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Meso-Interlaced 1D Finite Element mesh for Modelling Plain Wave Engineering Fabrics

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***Abstract*—Meso-interlaced 1D finite element mesh for finite element modelling has been developed from excited Varifab finite element variable mesh generator. Spline interpolation numerical method was used to model the wavy curvy geometrical shape of fabric warps by Matlab software. The stage of modelling split to two steps: step one generating a saw teeth finite element mesh by adding data coordinate points nodes to axes z and the second step adding more coordinate data points on warp yarns of axes z for further spline interpolation. Once the spline interpolation of warp yarns achieved, a meso-interlaced 1D finite element mesh is generated readily. An input file of Abaqus finite element software is also generated, immediately as the run of Matlab code meso-interlaced Varifab code completed. The mesh can be used for further modelling and characterization of plain wave engineering fabrics.**

Keywords—meso, interlaced, finite element, plain weave, engineering fabrics, spline interpolation

I. INTRODUCTION

The relentless seeking toward introducing textile composite products to mass production system was and still is the concern of textile composite forming researchers. In fact, mass production system enables suppliers to produce large quantities of products in record time (high production capacity), with considerable cost reduction, and with high quality and identically. Whereas in unit production system is vice versa, because products quality and identically depends on employee’s skills. Moreover, it provides low production capacity in great amount of time.

Accordingly, building an automatic design and manufacturing tool for obtaining textile composite products with high quality, identically, cost effective and …etc, it will not be developed unless taking the first step toward this goal. Which involving textile composite design and manufacturing processes to automation. In other words, changing textile composite production system from unit production to mass production. Achieving this goal depends on the most important factor including developing an appropriate constitutive model.

Developing an appropriate constitutive model is a hard task of tremendous efforts carried out by groups of researchers over the last three decades. The researches inside the frame of textile composite forming modeling categorizing in three different approaches: micro-scale, miso-scale and macro-scale. Considerable number of researches have been already carried out in each category of the three approaches.

However, each type of approach of the three mentioned approaches has its own advantage and disadvantage. Micro and macro scale approaches more realistic in terms of simulating the real deformation, however they are both very computationally expensive due to the complication of computation the non-linear behavior and the contact conditions results in large CPU times compared to macro-scale approach.

The common method used up to date in industry for modeling textile composite before draping on the required shape is mapping or kinematic method [1-3]. This method used to produce one product in the time depends on employee skills, therefore it considered under unit production system. The method considered simple in terms of analysis complication, because no stress-deformation calculation is needed, since no constitutive models is used. In this method, each unit cell of engineering fabrics in vacuum bagging infusion draping process or textile composite in heated vacuum bagging process are modeled as an inextensible pin-jointed net. Draping using kinematic method accomplish by choosing an arbitrary point on part's surface. The rest of fabric mapped from that point using pin-jointed net technique. In fact, the matter of predicting the exact shear deformation of draped part using kinematic method is depending on luck, because every time starting draping from different starting point and draping path. Consequently, this method not suitable to be used in mass production system and it not accurate in prediction the exact shear deformation and prediction the exact tension stresses required to avoid common defects associated with textile composite forming such as wrinkling.

From the inability of kinematic method to fulfill requests to use it to be a used method in textile composite forming process design of mass production system. Researchers turned their attention to invent a new method.

A mechanical method has been invented and developed to replace kinematic method by contribution of researchers from all over the world. The developments and enhancement of the mechanical method included applying constitutive models in design part and automatic forming process in manufacturing part. Mechanical method is categorized to three main categories: micro-scale, miso-scale and macro-scale. The basic principle of the micro-scale (discrete) method is that, modeling the textile composite or engineering fabric material from the lowest level which is fiber. Modeling each fiber individually as a 3D cylindrical part. Then connect each fiber part with the approached fiber part using contact tool to form one yarn or tow then form the whole fabric. The fiber part material model defined as isotropic or hyper-elastic or whatever depends on the fiber material behavior. However, although this method by logic considered the most accurate in terms of material structure and deformation, it tedious, time consuming and computationally extremely expensive (need massive powerful computational tool) [4-9].

The basic principle of the miso-scale (discrete) method is that, modeling the textile composite or engineering fabric material from the mid-way level which is yarn or tow. Modeling each yarn or tow individually as a 2D strip part or 3D cylindrical part. The interaction between the yarns or tows to form the whole engineering fabric or textile composite performed by suitable contact tool. The yarn part material model defined as isotropic or hyper-elastic or whatever depends on the yarn material behavior. The meso-scale method considered as less tedious, less time consuming and less computationally expensive than micro-scale method. However, only limited number of unit cells can be used to model for example engineering fabric or textile composite for characterization investigation or forming application without a need to a powerful computational tool [10-17].

In macro-scale (continuous) method a constitutive model also required to model the engineering fabric or textile composite as one anisotropic material to predict the shear deformation during forming. This method less expensive computationally than the last two mentioned methods (micro and miso-scale methods). Since elements such as membrane and shell elements available in commercially finite element softwares such as Abaqus can be used for modeling textile composite and engineering fabrics which noticeably reduced computational time significantly. Not only using standard elements available in commercial finite element softwares reduced the computational time but also the no demand of contact mechanism reduced the computational time significantly. Several researchers carried out researches of modeling textile composite and engineering fabric forming using macro-scale method by different ways in terms of defining different constitutive models such as (hyper-elastic material and hypo-elasticity material models) [18-25].

As mentioned earlier meso-scale modeling textile composite and engineering fabric technique is tedious, time consuming and computationally expensive. However, on one hand a number of CAD tools such as wisetex, texgen,….etc have been developed to cut off the time consumed in creating the complicated fabric geometry. On the other hand, conducting finite element modeling using texgen textile composite or engineering fabric model only possible if and only if on one unit cell or on a few unit cells in best situation with powerful computational tool.

A meso-scale modeling strategy or discrete approach is an approach of modeling textile composite and engineering fabric. The name discrete approach mentioned first time by Boisse, et al (2008) [26] as yarns or tows slide regard to each other. Some researchers have used contrapuntal engineering fabric and textile composite softwares such as Texgen and Wisetex [27-29] for modeling engineering fabric and textile composite geometry. While other researchers have used general CAD softwares such as Solid works, AutoCAD,.etc [30-33]. Texgen and Wisetex make the task of generating engineering fabric or textile composite geometrical models very easy, while using Solidworks, AutoCAD,….etc make the task very tedious, time and efforts consuming. However, Boisse, et al (2010) [26] carried out a successful simulation of picture frame shear deformation test with a generated digital fabric composed of warps and wefts slide on each other by contact tool using one of the meso-scale geometrical methods [27-33]. Engineering fabrics with different weave style (non-crimp, plain, 2:1 twill and 2:2 twill) have also been generated by Creech and Pickett [35,36]. Another way of modeling engineering fabric was developed by Ballhause, et al. [37]. Ballhause, et al. [37] followed a new technique for modeling engineering fabrics warps and wefts. Warps and wefts in fabric unit cells not slide on each another, instead they considered as a concentrated masses. The masses are connected with each other by links which modeled as finite elements. The links (finite elements) model the stretching, bending and shear behavior taken place in real engineering fabrics and textile composite deformation during forming.

Turing our attention to lower modeling scale, number of researchers have carried out modeling of fibers at microscopic level [38-43]. In terms of computational price, this textile composite modeling method (micro-scale modeling) is much more expensive computationally than macro (continuous) and meso-scale (discrete). However, with the rapid development of the world in software and hardware science, it provides great hope for the success of using such textile composite modeling methods (meso-scale and micro-scale).

The goal of this research paper is focusing on developing a novel discrete approach that modeled yarns as truss or beam elements with taking in account woven interlacing and orientation angles inherent fabric variability.

II. MATERIAL AND METHOD

Interlacing with fiber orientation variability mesh with 1D elements (truss or beam) simulate plain woven roving weave style of real fabric has been chosen to be modeled in this research paper. Novelly simple method created finite element interlaced mesh has been developed. The method named (Simple Interlaced Variable Mesh) SIVM. SIVM method working strategy based on modulating an excited 1D mesh with orientation variability has been generated from author Varifab code [44]. Varifab code [44] generated hybrid mesh composed of 2D elements (membrane or shell) each 2D element surrounded on its circumference with four 1D elements sharing with it their common cornered nodes. The generated mesh from Varifab [44] contain fiber variable orientation angles inherent in realistic engineering fabric. Instead of sharing a common node between 2D elements and 1D elements, 2D elements would be discarded. The new mesh contains of only 1D elements will be modified to introducing interlacing between orthogonal elements instead of sharing a common node. This will be carried out by adding a plus and minus values to a Z coordinate replacing a zero value to elements in just on orientation and remain the other elements in an opposite orientation unchanged.

III. INTERLACEING

The major types of woven fabric are plain, twill and satin. The threads interlacing (the weave technique) that is followed to produce woven fabric based on interlacing fabric warps and wefts with each other [45,46]. Attributable to woven fabric outstanding drapability and stability, it is used extensively in textile composite draping and forming as the most used 2D fabric.

Engineering fabric in general composed of warps and wefts, that are the foundation of turned yarns and threads into weaved fabric. Weaving process are carried out as followed: group of warps are stitched and fixed as straight lines in right and left loom arms, while same number of wefts are interlaced up and down over the group of warps [47]. The interlacing process always performed according to the woven style required (plain, twill or satin) see Figure 1-3. Twill weave fabrics differ regarding to its degree of warp to weft weave, there are 2/1 twill, 3/1 twill. 2/2 twill, 3/2 twill and etc. The numbers written before twill indicate to the degree of warps to wefts interlacing. For example, 2/2 twill means the degree of interlacing are two warps down and the next warp up (see Figure 2).

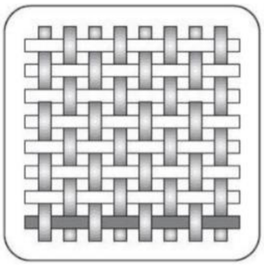

Figure 1. Plain weave woven fabric.

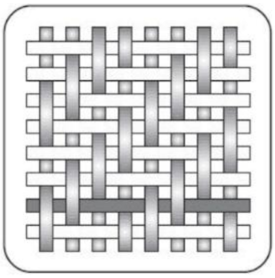

Figure 2. 2/2 Twill weave woven fabric.

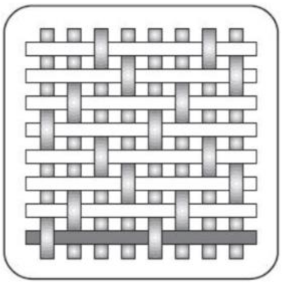

Figure 3. Satin weave woven fabric.

With fiber orientation variability mesh with

IV. MESO-VARIFAB FABRIC MESH GENERATION (GENERATING MESH INTERLACING METHOD AND MATLAB CODING PROCEDURES)

The Simple mesh obtained from Varifab code [44] composed of hybrid elements (the hybrid element is 2D element surrounded with four 1D elements) was taken as example for altering them to be SIVM. To start the task a mesh of four hybrid elements has been obtained from Varifab and a text file contain (X, Y and Z node set coordinates), element set of 2D elements (membrane or shell elements) (every element contains four nodes in its four corners) and element set of 1D elements (truss or beam elements. Also, from Matlab WorkSpace an array of node set and an array of element set of 1D elements are appeared in there. Plot of the mesh composed of 1D elements can be visualized on the screen for further treatment. On the plotted mesh figure coordinates of each node and number of each element can be illustrated from plotted figure window (see Figure 4).

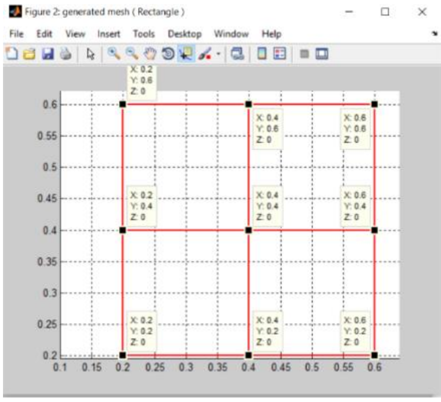

Figure 4. Varifab hybrid mesh with node coordinates datatip.

To establish or develop elements interlacing, the order and arrangement of all nodes and elements in a specific array can be easily and clearly shown comparing to the nodes and elements on the plotted figure. From here, interlacing between crossed elements can be generated by adding a third Z coordinate to elements in one direction only (for example at 90º). The specific values of Z coordinate are positive at node and negative at the next node on same element (see Figure 5).

Matlab coding steps start from here; creating two new node matrices from the node matrix created by Varifab. One node matrix for wefts and the other node matrix for the warps. Generating interlacing to warp node matrix by adding a positive specific value to Z coordinate to one node and a negative equal value to Z coordinate to the next node, respectively. To create meso-interlaced mesh with separated warp and weft yarns and to ensure connectivity and contact between warp and weft yarns, two element matrices has been generated. One element matrix for warp yarns and the other element matrix for the weft yarns. To this stage a sharp saw teeth meso-interlaced mesh has been created as shown in Figure 6.

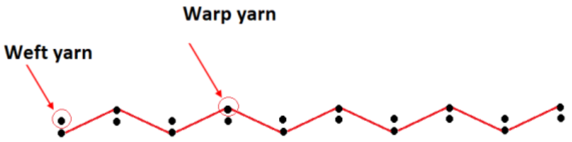

Figure 6. Sharp saw teeth meso-interlaced mesh.

major types of woven fabric are plain, twill and satin. The threads interlacing (the weave technique) that is followed to produce woven fabric based on interlacing fabric

V. MODELLING WARP YARN INTERPOLATION

The First attempt, a sharp saw teeth meso-interlaced mesh has been generated as shown in Figure 6. However, a real warp yarn architecture is curvature shape. In order of modelling real architecture of warp yarns, an improvement of the sharp saw teeth meso-interlaced mesh (Figure 6) has been carried out using a smoothy curvature tool between warp nodes. There are number of methods for producing smooth curvy transition between warp nodes such as (Quadratic Bézier curves [48], natural cubic spline interpolation [49], linear spline [50] and a simple harmonic motion [51]).

Quadratic Bézier curves [48] method has been used for modelling curvy architecture of warp yarns. Quadratic Bézier curves equation (1) [48] has been used to introduce curvature feature in warp yarns.

$$B(t) = P_{\circ}(1-t)^2 + 2tP_1(1-t) + t^2P_2 \qquad (1)$$

When t is time of every Bézier quadratic period. B(t) quadratic Bezier points of time boundary condition $0 \leq t \leq 1$. P_0, P_1 and P_2 three control points mapped from saw teeth warp mesh nodes. Zoomed in segment from figure 6 show five *B(t)* quadratic Bezier points generated from five quadratic Bezier time *t*=[0 0.25 0.5 0.75 1]. By sustituting the three given controal points and the five quadratic Bezier time in equation (1) result in five *B(t)* quadratic Bezier points *B(0)*, *B(0.25)*, *B(0.5)*, *B(0.75)* and *B(1)* as shown in Figure 7. Increasing number of time points *t* result in increasing *B(t)* quadratic Bezier points that lead to curve architecture warp yarns mesh with smooth round appearance.

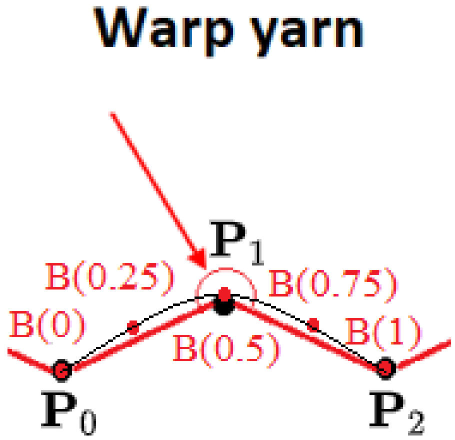

Figure 7. Five Bézier quadratic curve points B(t) generated from three control points in five time periods.

VI. MODELLING WARP YARNS SPLINE INTERPOLATION

Not as extrapolation that predicate extra data points outward, interpolation instead is inserting unknown data points between two known date points. As most, spline interpolation is a piecewise interpolation consisting of a number of interpolation fitting functions which can be linear, polynomial, exponential, or triangular, that restricted by certain boundary conditions keep smooth transition between start and end functions. Whereas polynomial interpolation consisted of one single polynomial function [53,54].

Converting the hybrid truss and membrane elements mesh generated from Meshgen or Varifab or VarifabGA codes to a meso-interlaced mesh consisted of same number of warps and wefts has been carried out using the method mentioned earlier in section Generating Mesh Interlacing method and Matlab coding procedures. Accordingly, introducing curvy shape to warp yarns instead of saw teeth shape that produced earlier has been done using Matlab Cubic spline data interpolation equation (2).

s = spline(x,y,xq) (2)

where x are the x coordinate data points vector of warps nodes and y is the z coordinate data points vector of warps nodes whereas xq are the query points of (new x coordinate data points vector of warps) and s are the corresponding to sq interpolated values (new z coordinate data points vector of warps) [55].

As shown in Figure 6 and 8 warp yarns were straight lines consisting of coordinate data points as nodes. Warp yarns were converted from straight lines to saw teeth lines by generating extra coordinate data points as a first step as mentioned and described earlier in last two sections. However, the coordinate data points generated are not sufficient to interpolate as curvy shape warp yarns as shown in Figure 8. Wherefore, new in between coordinate data points have been generated to obtain suitable spline interpolated curvy shape warp yarns simulate natural warp yarns of engineering fabric as shown in Figure 8. Once extra third coordinate data points were generated in each warp yarn's quarter wave, a spline interpolation is applied. The operation of the method is based on generating data points in between the excited data points of saw teeth warp yarns using equation (3).

$$\boldsymbol{y(x) = y_n + \frac{y_{n+1}-y_n}{x_{n+1}-x_n}(x_x - x_n)} \quad \textbf{(3)}$$

Where $x_n < x_x < x_{n+1}$

$y_{(x)}$ the in between data point that located in between the given independent data points from saw teeth warp yarn y_n and y_{n+1}, x_x is the independent data point which dependent to $y_{(x)}$ and in between the given dependent data points from saw teeth warp yarn x_n and x_{n+1}.

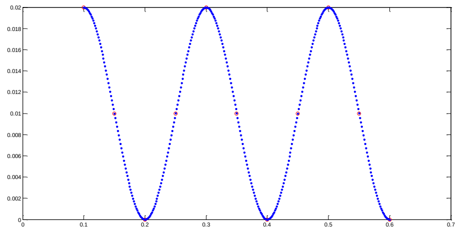

Figure 8. Adding in between points nodes to warp yarns and spline interpolation

At this stage, immediately after generating curvy shape warp yarns a full square meso-interlaced finite element mesh with curvy warps and straight wefts is possible to produce with different mesh density by this new Matlab code which named meso-interlaced-Varifab. Moreover, input file of Abaqus finite element software consisted of node and element sets of meso-interlaced mesh is also generated at the end of code running process for further finite element simulations. The flow chart of Meso-Interlaced-Varifab mesh code is shown in Figure 9.

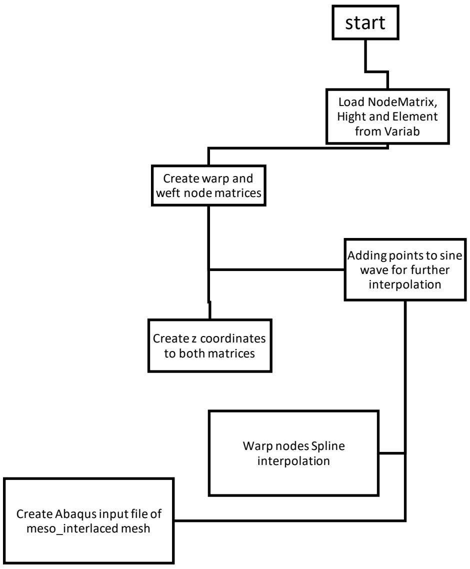

Figure 9. Flowchart process of Meso_interlaced code.

VII. RESULTS AND DISCUSSION

TMeso-interlaced-Varifab code originally developed to simulate the inherent variability of real plain weave engineering fabrics for further use in finite element simulations of forming and characterization of engineering fabric and textile composite.

Geometrical method was developed and applied to introduce interlacing and wavy style to 1D truss or beam finite element mesh generated from Varifab. Two stages have been applied to achieve this goal. The first stage which introduce interlacing to the finite element mesh (which result in saw teeth meso_interlaced finite element mesh) as shown in Figures 10a and 10b and the second stage is introducing curvy style using spline interpolation as shown in Figures 11a and 11b. The details of carrying out this method with the two stages can be read and find with more details in section Generating Mesh Interlacing method and Matlab coding procedures.

Comparison between saw teeth finite element mesh and finite element mesh with warp yarns with curvy shape (see Figures 10 and 11) yields to this fact: the warp yarns sharp tips of saw teeth finite mesh (see Figure 10) far away from simulating the exact shape of actual warp yarn, because the model has not curvy shape of warp yarns. Whereas, the curvy shape of warp yarns of finite element mesh (see Figure 11) simulating the exact shape of actual warp yarn. Simulating the exact natural shape of engineering fabrics with different of wave styles depends of parameters such as space or distances of adjacent yarns, sine function amplitude, wave style (plain, satin, twill, etc). Mesh density also may make different of appearance and geometries (see figures 11a, 11b, 12a and 12b).

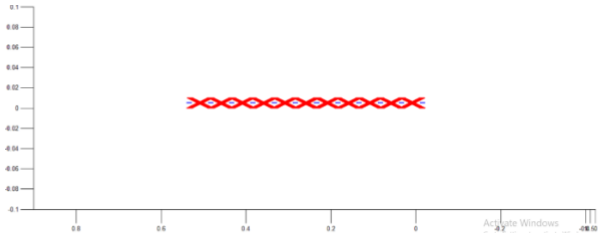

Figure 10a. Frontal projection of saw teeth meso-interlaced finite element mesh.

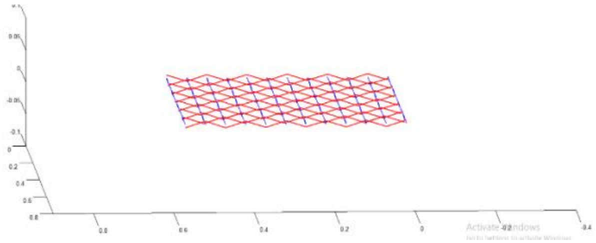

Figure 10b. Horizontal projection of saw teeth meso-interlaced finite element mesh.

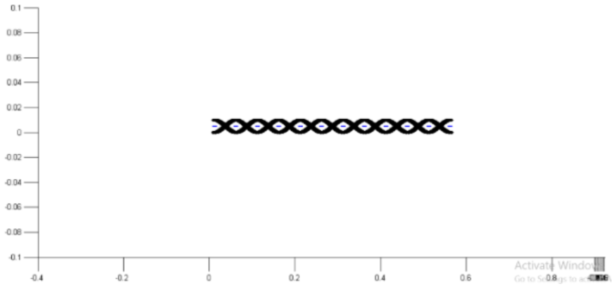

Figure 11a. Frontal projection of curvy spline interpolated meso-interlaced finite element mesh (coarse mesh).

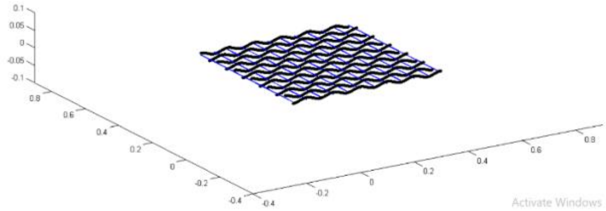

Figure 11b. Horizontal projection of curvy spline interpolated meso-interlaced finite element mesh (coarse mesh).

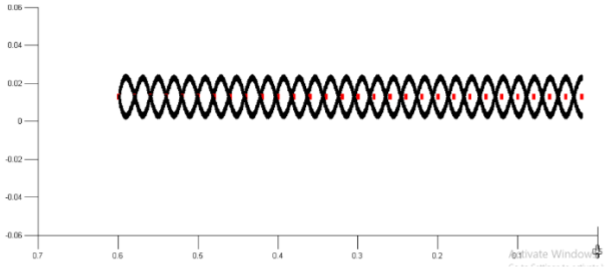

Figure 12a. Frontal projection of curvy spline interpolated meso-interlaced finite element mesh (fine mesh).

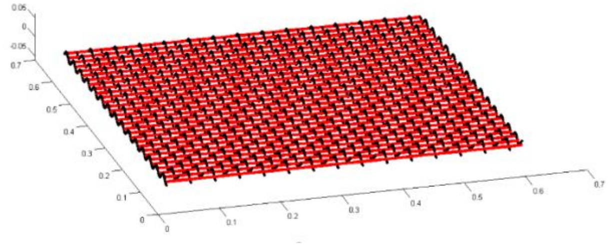

Figure 12b. Horizontal projection of curvy spline interpolated meso-interlaced finite element mesh (fine mesh).

VIII. CONCLUSSION

Meso-interlaced Matlab finite element mesh code generated has been developed. The code is a computational automatic tool of generating 1D finite element mesh for further use in finite element modelling and simulation of characterizing and modelling engineering fabrics characterizing and finite element forming. The code is another attempt toward make the design and manufacturing processes of engineering fabrics and textile composite fully automated. Further investigation in the next publication should be performed to examine this tool in textile composite forming applications.

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