CHAPTER 3

MODELLING OF MULTI MATERIAL STRUCTURE

3.1 INTRODUCTION

Employing Multi Material (MM) structure in engineering application results in limiting crack propagation and improving mechanical performance such as increasing strength and stiffness of the structures. Recent development in AM technology such as processing of multiple materials lead AM as one of the potential manufacturing process for fabrication of MM structure with complex shape. To take advantage of such a capability of AM process, one must develop a suitable CAD model with secondary material (reinforcement) distribution within a primary material (matrix) of MM structure. This chapter summarizes two methodologies developed for CAD modelling of MM structure which will be fabricated through AM process. First methodology is for modelling of MM structure with random distribution of reinforcement for which simple algorithm using Visual Basic (VB) script is developed. This algorithm has been developed by considering AM process capability (i.e. layer thickness, wall thickness, accuracy and number of material processes able). VB script in CAD software employs the use of embedded geometric algorithms programmed within the internal 3D kernel structure, which act as a library for generating reinforcement. In addition, the developed algorithm uses analytical equations that represent the dimension and spatial configuration (position and orientation) of reinforcement. CATIAv5r18 from Dassault Systems is used as the CAD modelling system and the methodology adopted for modelling is described in detail in Section 3.1.

Second methodology is for modelling of directional reinforced (unidirectional and multidirectional) MM structure and it was modelled based
upon the existing options in CAD modelling software. Section 3.3 of this chapter encompasses a method adopted for modelling of directional reinforced MM structure.

3.2 RANDOM REINFORCED MULTI MATERIAL STRUCTURE

As described in Section 2.2 of Chapter II, there are many different modelling algorithms which are capable to model MM structure (Cheng et al 2000), (Pan et al 2008) & (Jin Bo Cheng 2011). These algorithms have certain disadvantages such as control over size, shape and volume of reinforcement. Besides, most of these algorithms were developed for modelling of Representative Volumetric Element (RVE) of MM structure (natural and artificial) in order to perform finite elemental analysis, so these RVE models generally represent entire MM structure by repeating single unit (RVE) (Lusti et al 2002). In addition, few of these algorithms were not supported for exporting the developed MM structure into .STL which is a “defacto” format for AM process. So in this thesis, algorithm has been developed using CATIA VB script to model random reinforced MM structure for AM process. Generally CAD modelling with VB Script helps to automate repetitive tasks, accelerate design procedures, and automatically generate complex geometries. Due to these advantages VB SCRIPT is used for development of MM structure with random orientation of reinforcement. Developed algorithm doesn’t have any constrains over shapes and orientation of reinforcement. Modelling algorithm’s flowchart is schematically illustrated in Figure 3.1. The protocol to generate the reinforcement with random orientation and position in 3-Dimensional Euclidian space is described below:

**Step 1:** Initially, the volumetric percentage (vol. %), Aspect Ratio (dimension such as width (W_r) and length (L_r)) of the reinforcement is given as an input. (Reason behind selection of cuboid shape reinforcement and its size is described under section 4.3.2)
Step 2: Volume of the Euclidian space within which reinforcements have to be generated is defined. In this thesis work, cuboid domain is considered. So
parameters such as height (H), Length (L) and Width (W) are given as input to define volume of cuboid domain. Here, Cuboid domain is considered, because most of the ASTM standard specimens were symmetrical and has constant thickness which can be easily modelled based upon cuboid domain. However, the same methodology can be extended to AM MM structure with variable cross section which may require additional computation.

**Step 3:** Based upon volumetric percentage of reinforcement required within a volume of domain as defined in step 2, number of reinforcements (n) have to be generated is calculated using the formula described in flow chart.

![Figure 3.2 Constraints for placing reinforcement in 2D space](image)

**Step 4:** Once number of reinforcements (n) required is calculated, then for each reinforcement parameters such x, y and θ to position and orient the reinforcement in 2D space as shown in Figure 3.2 has to be defined. Since reinforcement has to be positioned and oriented randomly, input parameters (Xi, Yi and θ) for each reinforcement is assigned to random value through function called “rand” which is a sub-function in CATIA VB SCRIPT. Here, Xi and Yi co-ordinate value meant to position the reinforcement are respectively based upon width and length of the domain and angular coordinated (θ) value is generated between the intervals of [0°-360°] for orientation of reinforcement.
**Step 5:** If the reinforcement generated \((i)\) is equal to the number of reinforcements \((n)\) required to achieve required volumetric percentage as calculated in step 3, then programs ends, otherwise, step 4 is repeated until reinforcement generated reinforcement \((i)\) is equal to number of reinforcement \((n)\). Domain with random orientation of reinforcement generated is shown in Figure 3.3.

Step 1 to 5 represents generation of reinforcement with random position and orientation within 2 D space (see Figure 3.2 where only \(X\) and \(Y\) coordinate is mentioned and \(Z\) coordinate is constant i.e. \(Z\) value is based upon plane in which reinforcement is generated). In order to model MM structure with many numbers of layers, above mentioned procedure is repeated layer by layer by increasing \(Z\)-coordinate value.

To verify the random distribution of reinforcement within a domain, a dog bone shape tensile specimen according to ASTM D638 standard at horizontal, inclined, vertical orientation with respect to domain (3D Euclidian space) is modelled as shown in Figure 3.3 and it is fabricated in AM process for tensile testing. In this thesis, hereinafter these three MM structures are described as Horizontal Orientation (HO), Inclined Orientation (IO) and Vertical Orientation (VO) AM MM structure specimen. In addition, mechanical properties of random reinforced AM MM structure are expected to depend on the volumetric percentage of secondary material (reinforcement) (Ram Prabhu et al 2014), so MM structures with 10%, 20% and 30% vol. of reinforcement with an aspect ratio of 1:10 as shown in Figure 3.4. are modelled using the algorithm described in this section. Aspect ratio i.e. length to width ratio of reinforcement is selected as 1:10 which falls under the category of fibre form of reinforcement. Fibre form of reinforcement was selected over particulate or whiskers type of reinforcement, because of its superior load carrying capacity (Chawla 2012).
Figure 3.3  Random distribution of reinforcement within a domain

With 10 vol. % of Reinforcement

With 20 vol. % of Reinforcement

With 30 vol. % of Reinforcement

Figure 3.4  Random reinforced multi material structure model with various volumetric percentage of reinforcement
MM Model with random orientation of reinforcement is fabricated with AM process and fabricated MM structures are tested under various loading conditions to understand their mechanical behaviour.

3.3 DIRECTIONAL REINFORCED MULTI MATERIAL STRUCTURE

Orientation and stacking sequence of reinforcement in a MM structure yields the stiffness and strength required in a specific direction. To investigate the effect of various orientations and stacking sequences of reinforcement over the mechanical properties of AM MM structure, following designs (various orientation and stacking sequence) are considered for modelling.

MM model with reinforcement in its layers (six) is oriented in same direction, they are i) unidirectional ply - (0)_6 – Reinforcement in all six layers are along the loading direction (Longitudinal Reinforced), ii) unidirectional ply- (45)_6 – Reinforcement in all six layers are inclined 45° with respect to loading direction (Inclined Reinforced), and iii) unidirectional ply- (90)_6 – Reinforcement in all six layers are perpendicular to loading direction (Transverse Reinforced). Longitudinal and transverse orientations are considered because they are necessary to determine the elastic properties of MM with reinforcement in other orientations. Inclined reinforced MM structure is considered to validate the result (mechanical properties) obtained from experimental test with prediction (analytical and numerical) results based upon reinforcement inclined 45° to loading direction. Figure3.5 discloses the internal structures for the unidirectional reinforced MM tensile test specimen model with reinforcement oriented at longitudinal, inverse and transverse direction.
Figure 3.5  Internal structure of (a) longitudinal (b) inclined and (c) transverse reinforced MM model

Figure 3.6 Internal structure of MM model with (a) cross ply (b) angle ply (c) quasi-isotropic I and (d) quasi-isotropic II laminates arrangement
Based upon Classical Lamination Theory (CLT) of mechanics of composite materials as described in section 5.2.4, following four designs with symmetrical arrangement (i.e. reinforcement orientation in layer 1-3 is mirror image of layer 6-4) are considered for modelling of multidirectional reinforced MM structure with six layers. Consider arrangements are i) cross ply – (90/0/90), – Reinforcement is along the loading direction in first and it is third layer and perpendicular to loading direction in the second layer ii) angular ply – ((-45)/45), – Reinforcement is inclined 45° with respect to loading in clockwise direction in first and second layers and it is inclined 45° with respect to loading in anti-clockwise direction in third layer iii) quasi-isotropic ply I – (0/60/-60), – Reinforcement is along the loading direction in first layer, it is inclined 60° with respect to loading in anti-clockwise direction in second layer and it is inclined 60° with respect to loading in clockwise direction in third layer iv) quasi-isotropic ply II – (90/-30/30), – Reinforcement is perpendicular to loading direction in first layer, inclined 30° with respect to loading in clockwise direction in second layer and inclined 30° with respect to loading in anti-clockwise direction in third layer. Since each layer in MM structure has reinforcement oriented at different directions, these structures are known as multidirectional reinforced MM laminates. Figure 3.6 discloses the internal structure of MM tensile test specimen with angle ply, cross ply, quasi-isotropic ply-I and quasi-isotropic ply –II arrangement.

As reinforcement orientation and stacking sequence in directional reinforced MM structure is not as complex as in random reinforced MM structure, the existing options available in CAD software is used to model directional reinforced MM structure. In addition, majority of AM process accepts CAD model in .STL format. But .STL is a surface approximation only; there is no knowledge of the material representation. So for the purposes of representing multiple materials for region to region within a layer in a
directional reinforced MM structure model, Boolean operation coupled with assembly operation is used to create and represent MM model.

Figure 3.7 Modelling of transverse reinforced MM structure
Figure 3.7 shows modelling and assembly procedure involved in transverse reinforced MM structure CAD model. To model MM structure, initially reinforcement oriented in transverse direction as shown in Figure 3.7(a) is modelled and another model according to the shape of the tensile test specimen as shown in Figure 3.7(b) is modelled. Using Boolean intersection operation between Figure 3.7(a) and Figure 3.7(b) reinforcement structure is modelled (Figure 3.7(c)) and by using Boolean subtraction operation between Figure 3.7(a) and Figure 3.7(b) matrix structure is modelled (Figure 3.7(d)). Modelled matrix and reinforcement structure are exported to AM machine as two separate .STL files and respective materials are assigned to them. Procedure described above was repeated for modelling of other types of directional and random reinforced MM structure. Volume of reinforcement is kept constant as 30% for all reinforced structure.