Structural Finite Element Analysis of REBCO Tape Delamination with Solid-Shell Element under Various Loads

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Abstract. Structural Finite Element Analysis was performed to study the delamination behaviour of layer laminated REBCO tapes using a Solid-Shell element under various loading conditions, including (1) transverse tensile delamination, (2) shear delamination and (3) peeling delamination. A Solid-Shell element is well suited to simulate REBCO tape because the material and thickness of all the layers can be specified within a single element. The results obtained from the models utilizing Solid-Shell elements are compared to a more computationally intensive method known as Cohesive Zone Method (CZM), which has successfully modelled the initiation and propagation of REBCO’s delamination [1]. The results show that the stress state of REBCO tape in transverse tensile and shear directions can be accurately captured by the proposed method employing Solid-Shell elements if the transverse tensile and shear delamination stress is measured experimentally for a specific REBCO and used as failure criteria. In this work, the failure criteria adopted from previous experimental studies are 50 MPa in the transverse tensile direction and 10 MPa in the shear direction. This work provides a time-efficient modelling tool to predict and mitigate delamination in REBCO tapes used in complex systems.

1. Introduction
Layer laminated Rare Earth-Barium-Copper-Oxide (REBCO) high temperature superconducting (HTS) tapes are promising materials for high magnetic field applications due to their excellent mechanical and electrical properties. Experiments have shown that REBCO tapes are very strong in the axial tensile direction but very weak in the transverse tensile direction [2]. When the tape is subjected to excessive load, the tape will become permanently damaged and its performance degraded. The strength of REBCO tapes against delamination stresses can often be the limiting factor of the performance of the conductor. Delamination has been studied through experiments and simulations, and can be roughly classified into three modes: transverse tensile delamination, cleavage or peeling delamination, and shear delamination.

Experiments measuring the transverse tensile strength have determined that the delamination usually occurs either in the REBCO layer or at the interface between the REBCO and buffer layers, but can also happen at the buffer/substrate or REBCO/silver interfaces [3]. Critical current degradation tends to occur before mechanical delamination, and does so either abruptly or gradually depending on where the delamination occurred [3,4]. The danger of delamination caused by transverse tensile stresses during thermal cooldown (particularly in epoxy-impregnated coils), thermal quenches, and Lorentz forces is well documented in literatures [5,6]. Experiments to measure the transverse tensile strength of REBCO
tapes have shown that delamination can occur at stresses within the range of 10 to 100 MPa [7–9]. This wide range of strengths can be attributed to different manufacturing processes and voids or defects in the tape [10]. For example, the stress at delamination at the edges of a 4 mm wide REBCO tape that has been slitted during production, is significantly lower. Slitting can cause micro-cracks in the REBCO crystal layer, weakening its mechanical strength [7]. Delamination can also occur when the layers are peeled apart by cleavage stresses. This mode of delamination constitutes a significant risk as it causes high stress concentration. The nominal cleavage strength (defined as the cleavage force over the entire loaded area) at which delamination occurs can be as low as 0.5 MPa at the slit edge of a tape [8].

Tests measuring the behavior of tapes under pure shear stress reported delamination strength between 3.7 MPa and 7.2 MPa, depending on location of the loading edge of the tape, edge slitting, and temperature [11]. The critical current underwent abrupt and significant degradation as the stress increased past the delamination strength.

To better understand the stress distribution within the tape as well as delamination crack propagation, various numerical models of REBCO tapes subjected to delamination stresses have been developed. Earlier models focused on the yielding of individual layers without modelling delamination between layers [9]. In more recent studies, a finite element simulation technique known as Cohesive Zone Method (CZM), in which the delamination is modeled through a zero-thickness cohesive layer between two surfaces, was shown to accurately model the delamination of a REBCO tape at the REBCO/buffer interface [1]. To implement CZM, each layer of the tape has to be modeled. Due to the high aspect ratio between the width and thickness, a very refined mesh density to ensure the accuracy of the results is needed. Additionally, the plastic deformation and geometric nonlinearities associated with delamination require the use of small load-step increments in the FEA software to avoid computational errors. Given these requirements, the CZM method is computationally very expensive, and it would be hard to apply the same method to more complex multi-tape system, such as a Cable-in-Conduit Conductors (CICC).

In this work, a less computationally intensive FEA simulation technique, utilizing Solid-Shell elements in ANSYS®, has been developed to predict the delamination hazard in complex systems. The Solid-Shell element is well suited to simulate a REBCO tape, as the material and thickness of the individual layers can be specified. In previous studies, the Solid-Shell element was successfully used to reproduce the stress-strain behaviour of REBCO tapes under axial tensile load [12]. In this study, Solid-Shell elements are used to predict the delamination hazard of REBCO tapes. Three types of delamination modes including transverse tensile, peeling, and shear delamination are studied, and the results are compared to the one from the CZM method for validation.

2. Simulation Methods
To explore the options on modelling delamination with reduced computational efforts, each delamination mode considered (transverse tensile, peeling and shear) is modelled in three different ways (figure 1). The REBCO tape in this study is assumed to be 4 mm wide, 10 mm long and 0.096 mm thick. The layer composition and the corresponding material properties are listed in Table 1. The material properties at 77 K are adopted from our previous work, and gathered from the literatures [12]. The REBCO and buffer layers (ceramic materials) are modelled together with a combined thickness of 2 μm.

| Table 1. Material properties and thickness of the layers in REBCO tape. |
|-----------------|-----------------|-----------------|-----------------|
| Layer           | Thickness       | Elastic Modulus | Yield Strength  | Tangent Modulus |
| Copper          | 2 x 20 μm       | 70              | 120             | 5               |
| Silver          | 2 x 2 μm        | 76              | 65              | 4               |
| Substrate       | 50 μm           | 170             | 980             | 6               |
| REBCO/Buffer    | 2 μm            | 157             | 700             | --              |

In Model 1, all the layers of a REBCO tape are modelled with individual elements and are bonded together. The initiation and propagation of the delamination process is captured by a zero-thickness CZM layer located in between the silver and REBCO/buffer layer. In Model 2, the CZM layer is
removed. In both models, two elements are specified through each layer, and the element size is 0.1 mm in other two directions. The purpose of this model is to capture the deformation of the tape when the delamination initiates as predicted in Model 1. In Model 3, a single solid-shell element (SOLSH190) through the thickness of the tape is used for the model, greatly reducing the computational time. Within the solid-shell element, six layers representing each layer of a REBCO tape are defined, and each layer is assigned its own thickness and material properties as done with the other two models.

**Figure 1.** Three models are developed to reduce computational needs. For Model 1, all the layers of a REBCO tape are modelled, and the layers are bonded together. The initiation and propagation of the delamination process is captured by a zero-thickness CZM layer located in between the silver and REBCO/buffer layers. For Model 2, all the layers are modelled in the same manner as in Model 1, but the CZM layer is removed to capture the deformation of the tape when delamination initiates. In Model 3, the REBCO tape is modelled with only one element (Solid-Shell element) across the thickness with each layer specified.

### 2.1. Cohesive Zone Method

Cohesive Zone Method (CZM) is a FEA technique to model the initiation and propagation of delamination. The CZM applied in this work uses a bilinear traction-separation law to relate the relative gap of the two surfaces to the amount of stress at the interface. As shown in figure 2, in a bilinear delamination, the contact stress increases linearly with the contact gap up to the delamination strength, and then linearly decreases back to zero when complete decohesion has occurred. As loading is applied onto a layer laminated material, if the contact stress and gap are below the critical value (along line OA), the loading and deformation is fully reversible, and the material is not damaged. However, if the load exceeds the critical value the contact gap will continue to increase while the load will decrease following the AB path. If the load is removed at point B, the material is irreversibly damaged, and the contact is softened so the unloading and reloading process will follow line OB, instead of OAB. When the contact gap reaches point C, the material is fully delaminated. The bilinear tangential shear-sliding law could be an alternative approach to use, and it is very similar to the traction-separation law.

**Figure 2.** A demonstration of bilinear traction-separation law of Cohesive Zone Method applied in this work. For a REBCO tape, as load is applied, if the contact stress is below the critical values of 50 MPa, the loading is fully reversible. If the load exceeds the critical point A, the tape is irreversibly damaged, and the contact is softened so the unloading and reloading process will follow line OB with a lower slope than OA. When the contact gap reaches point C, the material is fully delaminated.

For REBCO tapes, four parameters are necessary to describe the delamination behaviour: maximum contact stress, fracture energy, and contact gaps at initiation and completion of delamination. Among
those parameters, the fracture energy in both transverse tensile direction, 10 J/m², and shear direction, 20 J/m², are measured from experiments [1,10,13]. The delamination strength in transverse tensile direction measured in experiment varies from 10 to 100 MPa [7–9,14]. In this work, an average value of 50 MPa is taken as the failure criterion in transverse tensile direction, and 10 MPa is taken as the one in shear direction [11]. The contact gaps at initiation and completion of delamination in transverse tensile direction are 50 nm and 400 nm, and the interlayer sliding at initiation and completion of delamination are 50 nm and 100 nm respectively. Those parameters, gathered from literature, are listed in Table 2.

Table 2. Parameters used in the CZM layer in Model 1.

| Parameter | Description | Value | Parameter | Description | Value |
|-----------|-------------|-------|-----------|-------------|-------|
| \( \sigma_{\text{max}} \) | Maximum normal tensile contact stress | 50 MPa | \( \tau_{\text{max}} \) | Maximum tangential contact stress | 10 MPa |
| \( G_{\text{cn}} \) | Normal critical fracture energy | 10 J/m² | \( G_{\text{ct}} \) | Tangential critical fracture energy | 20 J/m² |
| \( \bar{u}_n \) | Contact gap at the maximum normal contact stress | 50 nm | \( \bar{u}_t \) | Interlayer sliding at the maximum shear stress | 50 nm |
| \( u_{\text{fr}} \) | Contact gap at the completion of delamination | 400 nm | \( u_{\text{f}} \) | Interlayer sliding at the completion of delamination | 100 nm |

2.2. Solid-Shell (SOLSH) element

In finite element analysis, a solid-shell (SOLSH) element is a 3D, 8-node structural element with all the capabilities and the topology of a solid element but it allows for layers with different material properties to be defined within it. The solid-shell element is useful for modelling laminates and high-aspect ratio structures. Previous work has shown that the stress-strain behavior in axial tensile direction obtained from solid-shell elements can reproduce very similar results to the ones obtained with experiments [12]. In addition, the use of a single solid-shell element through the thickness of the tape can reduce the computation time by more than a factor of 10 compared to using solid elements for each layer. Using solid-shell elements to represent the layered structure of the tapes opens the door to useful and accurate modeling of REBCO tape-stack in complex systems, such as CICC [12].

Since the properties of each layer (substrate, buffer, REBCO, etc.) are defined within each solid-shell element, it is not possible to model the delamination process in all its details, but this technique can provide insights on locations where delamination could occur, particularly for complex systems in which utilizing the CZM technique would be computationally prohibitive.

2.3. Loading conditions

Three loading conditions, including transverse tensile delamination, peeling delamination, and shear delamination, are studied for a 4 mm wide and 10 mm long REBCO tape and are shown in figure 3.

For all three loading conditions, the bottom surface of the REBCO tape is fixed, and displacement is applied onto a portion of the top surface. For transverse tensile delamination, transverse tensile displacement is applied onto a 2 mm by 2 mm square in the middle of the tape. Taking advantage of symmetries in the geometry, only a quarter of the tape is modelled, and symmetry boundary conditions are used. For peeling delamination, a small portion at the edge of the tape (1 mm by 4 mm) is peeled in a circular path around the peeling axis at the other edge of the tape. The peeling radius is the distance from a point in the peeling region to the peeling axis, for example, the peeling radius at the outer edge is 4 mm, and the one at inner edge is 3 mm. Since the load is applied in a circular path, the peeling force is always normal to the surface of the peeling region. The reduced mechanical strength at the edges of the tape was not considered in this study. For shear delamination, shear displacement is applied in the middle of the top surface of the tape in a 4 mm by 4 mm red square. The reduced mechanical strength at the edges was also not considered.
3. Results

3.1. Transverse tensile delamination

For Model 1, the delamination process is described by the CZM layer, and the stress taken at the center of the loaded region as a function of applied transverse displacement is shown in figure 4. The vertical displacement in Model 1 is the sum of contact gap and layer deformation. Delamination initiates when the stress reaches 50 MPa and the contact gap reaches 50 nm, as expected from our definition of the CZM layer properties. As loading is applied, the layer deformation increases until the stress reaches 50 MPa. As the loading continues, the layer deformation goes back to zero when the loaded region is fully delaminated, and the vertical displacement is dominated by the contact gap behaviour. The vertical displacement and contact gap overlap when the transverse displacement reaches 400 nm due to the completion of the delamination as prescribed in the CZM layer. The non-zero stress observed at transverse displacement above 400 nm indicates the propagation of the delamination along the tape.

For Model 2 and 3, the transverse displacement is only caused by layer deformation (no physical separation is modelled). Comparing the layer deformation from all three models (figure 5) it can be observed that the stress as a function of layer deformation is very similar. In the same figure, the three models all reach a stress of 50 MPa when the delamination initiates as predicted in Model 1. The computation time for Models 1 and 2 is roughly 10 hours, while for Model 3, it is less than 20 minutes.

At the centre of the loaded region, the transverse tensile stress and strain distribution across the thickness of the tape of the three models are further compared in figure 6 when the stress reaches 50 MPa (initiation of delamination). The stress is about 50 MPa across the entire thickness of the tape.
for all three models, indicating the stress predicted by the Solid-Shell element agrees with Model 1 and 2 in which all individual layers are modelled. The strain distribution of Models 1 and 2 changes across the thickness of the tape as each layer has a different elastic modulus. For the Solid-Shell element (model 3), the layers are specified within one element only and therefore the strain is constant throughout the thickness (the element has nodes only at the top and bottom surfaces of the tape). The strain value is very similar to the one of the copper layer, since both the top and the bottom layers with nodes are copper. In conclusion, when the SOLSH element is adopted to model the REBCO tape, a failure criterion to predict delamination can be considered (in this example 50 MPa) reducing the complexity and the computational time needed when adopting the CZM model. Of course, if information regarding the contact gap is needed, the CZM model is the only effective method to capture the information.

Figure 6. The transverse tensile stress distribution of the REBCO tape (contour plot), and the strain and stress distribution across the thickness at the centre of loading region are when delamination initiates as predicted in Model 1 (M1).

3.2. Peeling delamination
For peeling delamination, a small portion at the edge of the tape is peeled in a circular path according to the peeling axis at the other edge of the tape. Three locations at the peeling region are studied: the outer edge (A, peeling radius of 4 mm), the centre (B, peeling radius of 3.5 mm) and the inner edge (C, peeling radius of 3 mm) as shown in figure 7.

Figure 7. Three locations of the peeling region studied are shown in the cross section of the REBCO tape.

For Model 1, the peeling pressure and the stress of the elements at the outer edge of the tape (location A) versus transverse displacement is shown in figure 8. As in the previous loading case considered, the vertical displacement is the sum of layer deformation and contact gap. The peeling pressure is defined as the reaction force over the entire area of 4 mm by 4 mm (figure 3), and the stress is from the elements at location A. The delamination initiates when contact stress reaches 50 MPa. When the contact gap at the outer edge reaches 400 nm, the stress decreases to zero while the pressure remains a non-zero value up to 500 nm. For transverse displacement in a range from 400 to 500 nm, the outer edge is fully delaminated while the other part of the loading region is still in the delamination process.

Figure 8. The stress as a function of applied transverse displacement for Model 1 at location A. Delamination initiates at a stress of ~ 50 MPa.
The stress vs layer deformation obtained from the three models are compared at all three locations (figure 9). As shown in the figure, delamination initiates when stress reaches 50 MPa, and the three models show similar results at all three locations of the peeling region. The slopes of the stress-layer deformation curve at three locations are different. The inner edge (C) has the highest slope, and the outer one (A) has the lowest. This is expected as, for a given stress with the same rotation angle applied to the peeling region, a higher peeling radius causes higher displacement therefore a lower slope is observed at the outer edge of the peeling region (location A).

Since the peeling delamination in this study is dominated by the stress in the transverse tensile direction, the stress and strain distributions across the tape when delamination initiates are very similar to the ones shown in figure 7. As in the previous loading case, a transverse tensile stress of 50 MPa can be applied as a failure criterion and Model 3 can be effectively employed to predict delamination.

3.3. Shear delamination
For the case of shear load, delamination initiates when shear stress exceeds 11 MPa (figure 10). As per the previous loading conditions, the three models show similar results (figure 11).

The shear stress and strain across the thickness at the centre of loading region was investigated, and the results show that the shear stress is about 11 MPa throughout the tape. As with the loading conditions considered earlier, a shear stress of 10 MPa could be applied as a failure criterion for Model 3 to identify possible delamination issues while reducing the complexity and computational effort of having to use a CZM layer.

4. Conclusion
To explore the options for modelling delamination with reduced computation efforts, three delamination modes of REBCO tape under transverse tensile, peeling and shear loads are modelled using three
different modelling approaches. The results show that the stress state of REBCO in transverse tensile and shear directions can be accurately captured using a Solid-Shell element with specified layer structure to avoid the complex and computationally expensive CZM approach. In this work, the failure criteria used for the Solid-Shell element are taken from available experimental results (50 MPa in transverse tensile direction and 10 MPa in shear direction) but since the architecture of REBCO tapes (deposition method, material selection, layer thickness, etc.) varies significantly among manufacturers, modelling a specific tape configuration would require the knowledge of those values as part of the manufacturing specifications. The Solid-Shell element cannot capture the delamination process with exact details as with the CZM approach, but it provides critical information to predict and mitigate delamination and could provide a more efficient technique to analyse complex systems.

5. References
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