb40) and the copper respectively.

2.3. Boundary Conditions and Loading
A total compressive load of 1000 kN/m with increments of 100 kN/m was applied to the stack to replicate the effect of the electromagnetic Lorentz load for a cable carrying 52.6 kA in a 19 T field. The load was applied as a nodal force, evenly distributed among the nodes of the 40 tapes of the stack and applied downward in the vertical direction to represent the accumulating effect of Lorentz load in the cross section (current flowing out of the page and horizontal magnetic field pointing left). The results were analysed considering the width and thickness directions of the stack of the tapes (see figure 2). Surface to surface contact pairs were used to describe the interaction between tapes and between the stack and the support structure as described in [6]. Following some studies performed in [6], a friction coefficient of 0.2 was used between the tapes of the stack. Symmetry boundary condition were applied at the two ends of the cable to reduce the computation time. A bottom rigid plate was used to support the structure under the applied load.

3. Support Method Investigations
In this section, the results of the simulations performed for this work are discussed in detail. The results discussed below show the maximum compressive stress as a function of load for the different studies. The maximum stress was found using average elemental stress data in the conductor for 95% of the elements through the cross section of the stack. Results for the remaining 5% of the element were neglected to mitigate the effect of localized stress concentration as described in [6].

3.1. Geometrical analysis of Solder Filled Tube
A parametric study on the characteristic dimensions of the solder filled tube stack-tape cable was performed to identify the effect of the size of the tube (for a constant thickness) and its thickness (maintain a constant outer diameter) on the stress accumulation on the tape-stack under electromagnetic transverse compression. Those studies help identifying the amount of copper and solder needed to reduce the overall stress experienced by the stack.

A study was conducted for four tube diameters: 8.4 mm, 8.9 mm, 9.4 mm and 10.4 mm. In all four cases, the thickness of the copper tube was kept constant at 0.8 mm. Figure 3 shows the effect of the tube diameter on the maximum stress values (for 95% of the elements) as function of load in both width and thickness direction (see figure 2). As shown, increasing the external tube diameter reduces the stress accumulated on the stack. This effect becomes more significant at larger loads. For example, at 1000 kN/m the maximum stress experienced by the stack differ ~60% between the 8.4 mm and the 10.4 mm tube external diameter (width direction, figure 3 (a)).
A similar study was conducted by varying the tube thicknesses while maintaining a constant outer tube diameter. The copper tube thicknesses were varied between 0.8 mm and 1.4 mm and the results indicated a lower maximum compressive stress in the tape stack for larger thicknesses.

Figure 3. Plot of the maximum compressive stress (95% of elements) in the tape stack as a function of load of the solder filled tube configuration for four copper tube diameters (constant tube thickness).

3.2. Conductor Width Investigation

A conductor width investigation was performed for both cable support methods by considering stacks made with HTS tapes of different widths. The number of tapes in the stack was modified with the width to maintain a square cross section of the TSTC, while the outer diameter of the copper (for both configurations) and the thickness of the copper tube (for the solder filled tube configuration) were scaled linearly. The element size in the FEA analysis was maintained constant while changing the geometrical dimensions (therefore wider tape, larger number of elements). Figure 4 illustrates the compressive stress (95% of elements) in the width direction (most critical for delamination) as function of the engineering current density of the tape-stack (total current over the stack cross section) for different tapes' widths.

The plot is characterized by two regions referred as region one (I) and region two (II). A stress value of 200 MPa delimits both regions horizontally. This value has been used as reference stress in cable for future generation magnets’ design [17]. Region I and II are vertically delimited by a current density of 0.45 kA/mm² and 3 kA/mm², which represent the critical current density of a REBCO tapes for a 19 T field perpendicular and parallel respect to the face of the tape [18]. The two areas on the plot help identifying the maximum achievable cable performance for each configuration based on the limitations of today’s tape technology. For example, with a perpendicular background field of 19 T, a 4-mm stack of 40 tapes will carry up to 7.2 kA, while the 8-mm stack of 80 tapes will carry up to 28.8 kA. If we want to carry the same current with a 4-mm tape-stack, a current density of 1.8 kA/ mm² would be necessary, which is higher than today’s limit of 0.45 kA/ mm² and is therefore a concern for applications. As shown in figure 4, the stress experienced in a stack using 4-mm tape would be lower than the 200 MPa limit for a stack current density below 2.5 kA/mm², therefore it would be possible to achieve larger cable currents while maintaining mechanical integrity if further improvements in the conductor are obtained in the future.

For the same Lorentz load the use of wider conductor results in smaller compressive stress. For example, for the solder filled tube configuration under a compressive load of 700 kN/m (shaded area in figure 4), the maximum stress is 250 MPa for the 4-mm, 180 MPa for the 6-mm and 140 MPa for the 8-mm tape stack. Finally, while the stress is significantly reduced between a 4-mm and 6-mm stack for a given load (28% reduction at 700 kN/m), a smaller reduction occurs between the 6-mm and the 8-mm wide tape-stack (22% at 700 kN/m), suggesting that the 6-mm tape-stack might be a good candidate for cable design, because it significantly improve the stress distribution compared to the 4 mm, while maintaining a high current density.
3.3. **TSTC Surrounding Conditions**

A finite element model was developed to analyse the effect of having an external support on the stress state of a TSTC cable. A structure made of copper was modelled around the cable for both the copper core and the solder filled tube configurations. The copper would mainly serve the function of stabilizer and/or structural material for applications like a cable-in-conduit-conductor for a fusion reactor. As shown in figure 5, two different surroundings conditions were investigated: “infinite” and “half infinite” surrounding. The study was conducted for the 45-degree orientation of the stack and a compressive load of 300 kN/m with the intent to identify the smallest size of the surrounding material for which a variation in the maximum stress experienced by the tapes was not observed. A ratio of two between the height (h) of surrounding copper block and the outer diameter of the copper tube (OD) was chosen. The cross section of the copper was modelled as a square. Bonded contact pair conditions were applied between the cable and the surrounding material to reproduce the effect of soldering. The maximum compressive stress results (95% stress value) in both width and thickness direction for both support methods and surrounding conditions are displayed in figure 6. The “rigid plate” configuration refers to the original configuration in which a rigid plate was used as external support to the cable. Stress results for the “half infinite copper” and “infinite copper” surroundings were significantly lower compared to the original support methods in both width and thickness direction. Although the copper core configuration still experienced the lower stress accumulation compared to the solder filled one, having additional structural material around the conductor reduces the differences between the two configurations from 50% in the “rigid plate” condition to only 2% in the “infinite condition”.

![Figure 4](image-url). Plot of the maximum compressive stress (95% of elements) as function of the current density of the conductor for both copper core and solder filled tube configurations.

![Figure 5](image-url). Cable surrounding conditions for the solder filled tube configuration: (a) rigid plate, (b) half infinite surrounding, (c) infinite surrounding. Copper would be used mainly for stabilization and a stronger material could be used for better mechanical support. The study is aimed at providing a guideline for establishing the feasible boundaries for a cable used in large magnets.
3.4. Critical Current Performance

It is well known that the electrical behaviour of HTS tapes is highly dependent on the strain state of the conductor. As shown in previous sections of this paper, the stack of tapes experience large stress/strain during operation (accumulating electromagnetic loads). It is therefore important to characterize the critical current performance of the cable keeping in mind the limitations of the model, such as the impossibility to model micro-cracking and delamination. The critical current estimates shown to follow are based on the strain state of the tapes obtained with FEA and fracture and delamination will be taken in consideration by assuming that the tape does not carry any current beyond a certain strain value empirically determined from [19]. Despite those limitations, the analysis discussed below can provide useful insight during the design phase of a cable and a magnet.

Our analysis was performed for the untwisted 40-tape TSTC with an orientation angle of 45 degrees (worst condition). The goal of the analysis was to determine the strain map of the tapes under applied transverse compression and associate those strain to a critical current value by utilizing available literature critical current data as a function of axial strain at 4.2 K and 19 T [19]. To represent the effect of the strain experienced in all three directions of the conductors, von Mises strain results were used to calculate the electrical performance of the cable. We believe this approach is justified because the strain state of the tape is rather complex and this is a conservative approach to our analysis.

To accurately predict the strain generated in the brittle superconducting layer, the superconductor was modelled as a layered structure so the strain at the REBCO layer could be easily identified (vs. the homogenized approach described in previous sections). The material properties of each individual layer of the tapes were prescribed using published literature data [20]-[22]. The von Mises strain results were collected for the cross section of each tape at the location of the REBCO layer and at eighty weighted Gaussian points along the width.

The normalized critical current as function of the applied load was calculated for each tape of the stack independently. Results of the 40 tapes were then averaged to estimate the electrical performance of the entire cable. Figure 7 displays the normalized critical current as function of the Lorentz load for both copper core and solder filled tube configurations. As shown, the TSTC supported by the copper core experience minimal critical current degradation up to 1000 kN/m (figure 7, (a)) while the solder filled configuration shows degradation for loads above 500 kN/m (figure 7, (b)). Figure 8 shows the critical current behaviour of some specific tapes in the stack (bottom, middle and top). As it can be seen, in both copper and solder filled cases, the bottom tape experiences the highest degradation, dominating the critical current behaviour of the entire cable. The higher stress experienced in the bottom tape is the result of two factors: the compressive load accumulation from the tapes above and the surrounding conditions of the model. Unlike the majority of the tapes in the stack, which are allowed to slide past one another, the bottom tape is bonded to the solder and therefore the sliding motion is restricted. This results in higher stress in the tape. In the case of a cable supported by a copper core (figure 8, (a)), the analysis suggests that a significant improvement on the critical current performance of the cable can be
achieved by replacing the bottom tape with a structural tape. For the solder filled tube configuration (figure 8, (b)), significant degradation is also experienced by the middle tape for loads higher than 600 kN/m. To improve the electrical performance of the conductor in this case one option could be to interlay the superconducting tapes with support structural material. This would come at the expense of reducing the overall current density of the cable.

![Figure 7](image1.png)
**Figure 7.** Plot of the critical current performance of the 40-tapes TSTC for both support methods as a function of electromagnetic Lorentz load.

![Figure 8](image2.png)
**Figure 8.** Plot of the critical current for individual tapes of the TSTC for both support methods as a function of electromagnetic Lorentz load.

4. Conclusions
A finite element investigation of a 40-tape untwisted stack cable under electromagnetic Lorentz load up to 1000 kN/m was presented for two cable configurations: copper core and solder filled tube. Several simulations were performed with the intent of guiding the design process of high current cables used in high field magnets and offer insights on the parameters that could be changed to reduce the effects of large accumulating Lorentz loads. Parametric studies were performed for the solder filled tube configuration, highlighting how the maximum compressive stress experienced by the cable can be reduced by increasing the tube external diameter (with a constant thickness) or its thickness (with a constant outer diameter). It was shown that wider tapes reduce the maximum compressive stress experienced by the stack for the same Lorentz load and that having enough material surrounding the cable significantly reduce the stress accumulation in the tape stack. The critical current performance of the cable under Lorentz loads was estimated, indicating a minimal degradation up to 1000 kN/m for the copper core configuration and up to 600 kN/m for the solder filled tube. In both cases the degradation observed was driven by the behavior of the tapes at the bottom of the stack.

Future work will focus on investigating a fully twisted model. A study currently under development and performed for a linearly scaled down model suggests that the twisted and straight models experience similar stress distribution at each corresponding orientation angle of the stack. Additional work will
include the analysis of a full scale three-dimensional model for a twisted cable and the results will be compared with available experimental results.

5. References
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