# GENERATING FINITE ELEMENT MODELS OF TUBULAR BRAIDED COMPOSITE USING MICRO-COMPUTED TOMOGRAPHY METHOD

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ABSTRACT

Tubular Braided Composites (TBC) are composite materials with a woven structure with different applications in different industries. One way to create a 3D model out of a TBC is using the Micro-computed tomography($\mu$CT) method. $\mu$CT is an X-ray-based method used to inspect objects both internally and externally accurately. Because of the high resolution of the $\mu$CT, the generated model includes all the details of the scanned TBC. In this paper, the $\mu$CT is used to scan a TBC, and after applying image processing techniques in ImageJ, MATLAB and Avizo software packages, the 3D model is generated. Also, one of the yarns is segmented out manually and is meshed and imported separately. Finally, the 3D model of the complete TBC and the single yarn are meshed in Avizo and then imported into COMSOL Multiphysics. The used process in this paper shows Avizo software's potential in combination with other software to create an accurate FEM simulation. The FEM based on $\mu$CT is expected to show more accurate results than the FEM based on different geometrical results. Having an accurate model will help to understand the behaviour of TBC better. Also, it helps to optimize the current applications and find new ones.

## 1 Introduction

Different methods have been used to inspect composite materials externally and internally [1] [2]. Among all the Non-destructive Evaluation (NDE) methods, micro-Computed Tomography ($\mu$CT) has shown significant advantages by revealing the inner structure of the samples. This X-ray-based method can create cross-sectional images out of objects [3]. The cross-sectional images can be imported into software to generate an accurate 3D model. The applications of CT were initially limited to medical fields. However, more recently, $\mu$CT has been widely used in various research areas and industries such as 3D printing, sport, marine and aerospace[4] [5].

Mendoza et al. [5] used an automated method to segment yarns from CT images of woven composite. Also, they extract Finite Element (FE) meshes from the composite material that can be imported into FEM software packages for further analysis. Naouar et al. [6] developed a simulation model for a textile composite. The geometrical model was generated from $\mu$CT scan, which was imported into the FEM software for analysis. Also, another FEM was developed based on a textile geometrical modeller. The result of the two models shows that the FEM based on $\mu$CT shows better results than the FEM based on the textile geometrical modeller. The focus of this study was on flat braided composite using periodic boundary conditions, and TBCs were not studied. Auenhammer et al. [7] developed an automated process for segmenting $\mu$CT images of non-crimp fabric reinforcement composites. Then, the segmented sections were meshed and prepared for creating a FEM simulation.

Tubular Braided Composite (TBC) is a type of braided composite in a tubular shape [4]. Braided composites are a type of composite in which a set of continuous fibers are interwoven around each other. There are three patterns in TBCs; Diamond, Regular, and Hercules. The patterns are shown in Figure 1. The yarn moves above one yarn and then below the next one in the Diamond pattern. Therefore, the pattern is one-by-one. In the Regular pattern, the yarn moves above two yarns and below the next two ones (two-by-two pattern). Finally, in the Hercules pattern, the yarn moves above three yarns and below the following three yarns ( three-by-three pattern).

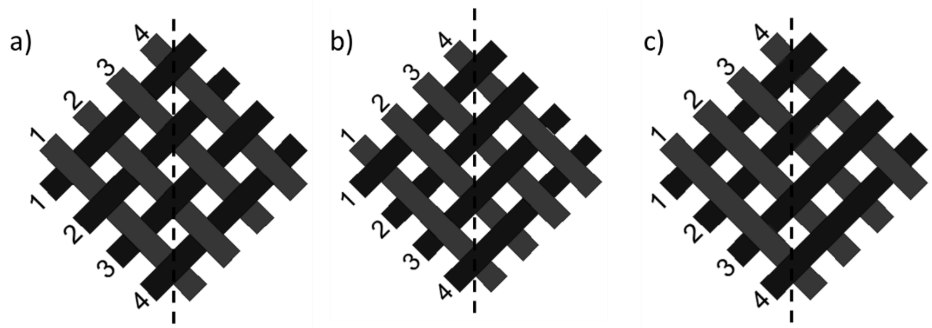


Figure 1 Different patterns of TBC, a) Diamond pattern, b)Regular pattern, and c) Hercules pattern

There are two forms of TBCs; open-mesh and closed-mesh. The shape of the TBCs is shown in Figure 2. In open-mesh TBC, there is an open space between yarns. However, in closed-mesh, TBC yarns are in contact with each other. Braided composites have significant advantages compared to other conventional composite materials. For example, braided composite shows better out-of-plane strength and toughness properties. Also, they have better impact and delamination resistance [9], [10]. Some geometrical developers based on mathematical equations have been developed to generate models. However, due to the complex and flexible nature of the TBCs, the developed geometrical models do not fully represent the characteristics of the TBCs. Therefore, $\mu$CT can be used to fill this gap and provide an actual and accurate model.

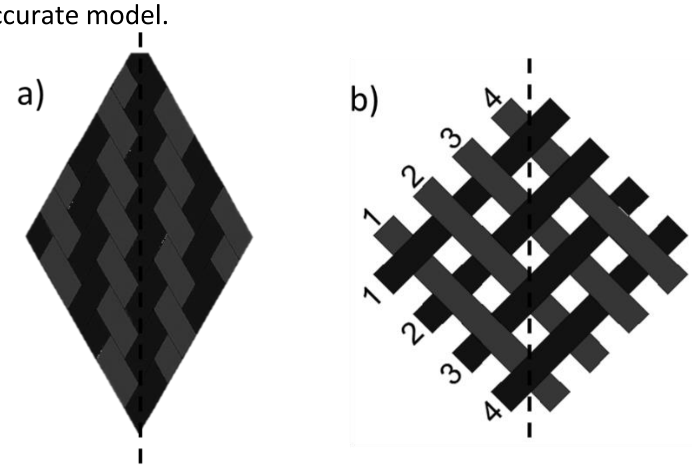


Figure 2 Different forms of TBCs. a) Closed-mesh and b) open-mesh TBC

Our previous publication [11] used $\mu$CT to scan a TBC and Avizo software package (2021.2Thermo Fisher Scientific, MA, USA) to analyze the fiber orientation and extract some of the properties of the scanned TBC. Because of the high resolution of the scanned samples (1 $\mu$mm), the individual fibers of yarns were detected, and their orientation angles were measured. This study shows encouraging results to extend the method for developing a complete model out of the TBC using $\mu$CT and then importing it into a FEM software package for analysis. Also, in [12] simulation FEMs were developed based on geometrical models generated by TBC-Gen software. Furthermore, the geometrical model FEM results were compared against experimental and analytical results. Finally, it was shown that FEM simulation shows better results compared to analytical models.

In this paper, the process for using $\mu$CT to generate a geometrical model for a FEM application is presented. First, an open-mesh TBC will be scanned by $\mu$CT, and after applying image processing techniques to the cross-sectional images, they will be imported into Avizo software for further analysis. Then, in Avizo, a 3D model of the scanned TBC will be generated. Next, a set of meshes compatible with COMSOL Multiphysics will be generated. Finally, the mesh will be imported into COMSOL Multiphysics, and the developed model will be displayed there. Following this process will generate an accurate FEM model, which will show better and more precise results than the FEM model based on the geometrical model.

# 2 Methodology

## *2.1 micro–Computed Tomography ($\mu CT$)*

The SkyScan 1272 desktop microtomography (Bruker-MicroCT, Kontich, Belgium) was used for scanning the open-meshed TBC. Figure 3 shows the schematic of a $\mu$CT setup. In a $\mu$CT scan, X-Rays are sent towards the sample (the TBC) and based on the density of the sample, part of the energy of the X-Ray is absorbed, and the remaining energy passes through and is absorbed by a detector. The transmitted X-Ray has a different amount of energy, which affects the detector surface. Finally, a 2-D image from the test piece is projected on the detector after absorbing all the energies. Then the test piece will be rotated with a predefined rotate angle, and another 2-D projection will be recorded from the test piece. For symmetrical test pieces, only 180° of it must be scanned [ref]. After collecting all the 2-D images, they are imported into NRECon software (NRECON 1.7.1.0, Bruker, Belgium) to create 2-D cross-section images (Figure 3).

The scanned open-mesh TBC was made of Kevlar, and it consists of 48 yarns with a Regular pattern. The TBC's braid angles and yarn width were measured by analyzing the images taken by a digital camera (Nikon Digital Camera D3500 with AF-P NIKKOR 18-55 mm 1:3.5-5.6G lens). Ten measurements were done for each parameter, and the average value was reported in this paper. As a result, the average braid angle of the TBC is 40.53°, and its average yarn width is 0.88 mm. Figure 4 shows the measurement of the braid angle and yarn width of the open-mesh TBC. Because of the flexible nature of raw open-mesh TBC, a 10 mm mandrel was 3D printed to form a cylindrical shape. Then, the upper and lower ends of the braid were connected to the mandrel using masking tape.

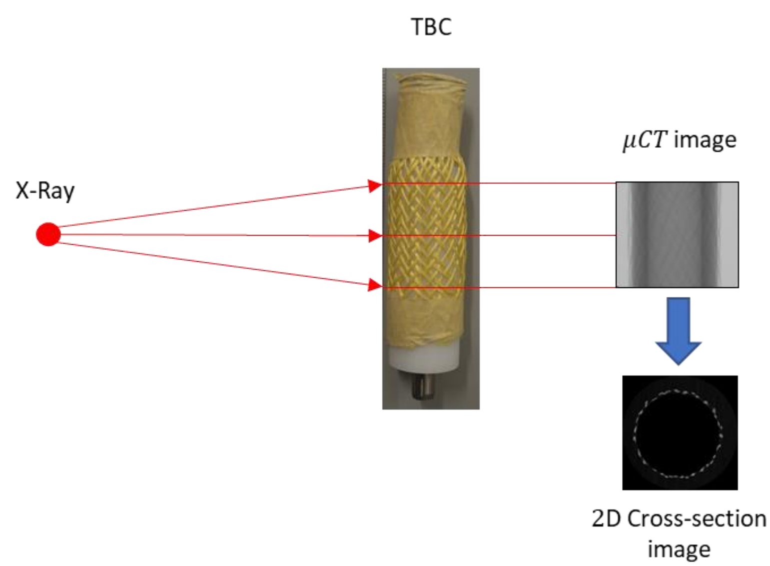


Figure 3 the schematic of a $\mu$CT setup for scanning an open-mesh TBC to generate 2D cross-sectional images

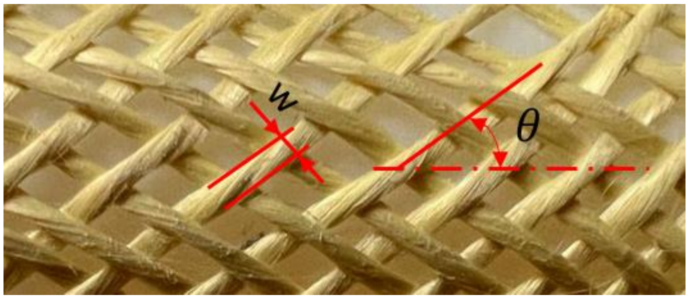


Figure 4 Measuring yarn width and braid angle of the open-mesh TBC using a digital camera (10 measurements were done, and the average values were reported)

The setting used for capturing the $\mu$CT scans and the output results of the scans are tabulated in Table 1. The settings were selected based on the experience and optimized by evaluating the effect of each parameter. The rotation angle was set to be 0.1°, and 180° of the TBC was tested. In other words, 1800 projections at different angles were captured from the TBC. Also, the frame averaging was set to 4. Frame average takes an average of several images taken in the same position. For example, four projections were taken at each step in this setup, and the averaged image was saved. The higher the frame averaging, the clearer the images. However, it would increase the scan duration of the test. The pixel size of the obtained images was 10.88 $\mu m$.

Table 1 setting of the $\mu$CT scan

| **$\mu$CT parameters** | **Value** |
|---|---|
| Image pixel size | 10.88 $\mu m$ |
| Source Voltage | 55 kV |
| Source Current | 166 $\mu$A |
| Number of scanned Images | 1533 |
| Exposure | 1876 ms |
| Rotation step | 0.1° |
| Rotation angle | 180° |
| Frame Averaging | 4 |
| Duration | 4 hour and 35 minutes |

# 3 Results and Discussion

## 3.1 Generating 3d Model

Different software can edit the 2D cross-section images and create the 3D Model. ImageJ (National Institutes of Health, USA) is used to binarize the images in this research. Also, the threshold setting was adjusted between 165 and 226. Finally, the despeckle filter removes noises and applies to all the 892 2-D cross-section images. The raw 2-D cross-section image and the edited binarized image are shown in Figure 5.

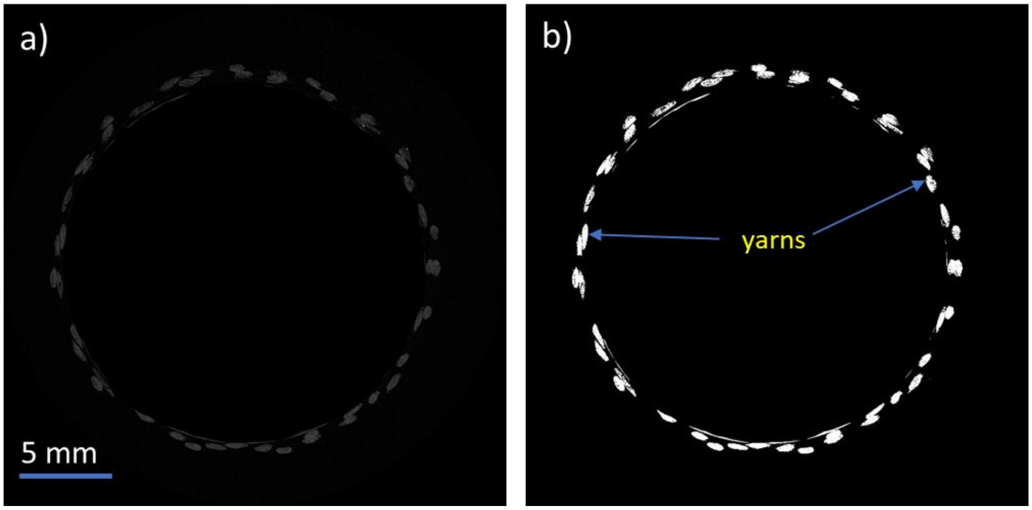


Figure 5 2-D cross-section image of the scanned TBC. a) the raw cross-section, b) the binarized and edited cross-section

After editing the 2-D images in ImageJ, there were imported into the MATLAB software package (R2021B, The MathWorks Inc, Natick, MA, USA) for further image processing. The "bwboundaries" function is used to detect the yarn cross-sections. While this function can detect most yarns, some yarns with overlapping cross-sections cannot be segmented separately. Therefore, a method was developed to separate the two-overlapping yarns by splitting them in half. However, in some cases, three yarns were overlapping, which made the splitting process more complicated, and the algorithm could not provide appropriate results.

Therefore, this method cannot detect a single yarn through the image sequences. The detected yarn cross-sections and the overlapping yarns are shown in Figure 6 a). Alternatively, one of the yarns was detected and segmented manually throughout the image sequences. This process was done in ImageJ, and the stack of images was imported into the software. After applying the image processing algorithms, the whole braid cross-section was deleted except for the selected yarn. This process was done for the entire stack of images manually, and in the end, a stack of images only remained, including the selected yarn. Then, the images were imported into MATLAB, the developed detecting algorithm was applied to the images and parameters of the single yarn were extracted. Yarn area, center, and orientation were the three main results extracted from the yarns. One of the 2D images with segmented yarn is shown in Figure 6 b). Then the image stack, including the yarn cross-section, is imported into Avizo to generate the 3D Model and prepare the meshes required for FEM.

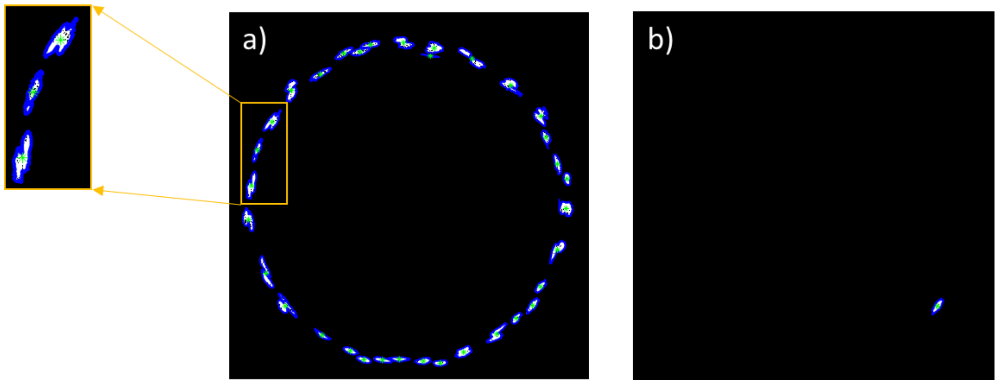


Figure 6 Imported 2D cross-section images into MATLAB for detecting yarns, a) detected yarns and two overlapping yarns, b) single yarn segmented manually.

After applying the image processing techniques, the 2D images are imported into Avizo Software, an image processing software used for processing $\mu$CT images. After importing all the 2D images of the complete TBC and the single yarn, using the "Volume Rendering Settings" option, the 3D model of the scanned TBC is generated, which is shown in Figure 8. In Figure 6 a), the complete TBC is demonstrated. The mandrel of the TBC has already been removed in ImageJ. However, the Avizo can be used for removing and image processing techniques. Figure 6 b) shows the 3D Model of the single yarn segmented manually in the previous section. These models can be saved and imported into COMSOL Multiphysics as a geometrical model, or they can be meshed in Avizo and then imported into the COMSOL Multiphysics. The flow chart of the used software to generate meshes is shown in Figure 7.

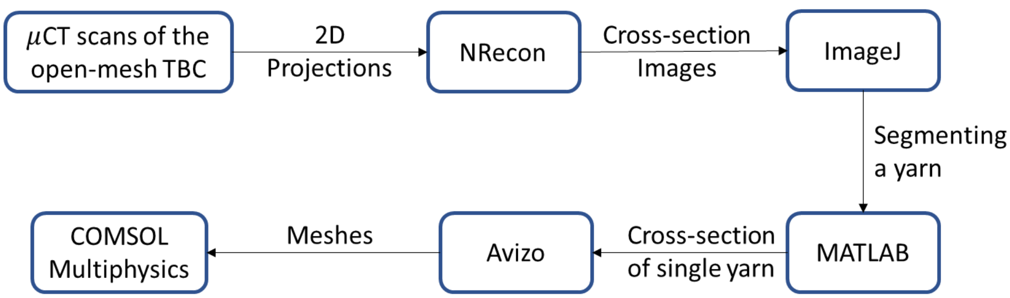


Figure 7 The flow-chart of generating meshes using different software

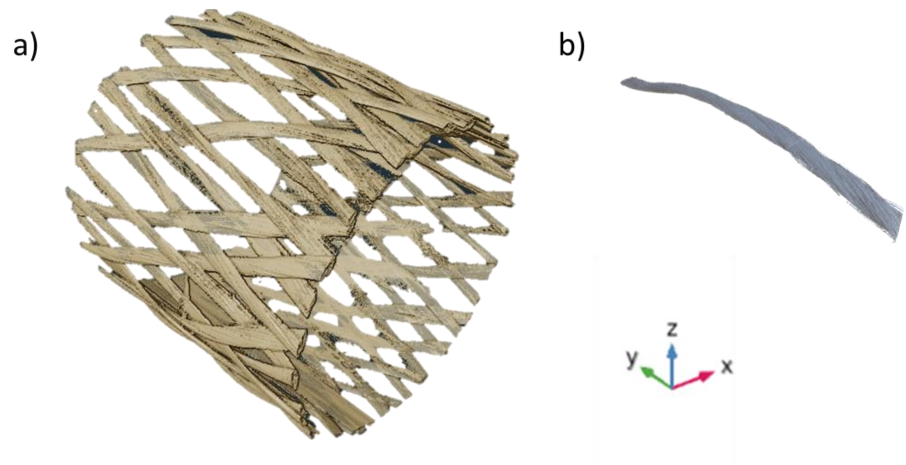


Figure 8 the 3D model was generated from the 2D cross-section images using theAvizo Software package. a) the 3D Model of the complete TBC, b) the 3D Model of the segmented yarn

### *3.2 Meshing the Model*

The Avizo software generates the mesh for the 3D models developed in the previous section. The type of the used mesh was tetrahedral mesh. The mesh can be defined in five qualities, from "Low" to "High." The selected quality in this study was set to medium. It resulted in the following mesh properties for the model shown in Figure 6 a): number of nodes: 4,098,315, number of triangles: 29,858,029, and number of tetrahedrons: 12,915,211.

Avizo provides different formats for different FEM software packages. For this research, the COMSOL mesh type was used. The mesh was exported in the appropriate format to be used in COMSOL. Figure 9 a) shows the generated mesh in Avizo for the segmented yarn, and Figure 9 b) shows the zoom section of the entire TBC where meshes can be seen with more details. After importing the meshes into COMSOL Multiphysics, the properties of the Kevlar, as tabulated in Table 2, can be applied to the model for analysis.

The generated mesh for the complete TBC is for the entire shape of the TBC. However, for having a more accurate model, the yarns can be segmented and meshed separately. Alternatively, the single extracted yarn shown in Figure 9 a) can be patterned around the axis of the mandrel 24 times. Similarly, a clockwise yarn can be extracted and repeated. The results will give 48 yarns meshed separately that need to be linked together.

Table 2 The mechanical parameters of Kevlar TBC

| | $E_{f11}(GPa)$ | $E_{f22}(GPa)$ | $G_{f11}(GPa)$ | $v_{f11}(GPa)$ |
|---|---|---|---|---|
| Kevlar 49 fibres | 130 | 7.3 | 2.86 | 0.35 |

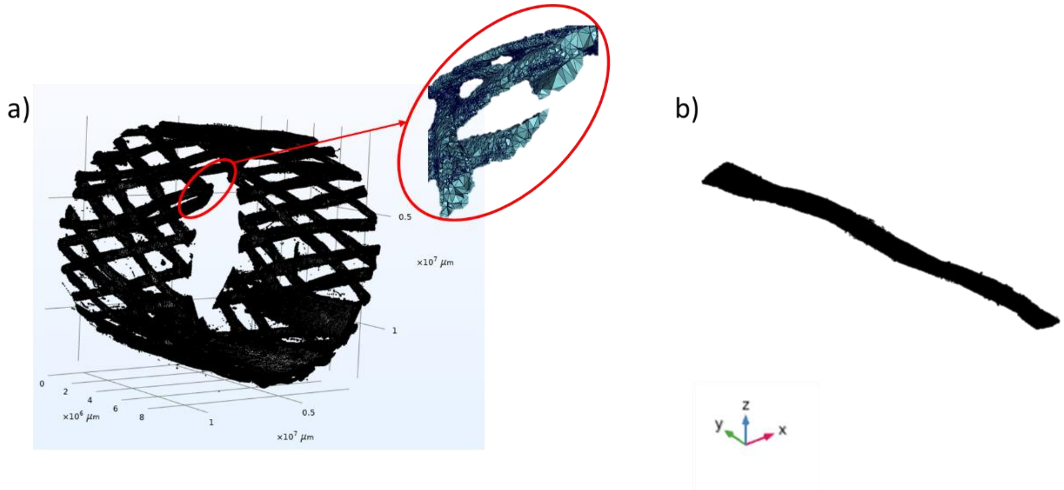


Figure 9 Generated tetrahedral mesh for the $\mu$CT scan models, a) the single extracted yarn, b) part of the complete TBC

# 4 Conclusion

In this paper, the potential of using $\mu$CT technique for generating a geometrical model for FEM was studied. An open-mesh TBC was scanned because of its space between yarns. The distance between yarns made it easier to analyze. Because the TBC was not cured and had flexible nature, a mandrel was 3D printed and used to hold the sample. The projections were used to generate cross-sectional images, and after applying the image processing techniques, they were imported into Avizo software for creating 3D geometrical models and meshes. Thanks to the 10.88 $\mu m$ voxel size of the 3D Model, the generated model in Avizo includes details of the actual TBC. The accurate geometrical model then meshed, and the mesh was exported in a compatible format for COMSOL Multiphysics. Finally, the mesh was imported into COMSOL Multiphysics and was displayed.

This paper shows the application of Avizo software for generating meshes for TBC for the first time. Previously, the mesh has been generated for $\mu$CT models of flat woven composite materials. The simulation FEM developed based on the $\mu$CT model is expected to show more accurate results than the FEM based on geometrical models. However, for further analysis, the FEM of the $\mu$CT models should be developed, and its results should be compared against the results of FEM based on the geometrical models. The $\mu$CT-based model includes some of the complex and flexible nature of the TBC that are not captured in the geometrical Model. The FEM of these two geometrical models need to be developed for a similar TBC for comparison.

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