A numerical study examining the formation of consolidation induced defects in dry textile composites

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Abstract. A key factor in the performance of composite materials is the quality of the final manufactured part. Regardless of the material form or process there are two common steps to produce this; the forming of an initially planar material into a three-dimensional shape and the consolidation of the material to achieve the required thickness and fibre volume fraction. During these processes the material is required to deform to achieve the final geometry. Defects which are induced by these processes can severely degrade the performance of the final structure. While a large body of research has been dedicated to understanding and modelling forming induced defects, consolidation induced defects have gone relatively unexplored. In this paper a simple approach is introduced to include the high transverse compliance of textile materials into conventional forming simulations, using 2-d finite elements, so that consolidation induced defects during forming can be analysed. This approach allows for the high stiffness of the fibre direction, non-linear shear stiffness, out-of-plane bending stiffness and through thickness compressibility of textiles to be fully present within the model. Using this approach, the consolidation of a large numbers of plies over curved tooling is simulated to examine the various parameters that contribute to the formation of defects.

1. Introduction
The consolidation of textile reinforcement materials is an integral process in composite manufacture. Its purpose is to increase the fibre density in the composite to ensure a high volume fraction (Vf) is achieved. This is crucial for high performance composites as the Vf corresponds directly to the mechanical properties of the composite. The maximum achievable volume fraction is dependent on both the internal architecture of the textile and the applied pressure.

Fibrous materials are highly compliant in the plane transverse to the fibre direction (i.e. the application of small pressures can significantly reduce their thickness). This is due to initial gaps which exist between the individual fibres, only small pressures are required to close these gaps which force the fibres to rearrange through sliding and bending. As the fibres come into contact and the number of contact points increase, rapid stiffening occurs until the inter-fibre contacts fully constrain the fibrous network.

For consolidation on a simple flat surface, the distortions induced by the reduction in thickness typically occur at the meso scale, where the architecture of the textiles distorts to accommodate the change in shape through migration of crimp, increase crimp angle and change in yarn cross section [1]. When consolidated over curved tooling, severe defects can form such as ply waviness, wrinkles and thickness variation. Tools with even single curvature can be a catalyst for the formation of such defects. One example of this is when multiple layers are laid up and consolidated over a radius. During this
process the external radius of the lay-up is reduced producing an excess of material. If the material is constrained in-plane, via inter-ply friction or geometric features of the tool, the excess material in the radius is unable to migrate and hence will be accommodated through buckling of the fibres out of plane, causing wrinkles, or in-plane, causing severe fibre misalignment [2]. An example of such a defect can be seen in Figure 1.

![Figure 1. example of a consolidation induced wrinkle, formed in the corner radios of a non-crimp fabric composite part](image)

Research into consolidation induced deformations has increased in recent years for pre-impregnated fibrous materials, with mechanisms behind their formation and models to predict their occurrence being presented [2-4]. For textile materials, consolidation-driven defects have had little attention as their magnitude is often superseded by deformations caused during the forming process. In this paper a simple approach for including the high transverse compliance of textile materials into conventional forming simulations, using 2-d finite element analysis, is introduced. Implemented into the commercially available Abaqus Explicit finite element software, the method allows for the high stiffness of the fibre directions, non-linear in-plane shear stiffness, out-of-plane bending stiffness and through thickness compressibility of textiles to be present within the model. With this approach a large number of layers consolidated over curved tooling can be simulated.

2. Modelling approach
Deformations induced during the consolidation of the material are dependent on the change in path length of the material and how much excess length is generated. This is determined by the geometric features of the tool and the change in thickness of the layered material. The way the excess length is accommodated is dependent on the material behavior and the constraints enforced by the geometry. Simulating this phenomenon therefore necessitates the inclusion of the through thickness compliance of the material into a model, as well as the other characteristic material behaviors typically included in forming simulations, i.e. stiffness along the fibre direction, in-plane shear stiffness, out of plane bending stiffness etc.

The starting point of this method is a model typically used for forming simulations where the fabric is represented as a continuous planar material. The mechanical behavior of the meso-scale structure is represented implicitly through constitutive models. A hypo-elastic material model [5] is used to ensure the directions of the high stiffness fibres are tracked during the simulation and to implement the non-linear in-plane shear stiffness of the material. Both shell and membrane elements are used to represent the material, which are superimposed and their nodes mutually constrained. The hypo-elastic material model is assigned to both element types, the membrane elements are assigned the in-plane material properties (tensile modulus of fabric fibre directions and the non-linear shear stiffness) the shell elements are assigned with just the flexural modulus of the material.
This approach has been successful at modelling the forming of textiles over complex geometries, capturing both the shear and wrinkle deformations accurately as well as the interaction of multiple layers, as shown in Figure 2.

**Figure 2.** Comparison of experiment with prediction for two layers of plane woven fabric [+/-45 0/90] formed over tetrahedron tool using double diaphragm forming process – experiment (left), simulation using shell/element forming approach (right)

A limitation of 2-D elements, both shell and membrane, is that they have no through thickness compliance, so are unable to include the high transverse compliance of the fibrous materials, preventing them from modelling consolidation processes. A compliant contact was therefore introduced to include the through thickness compliance of the material into the shell/membrane forming approach.

A commonly used contact in finite element analysis is the penalty contact algorithm. This method introduces a force at contact detection points which have penetrated across a defined surface. The purpose of this force is to eliminate the penetration by pushing the two surfaces out of contact. The method uses a simple formula:

$$F_c = k_c D_p$$

where $k_c$ is the contact stiffness, often referred to as the penalty stiffness, and $D_p$ is the depth of the penetration. The magnitude of the force required to remove the penetration is typically unknown, consequently there is often a finite amount of penetration at the end of each time step. The value of $k_c$ is a fictional stiffness which must be large enough to minimise the penetration while at the same time not be too large as to cause instability. The contact stiffness is defined as the contact pressure between two surfaces as a function of the overclosure. The overclosure of the two surfaces is the depth of the penetration. By manipulating this relationship, to capture the non-linear through thickness stiffness of the textile material, through thickness compliance can be included in the forming simulations as inter-penetration between adjacent layers.

**Figure 3.** Pressure-overclosure relationship derived from compaction results of a plain woven fabric.
Figure 3 shows the pressure overclosure relationship for a single layer of a carbon fibre plain woven fabric, with 6000 fibres per tow, areal weight of 320gsm and 7 micron fibre diameter. This relationship was deduced from a compression test on samples of the material, where the overclosure is considered as the change in material thickness and the contact pressure is the externally applied pressure.

2.1. Verification

A simple compaction test on a stack of 2D elements was first performed to verify the approach. Single square shell elements with a length of 1 mm were stacked up, with each element representing a layer of material and given a thickness of 0.4mm. A displacement boundary condition was applied to all of the stacked elements, constraining their displacements to just vertical translations. The stacks were placed on a rigid surface prescribed with a fully fixed boundary condition. The pressure-overclosure relationship shown in Figure 4 was applied to the general contact definition in tabular form. Three models were created, each with a different number of layers, to examine the performance of the contact. A schematic of the verification model for two layers is presented in Figure 4.

![Figure 4. Schematic of consolidation model verification study for the compression of two shell elements onto a flat plate. Each shell element representing a layer of material](image)

Figure 5 shows each of the models before and after compaction. As expected, thickness reduction is achieved through inter-penetrations of contacting elements. The thickness-pressure response output of each model is shown in Figure 6. The model with just two layers matches well with the expected values, however as the number of layers is increased the models become more compliant and diverge from the input values. This is likely due to the build up of small numerical errors which will increase with the number of layers. The difference is still relatively minor, with less than 3% error in the 24 layers at 0.1MPa.

![Figure 5. Verification of compliant contact – pre and post consolidated models](image)
3. Consolidation of C-section geometry

Consolidation-induced wrinkles form as a result of multiple plies being compacted over three dimensional surfaces as the planar materials is forced to assume the shape of the tool surface. Taking a simple male radius for example, during the consolidation process the external radius of the layup is reduced, forcing the material into a tighter geometry. If the material is constrained in-plane and the layers are unable to shear relative to one another, then excess material becomes present in the region of the radius. To accommodate this excess material the individual layers are forced to deform out-of-plane, causing wrinkles, or in plane, resulting in severe fibre misalignment. Depending on their severity, these deformations can compromise the structural integrity of the final part, so developing an understanding of how these defects form and the parameters which affect them is of major importance.

The magnitude of excess length created through the consolidation of plies over a radius can be determined using Equation 2.

\[ L_{ex} = \frac{2\pi \Delta t}{4} \]  

The change in thickness \( \Delta t \) is the only physical parameter which affects the amount of excess length, with \( L_{ex} \) increasing with increasing magnitudes of \( \Delta t \). The change in thickness is dependent on the compliance of the material as well as the number of layers being consolidated. It is evident from Figure 6, for example, that there is a greater change in thickness in the 24 layers than in the consolidation of 2 layers, this is due to there being the same strain but applied to a much thicker sample, therefore compaction of 24 layers is likely to lead to more severe defects than thinner samples.

The formation of these defects is dependent on details of the geometry and the deformation modes of the material. The compliant contact is used here to analyse the effect of consolidating multiple layers of the plain woven fabric over a simple, male C-section tool. In order to do this, the compliant contact has been combined with the shell-membrane forming approach. The through thickness compliance, high tensile stiffness, in-plane shear and out-of-plane bending behaviour are therefore all present within the model.
The male C-section tool considered has a web length of 300mm, flange length of 150mm and 15mm radius. The width of the part is 150mm. The tool was modelled as a rigid surface. A stack of 24 plies, each with 0.4mm thickness was created above the tool. The layup was quasi-isotropic with a layup of \([0/90\, +/-45\, 0/90\, +/-45\, 0/90\, +/-45\, 0/90\, +/-45\, 0/90\, +/-45\, 0/90\, +/-45]\). As the tool only exhibits single curvature it was assumed that the forming of the geometry caused no deviation of fibre angle and formed perfectly to the tool. Furthermore, it was assumed that the pre-consolidated formed part had a constant thickness of 9.6mm (0.4mm x 24 plies) across the profile of the tool. Only half of the C-section was modelled and a symmetry boundary condition was applied along the centre of the web. The input properties for the model are presented in Table 1. The pressure-overclosure relationship in Figure 3 was used for the contact between layers. Coulomb friction was used to model the tangential interactions between the plies, with a coefficient of 0.28. This value was taken from experimental results of the frictional interactions between layers of plain woven carbon fibre fabric in [6]. A ramped pressure load of 0.1MPa was applied to the top ply to simulate vacuum consolidation.

**Table 1.** Properties for material model. E represents the stiffness in the two fibre directions and G\(_{12}\) is the shear stiffness as a function of the shear angle \(\gamma\). Membrane elements include the in-plane material properties and shell elements the flexural stiffness

| Element Type | \(E_{11}\) (MPa) | \(E_{22}\) (MPa) | \(G_{12}\) (MPa) |
|--------------|------------------|------------------|------------------|
| Membrane     | 40,000           | 40,000           | 32.37\(\gamma^4 - 59.31\gamma^3 + 36.36\gamma^2 - 7.384\gamma + 2.37\) |
| Shell        | 33               | 33               | 0                |
The deformed model is shown in Figure 7, where it is evident that substantial thickness reduction has occurred, which has produced excess material in the region of the corner radius. To accommodate this excess material, out-of-plane wrinkles have formed; two at the junctions of the radius and a smaller one in the centre. The method appears to capture the mechanism behind consolidation induced wrinkles well and the deformed geometry shows a similar trend to what has been observed in literature for the case of a prepreg laminate consolidated over a C-section, Figure 8.

![Figure 7. Deformed model showing excess material and out-of-plane wrinkles.](image)

**Figure 8.** Consolidation induced wrinkles in prepreg C-section geometry, taken from Dodwell et al. [2]

### 4. Consolidation of different lay-up configurations

Four different lay-ups have been modelled, the lay-up orientations for each model is presented in Table 2. It was assumed that the compressive stiffness and interface friction was independent of ply orientation, the only varying parameter was the orientation of the fibres in each layer.

| Lay-up | Orientation |
|--------|-------------|
| LU1    | [0/90]      |
| LU2    | [+/-45]     |
| LU3    | [0/90 +/-45 0/90 +/-45 0/90 +/-45 0/90 +/-45 0/90 +/-45]s |
| LU4    | [0/90 0/90 +/-45 +/-45 0/90 0/90 +/-45 +/-45 0/90 0/90 +/-45 +/-45]s |

The thickness variation of each of the consolidated models in Figure 9 shows that in each layup, the presence of the radius causes some non-linearity in thickness around that corner region. The aligned configurations LU1 and LU2 vary significantly, the magnitude in LU2 is higher and varies across part width as well as length. When ply orientation is varied through thickness of the laminate, the presence of two large wrinkles becomes evident at both the web radius and flange radius junctions. There is little difference evident between LU3 and LU4.
5. Conclusion

Modelling of textile composite manufacture has primarily focused on the forming of the planar materials into three dimensional shapes. This process typically induces large shear strains, in the plane of the material, which is considered to be the main driving factor behind the formation of defects. As such, few models have been presented that focus on predicting consolidation induced defects. Although the magnitude of these deformations is often smaller, their presence can still have detrimental effects on the performance of the final composite component. A simple numerical approach has therefore been developed to include the non-linear through thickness compliance of textiles into modelling approaches designed for forming simulations. This method allows for the compliance of the material to be captured through surface interactions, rather than the material behaviour, by manipulating the pressure-overclosure relationship of the penalty contact. As this method is simple and fully separated from the material definition it can be easily applied to different approaches for modelling fabric forming behaviour. The approach has been used here to examine the consolidation of multiple layers of fabric over a C-section tooling showing the effects of consolidating different lay-up configurations.
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