Two dimensional (2D)/laminated composites have high moduli and strength inplane but, depending on the loading, are susceptible to damage in the form of ply delamination [74], which degrades the through-thickness mechanical properties. This leaves them less well equipped for applications such as T and I-joints (see figure 4-3) where there is significant out of plane loading.

One method to measure through-thickness strength can be found in [75] where aluminium bars were bonded to a specimen to directly transmit load along the composite z-direction and generate pure 𝜎z loading. Details of a similar test can be found in the standard ASTM 7291M [76]. A common problem that arises is failure of the adhesive bonding between the surfaces of the composite and the aluminium bars. A method to address this was developed by Gerlach et al. [77] to manufacture a cross shaped specimen, bonded to plates with U-shaped steel rigs that allowed a pure tensile stress to be generated in the through-thickness direction (see figure 4-1).

### 4.5.2 Cohesive Zone Modelling

Recent developments in meshing have allowed automatic surface generation in TexGen [12]. The interface interaction between the yarns and the matrix are modelled using the surface based cohesive zone formulation, readily available in Abaqus [67]. This was preferred to element based methods due to the small thickness of the interface between the yarns and the matrix. The model used a bilinear traction law with one region of linear elasticity and the other of stiffness degradation with differing traction-separation behaviours in the normal and shear directions [67]:

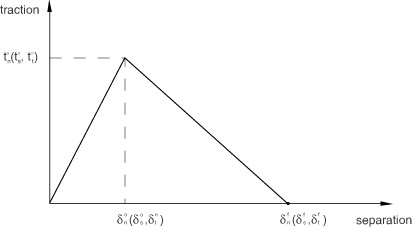


Figure 4-15 Bilinear form of the traction-separation behaviour[67].

With the normal and transverse traction separation behaviour uncoupled, taking a local co-ordinate system aligned normal to the interface surface, the initial stiffness differs in the normal, first, and second shear directions.

The quadratic stress criterion is used for damage initiation of the interface [87].

Delamination occurs when equation (2) is satisfied.

|  |  |  |
| --- | --- | --- |
|  |  | (2) |

Where the 𝑡𝑖0 are the initial failure stresses in the normal and first and second shear directions of the fracture surface when undergoing pure mode delamination.

Delamination under mode I loading occurs only under tensile loading so the stiffness degrades according to:

|  |  |  |
| --- | --- | --- |
|  |  | (3) |

Where D is a scalar damage variable that increases with the loading after interface damage has occurred.

A mixed mode power law based on the critical fracture energy release rates is used to model the damage evolution:

|  |  |  |
| --- | --- | --- |
|  |  | (4) |

Where the GC are the critical energy release rates in each of the axial directions.

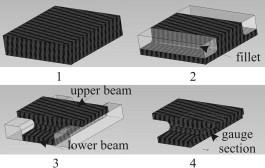
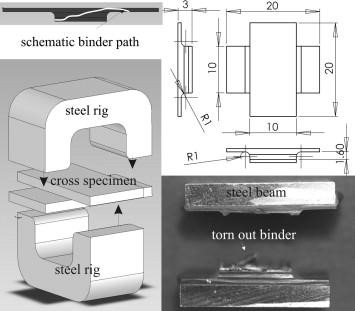


Figure 4-1 Cross shaped specimen for applying load in through-thickness direction [77].

T-Joints undergo a mix of flange bending and through the thickness loading

[16][21]. Several techniques have been investigated to mitigate the risk of TJoint delamination [78] such as tufting [27][25], stitching [15] and z-pinning [79]. Recent developments [80], [81], [82] in the field of 3D weaving technology have opened up the possibility of weaving carbon fibre T-joints as an integral net shaped preform. Three dimensional (3D) woven composite preforms are composed of warp and weft tows aligned along different axes, bound together using through-thickness binder yarns between the warps. Once resin-infused, the binder yarns’ load carrying capabilities lead to a high out-ofplane strength for 3D woven composites in addition to the high in-plane stiffness and strength of laminate composites.

A close up of a device

Description automatically generated

Figure 4-2 TexGen model of simple split woven T-joint geometry.

It has been shown in [13] and elsewhere that the choice of weaving pattern can have a significant effect on the strength of the woven component. Tensile pulloff tests [13] found that delamination is one of the significant damage mechanisms in the flange of the T-joint (see figure 4-3).

A picture containing sitting, black, red, person

Description automatically generated

Figure 4-3 μCT image of post tensile pull off test T-joint with delamination evident along the flange. Image adapted from [13].

Due to the complex stress fields exhibited in 3D woven materials under loading, it is difficult to ascertain the optimum pattern for a given loading condition and it is often left to the weaver use their intuition and design experience to design such patterns. Given the wide array of possible woven architectures and the possibility for model parameterisation, the question of which weave pattern to use for the T-joint lends itself to the use of numerical optimisation techniques [13].

Some research has already been conducted to optimise 3D structures [57], [59]. These optimisations have used finite element simulations of flat piece unit cells under loading prescribed by periodic boundary conditions, as set out by Li in [43], to find the elastic properties of the unit cell. These works have developed methods to vary the parameters of 3D weaves but are less applicable to more complex geometries such as T-joints where there is often limited periodicity. 3D woven composites are primarily used over laminated composites because of their damage resistance properties, making design optimisation of these properties highly desirable. In addition to this, simulations based on periodic boundary conditions are inapplicable to the prediction of delamination. This application to delamination resistance optimisation is a novel development allowed by the usage of advanced computer clusters, careful selection of the objective function and the ability to categorise weaves as feasible or nonfeasible before the finite element simulations are run.

Optimisation algorithms have been used in engineering applications since the late 20th century [46] as a tool for finding optimum designs for cases where an exhaustive search of the design space is not possible due to its size. The best choice of optimisation algorithm is highly problem dependent and so needs to be investigated on a simpler problem before application to optimisations with more time and resource expensive objective function evaluations.

### 4.2.1 Genetic Algorithm

Genetic algorithms are a class of algorithms based on the Darwinian principle of survival of the fittest [46], where competition within a population results in the best members being more likely to pass on their characteristics into the next generation. Genetic Algorithms have been used widely in composite design optimisation [48], [53] where their ease of use and robustness are valued.

In the optimisation, the design variables are analogous to the genes of the population member and a specified population size is created by sampling a range of design variable values. Each member of the population will generate a corresponding finite element model with the characteristics based on their design variables. After all the members of the generation have been run, the genetic algorithm ranks the population members according to their objective function values. The best performing members, or the elite members, are directly entered into the next generation, they pass on their full genes. The better performing members are more likely to undergo a series of operations including mutation and crossover to generate the next generation. These operations mimic the reproductive mixing and mutation of genes so that better performing members are more likely to pass on some of their characteristics into the next generation. This process is repeated until either the maximum number of generations is reached, or the algorithm converges to an optimum solution.

### 4.2.2 Pattern Search

Pattern search algorithms work by sampling points in the design space around the point currently being evaluated [55], [85] . The algorithm has two steps: search and poll. The algorithm is initialised at a point in the design space. It then computes the objective function at a number of “mesh points” surrounding the initial point. In the polling stage, the algorithm sorts through the points in the order in which they were evaluated. As soon as a point is found with a lower objective function value than the current iteration, the algorithm updates its position to that point. The mesh size is then increased by a pre-determined factor. If no lower objective function value is found, the algorithm decreases the mesh size. The algorithm converges when the limit of the number of mesh size reductions is reached or when the mesh size is smaller than the distance between designs in the design space.

### 4.2.3 Particle Swarm Algorithm

The particle swarm algorithm [56] is another algorithm that seeks to mimic biological processes. In this case, the algorithm mimics a swarm of insects searching for food. As insects search for food they lay down a pheromone trail which other members of the swarm are attracted to. Once food has been found, more insects from the swarm converge on that location, laying down more pheromone and increasing the likelihood more insects will go along the same path. The algorithm is given a set of starting designs each with a position and velocity in the design space. All the designs at the current time are evaluated and the design space velocity of the particles are updated based on the results.

The more optimal designs lay down a stronger “pheromone trail” so the individual’s velocity is more likely to be in the direction of the most optimal design. In this manner, the design is iteratively improved until the points converge on the function minimum.