8. Discussion

# 8.1 Introduction

The purpose of this work was to develop and demonstrate an optimisation design process for the weaving patterns of 3D woven carbon fibre reinforced T-joints. This was to aid in solving the problems associated with designing weave patterns for 3D woven reinforced structures, namely the large design space and difficulty in knowing the effect of weave changes on the mechanical properties of T-joints. The challenges included picking the correct optimisation algorithm, developing a method to predict and implement the interlacement pattern, automatic generation of meshes, overcoming the length of time it takes to run each candidate design through the objective function evaluation and running a permutation optimisation of the initial failure load of the composite T-Joints.

This chapter will discuss the results from the previous chapters and evaluate them against the aims and objectives set out in the introduction chapter. It will be noted for each whether these fill research gaps identified in the literature review. The methodology used will be discussed including an overview of the software developments associated with the work completed. This will be followed by a summary of the work completed and a suggestion for next steps.

# 8.2 Comparison of Research Work to Aims and Objectives

In the introduction, the main research question on whether it is possible to use optimisation algorithms to improve the design of 3D woven composite T-joints, was broken down into five aims and objectives. This section will evaluate each of the five core aims and objectives against the work included in the subsequent chapters. The purpose is to identify where they were met and whether the overall research question posed at the start of the work has been answered, noting where gaps in the literature have been filled. Each of the aims are listed followed by an assessment of the work completed as to whether those aims were achieved.

### 8.2.1 Experimentally investigating T-Joint Behaviour

The literature review identified that there had only been one example [1] of published data regarding 3D woven carbon fibre reinforced composite T-joints. This is in addition to a limited amount of μCT data [2] of the junction region of 3D weaves with weft yarn crossover. More data was needed before being able to conclude that the nesting of the weft yarns was a phenomenon not restricted to the particular weave in the paper.

A set of μCT data was collected for the T-joint with crossover; the same nesting effect of the weft yarns can be seen. However, due to the size of the carbon fibre sample used, the resolution of the images was low. Even so, the images were enough to provide some extra validation for the nesting effect.

In the experimental chapter, the manufacturing process for two different 3D woven composite T-joint reinforcements was set out. This included preparing the reinforcement samples, mixing the epoxy and the RTM process. The two weave patterns had several key differences, one had axial weft and warp yarns (±45°) with no crossover of the weft yarns at the junction, the other had straight (0°) yarns with weft yarn crossover. It was found that the straight yarned T-joints were both stiffer and able to reach a higher peak load than the T-joints made from the axial reinforcement. One hypothesis in [3] is that weft crossover in T-joints has a crack arresting effect due to the misalignment of the yarns in the junction region shortening the average crack length. The results in this chapter provide further evidence to support this.

An ideal way to achieve the main aim of the research to optimise 3D woven T-joints would have been to perform the tensile pull-off test on a T-joint made using a reinforcement in the final optimised weaving pattern. This would have validated the modelling work done in Chapter 6 and provided confidence in the overall zoptimisation process. However, as mentioned in Chapter 2, the Covid-19 pandemic alongside the cost of setting up a loom to produce the fabric meant that it was not possible.

### 8.2.2 Composite Optimisation

Previous work completed at the University of Nottingham [4], [5] had demonstrated optimisation of the unit cell of flat weaves using genetic algorithms. These unit cell optimisations relied upon periodic boundary conditions finite element analyses to obtain an objective function value made up of the elastic constants and so were only applicable to periodic textiles. This raised the question of whether it would be possible to use numerical optimisation algorithms for a significantly more complex structure like T-joints. Furthermore, the T-joint design criteria includes the failure behaviour to a greater extent than for flat weave unit cells because it is a structural component. This meant that some failure-based modelling approaches such as modelling the yarn/matrix interface, would be of interest. However, as the flat weaves are smaller models than the full T-joint models in terms of mesh size and problem complexity, they provided a good opportunity to test cohesive surfaces in the context of an optimisation.

In Chapter 4, three optimisation algorithms were compared to find the most appropriate for flat 3D woven unit cells, the genetic algorithm alongside the particle swarm and pattern search algorithms. The objective function value was the through-thickness stiffness, E3. As part of that work, a new test for feasibility was developed to rule weave designs that would not be able to be woven out of the optimisation, thereby reducing the overall time to reach a solution. The genetic algorithm was chosen out of the three because it reached a solution in significantly fewer function evaluations.

In the next part, an optimisation was run again for unit cell 3D weaves, optimising for peak load in the through-thickness direction. Cohesive surfaces were used to model the yarn/matrix interface. One of the barriers to the use of cohesive surfaces in previous optimisation attempts was the length of time it took to generate the surfaces. To speed up the surface generation in TexGen, OpenMP was used to parallelise the key parts of the code. This significantly cut down the length of time to automatically generate the mesh with the cohesive surfaces. However, when applied to T-joint models the length of time remained too long to include cohesive surfaces as part of an optimisation run. An extension of this is also that using UMATs to model material failure was evidently not going to be possible for T-joints as they take longer to run than cohesive models.

This work on composite optimisation of flat weaves may not have been directly linked to T-joint optimisation but contributed overall by guiding the process. An example is by ruling out the possibility of using cohesive surfaces, and consequently UMATs, within optimisation runs.

### 8.2.3 Automatic Generation of T-joint Models

One of the main barriers to the optimisation of 3D woven T-joints at the start of this work was the ability to automatically generate the weft interlacement pattern from any starting weave pattern. This was difficult because of the need to be able to predict the order in which the wefts wrap around each other and the difficulty in then Python scripting a parameterised model that would be able to take the inputs from the predicted interlacement ordering and generate a high quality geometry model to accurately model the as-woven textile. This represented a gap in the literature that previous work by Yan and Brown had tried to fill.

The models generated in this work are idealised representations of the actual textile architecture. To get a parameterised model that is more representative would be difficult and require a large amount of μCT data to validate against. One of the key differences between the idealised models and the actual textile is yarn path waviness and cross-section variability. TexGen already has the capability to model these types of woven features so this is an area for future research.

This work was the most pivotal in paving the way towards running an optimisation and answering the research question posed by the work. An additional outcome is the Python scripts can be used as a tool to automatically generate T-joint textile designs. This is useful for weave designers of 3D woven T-joint reinforcements.

8.2.4 Automatic Generation of Meshes

One of the key aspects of numerical optimisation algorithms is the lack of user interaction once the optimisation process has begun. This means once the textile geometry models have been generated they need to be meshed. Previously, automatic generation methods for T-joints relied on using voxel meshes, this allowed fast generation of a good quality mesh with elements of a consistent aspect ratio. However, they produce a stepped interface between the yarn and the matrix which can act as stress concentrators and require many elements to get a sufficiently accurate mesh of the yarn volumes. The effect of the stress concentration effect can be seen in Chapter 4 when choosing a mesh for the peak load optimisation where the denser meshes with the smaller elements have lower peak shear stresses.

Subsequent to the commencement of this work, a new version of TexGen was released that used an octree voxel mesh refinement [6] to subdivide elements close to the yarn/matrix interfaces. This had the advantages of the voxel mesh while also being able to mesh yarn volumes more closely with fewer elements. In addition to this the octree voxel mesh came with a smoothing algorithm which was able to reduce the stepped effect along the material interfaces, the disadvantage of this is a less consistent mesh quality as there is no longer a constant aspect ratio. This work tested out the octree voxel mesh on the T-joint models and compared it to the voxel mesh while also varying the degree of refinement and the number of smoothing iterations.

For the optimisation, the accuracy of the finite element mesh, which usually increases with the number of elements, must balance with the length of time it takes to run the model. As a result, choosing the best mesh relies on judgement. Increasing the number of smoothing iterations above 5 led to oscillations in the force-displacement response, probably due to the generation of poor-quality elements by the smoothing algorithm. Increasing the number of refinements above 2 did not yield a change in the force-displacement curve and the number of elements was chosen to be 20 as increasing the number of elements again saw oscillations in the force-displacement response.

Overall, the ability to use an octree voxel mesh with the optimisation facilitated the optimisation of the T-joint weave by providing a robust method of automatically meshing the geometry in a similar way to the voxel mesh but with the advantage of the refinement and smoothing.

8.2.5 Method to Score Each Weave

The final aim and objective from the literature review was to find a method of scoring each 3D woven T-joint design. The literature review revealed that one of the key aspects of T-joint design is its resistance to failure. Previous runs of optimisations for 3D woven composites have used elastic properties calculated from periodic boundary conditions analyses as the basis of the objective functions. These are not so applicable to T-joints so a different method of scoring the weaves was needed that would satisfy the design requirements.

In chapter 4, the optimisation of the peak load for the flat woven models using cohesive surfaces to model the interface damage, while successful, took too long. The T-joint models were larger so would have taken much longer meaning that using cohesive surfaces to model yarn delamination in the T-joints was a less favourable option. Following on from that, modelling the failure behaviour of the T-joints using Abaqus user subroutines, which are also time intensive, was also not a realistic option for the optimisation.

In chapter 6, a new idea was developed to score the weaves. A post-finite element analysis script was used to iterate through each point in the time step and evaluate the stress levels against Hashin’s failure criteria. Once 2% of the elements were deemed to have failed, the load at that point in the analysis was determined and used as the initial failure load. It would have been better if this was able to be validated against experimental data but shows a new approach that was able to provide a consistent measure across all the T-joint designs generated in the optimisation.

# 8.3 Methodology

The strategy for this work was a combination of developing the software capability to carry out the geometry modelling and analysis needed for the optimisation alongside a program of experimental work. This section will focus on the software development as the experimental work has been touched upon and discussed in previous sections.

## 8.3.1 Software Development to Facilitate Research Work

To facilitate the optimisation processes, the further development of several aspects of TexGen was required alongside Python scripts to automatically generate the woven reinforcement geometries of both the flat woven and the T-joint textiles and mesh the full composite domain.

In chapter 4, the *CheckBinderPaths* Python code is used to evaluate whether the binder yarn path of different weave designs represent feasible textiles. This meant that an unfeasible textile design generated by the algorithms would have been removed from the process without being run through the finite element analysis. A large penalty value is used in its place as the objective function value. In addition to this, the OpenMP library was introduced to the *COctreeVoxelMesh* TexGen class to split up the processing of surface elements across multiple CPUs. This allowed surfaces for the cohesive contact analysis optimisation to be output quicker, which was important for reducing overall function evaluation time.

In chapter 5, the *CTextileOrthogonal* class was modified to allow placement of binder yarns at any height in the weft stack. This was so that the separated woven flanges could be completely bound by binders looping above and below the new reduced weave pattern formed after the junction. A set of Python scripts were used to generate the woven T-joint geometry. The *GenerateTextile* script was used to set up the *CTextileOrthogonal* class and call the *WeavePattern* module which reads the weave pattern and calculates the information required to determine the weft yarn interlacement order.

Further work, detailed in Chapter 6, required the new *CPrismDomain,* developed prior to the start of the T-joint modelling work detailed in Chapter 5, to work with the *COctreeVoxelMesh* class. This allowed the T-shape profile of the composite T-joint to be meshed with the octree voxel mesh.

In addition to the Python and TexGen software, code was developed to run the optimisation of the T-joints using a parallel architecture on the HPC as detailed in Chapter 7.

# 8.4 Future Work

The following section describes suggested future research work that would continue to develop the work set out in this thesis.

It would be useful to manufacture the optimised textile and use the results to validate the results of the finite element analysis. This would provide further confidence in the optimisation process.

A further extension of the finite element modelling work would be to explore the T-joint designs more closely by creating full failure models with cohesive surfaces to do a back to back comparison to the optimised textile model presented here. Additionally, with the aid of more μCT data, additional real life weave features such as yarn waviness and crimp could be included in the geometry models.

It would be instructive to conduct optimisations with other objective function values. For example, the same models could be used to optimise 3D woven T-joints for initial load in the T-bend test. Additionally, the methodology to model the weft yarn interlacement ordering could be applied to 3D woven I-beam reinforcements and could then be used to optimise the I-beam architecture in a similar way to the approach set out in this thesis.

It would be beneficial to users interested in designing T-joint architecture to integrate the T-joint code deeper into TexGen. This could use C++ to rewrite some of the Python code. A further benefit could be gained by the creation of a user interface for the T-joint design tool, this would make it easier to expand the range of T-joints able to be designed.

# 8.5 Conclusions

The purpose of the work set out in this thesis was to address the issue of optimising T-joint performance by bridging the gap in the existing literature between optimisation of flat woven models using genetic algorithms and the modelling of 3D profiled structures such as 3D woven T-joint reinforcements. In chapter 3, T-Joint performance under mechanical testing was evaluated using two different specimens to provide some information about the failure behaviour of T-joints under tensile pull-off loading. This was followed by a re-evaluation of methods in the optimisation of flat woven structures including finding means to speed up the analysis and include cohesive surface modelling. In chapter 5, a method for the automatic generation of T-joint models with weave variations was developed by determining the order of weft yarn ordering from the weave pattern draft. Subsequently, a modelling scheme was required to evaluate performance in an optimisation run by determining the point of initial failure using the stresses at each increment where speed of analysis and evaluation was required to make the optimisation possible within a reasonable timeframe. Finally, an optimisation run using a NSGA algorithm with MATLAB was carried out to find the optimum weave pattern to maximise initial failure load subject to the geometrical constraints provided by standard 3D weaving looms.

The literature review revealed some barriers to the optimisation of 3D profiled structures at the start of the work. The first is that while periodic boundary conditions allow elastic properties to be optimised in flat woven models, woven T-Joint reinforcements only have periodicity along one axis so these methods are not applicable. The second is that elastic properties are not particularly relevant to T-Joint design where the important mechanical properties relate to the failure behaviour. Finally, 3D woven T-joint reinforcements have been successfully modelled in the past but these models required extensive manual modification to accurately model the interlacement of the weft yarns in the junction region. These were produced in limited number so any conclusions drawn about the weft yarn configuration’s effect on the mechanical properties were from a limited set of designs.

The behaviour of two types of 3D woven T-Joints were characterised under tensile pull off loading. One weave had a layer-to-layer form with weft crossover in the junction region while the other was an axial fabric with no yarn crossover. The axial fabric joints with no crossover performed poorly reaching a peak load of approximately 3.1kN, unable to sustain the same load as the layer-to-layer weave which reached 5.2kN. Images from μCT scanning were used to measure the yarn widths and heights in order to set these values in the geometry of the T-joint models in the later chapters. They were also used to set the circular cross sections of the weft yarns in the junction regions.

By starting with optimising flat 3D woven structures, barriers to the use of applying optimisation to T-joints were identified: slow manual modelling of geometries, automatic meshing and limited periodicity of weave reinforcement as well as the large computational cost of such methods. A novel method was developed to reduce the number of spurious function evaluations during optimisation of flat woven structures. The effect of this was the ruling out of weaves that are unable to hold their own integrity from the optimisations. The method consisted of using a set of simple checks applied using Python scripting. This was able to significantly reduce the computational cost by reducing the number of function evaluations that needed to run the finite element analysis.

Reducing delamination in composite materials is one of the reasons to use 3D woven reinforcement where the binding yarns can apply closure pressure on cracks. This work also explored the use of cohesive surfaces in optimisation algorithm runs by applying them to the flat woven models. While its use is a possibility for flat woven models with limited size and number of design variables in the optimisation, the duration to both generate the mesh and analyse the model would altogether exceed reasonable timescales for optimisation, using the current HPC facilities, of more complex reinforcement models such as those of T-Joints. However, methods to speed up the generation of surfaces in TexGen using the OpenMP C++ library to parallelise the code were implemented as part of this work. Furthermore, alternative optimisation algorithms were used and compared to find the most suitable for use.

The 3D woven T-Joint reinforcements were modelled using TexGen. Parameterised models were developed to enable them to be automatically generated with varying weft yarn configurations. Determining the ordering of the weft yarns as they wrap around each other from the pattern draft was automated with a new Python tool, allowing the generation of T-Joints for input into the optimisation. The methodology for producing the weaves after determining the ordering of the weft interlacement was described with the process of adding nodes, changing sections and moving them into the correct positions.

Voxel meshing was compared against smoothed octree voxel meshing to establish which is the most efficacious for the automatic meshing needed for optimisations of T-Joint weaves. Voxel meshing has historically been the standard meshing method for 3D weaves due to its robustness and quick method of generating good aspect ratio, consistent quality elements. Octree voxel meshing builds on this by subdividing the elements at the material interfaces allowing a closer approximation of the true interface surfaces. Further smoothing iterations remove the stepped interface but can lead to distorted elements so care should be taken to limit the number of iterations ensure the element quality does not deteriorate. In either case, it was found these do not contribute to the overall stiffness response but can reduce interface stresses caused by shear locking. The T-joint models were created within a TexGen prism domain which allowed the outline of the T-shape to be specified before being meshed with a voxel mesh. As part of the work to generate finite element models of T-joint weaves, the octree voxel mesh was extended to be used with this form of domain.

After this a modelling scheme for determining the failure initiation load under tensile pull off testing was described using Hashin’s failure criteria and the modified Von Mises criteria for the yarns and matrix respectively. This relied on evaluating the stresses, post-completion of the finite element analysis, in the elements at each frame and accumulating the number of failed elements until a threshold was reached. The advantage to this approach is the speed of determining an initial failure load without having to run user subroutines which are called at every iteration.

Building on the work in the earlier chapters, the ability to automatically generate weave patterns from the pattern draft, mesh them and model the tensile pull-off test determining a point of initial failure enabled an optimisation to be run to find weaves with the highest initial failure load under tensile pull-off testing. To perform the optimisation, which relies on generating permutations of design strings, the design variables were encoded as 4 bit binary strings. The best weave was compared against both the orthogonal weave with no weft crossover and the worst performing textile evaluated during the optimisation. The feature that caused the weave chosen to be the best performing was determined to be the flattened junction region which was formed by a combination of some crossover and self-entanglement of the weft yarns as they entered the bifurcation region.

Automatic generation of the T-joint geometry is not only useful for performing optimisations. Full scale models with higher mesh densities and more expensive modelling techniques can be accurately produced for finite element analysis using the methodology set out in Chapter 5. Furthermore, the use of the OpenMP library to speed up the generation of surfaces is another advantageous outcome of this work for those seeking to employ cohesive surfaces on textile models. Finally, the application of the octree voxel meshing technique to the prism domains is an important step in the process of generating these meshes for textiles that do not fit the regular cuboidal flat woven profile.

By providing the methodology with which to automatically generate the T-joint models and evaluate an objective function, this work paves the way for optimisation of other forms of optimisation objective functions under different loading conditions.