DAMAGE DEVELOPMENT OF WOVEN COMPOSITES BASED ON MULTI-SCALE ANALYSIS

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Abstract

Woven composites have been used in many fields such as cars and ships, etc. However, it is very difficult to evaluate the mechanical behavior and the strength because of the complicated geometrical shape. In order to solve the difficulty, we have developed a numerical multi-scale simulation program based on damage mechanics. The following points are the keys to simulate the mechanical behavior; (1) The generation technique of FE model with yarns and matrix, (2) The classification of anisotropic damage mode based on damage mechanics, (3) Multi-scale modeling by Mesh superposition method. In this paper, the numerical technique is described, and the damage development for woven GFRP laminate based on multi-scale analysis of M^3 method has been estimated.

1 Introduction

Woven composites have many design parameters such as volume fraction of fiber, architecture of reinforced fibers, the mechanical properties, etc. There are some problems as cost and protracted development period for airplanes and vehicles that must perform reliability evaluation by experiments with a real scale. And, the practical modeling technique and the systematization considering the complicated non-homogeneity of woven composites have not been developed completely. Furthermore, it is very difficult to evaluate the damage development of composites because of the complicated geometrical shape. Recently, many researchers have studied the finite element analysis to predict mechanical properties of textile composites, and mechanical properties and failure behaviors of plain weave composites have been estimated [1][2]. Local delamination appears in resin region of crossing parts of yarns, however, the effect of resin region and the damage development have not been considered completely.

To solve the above difficulty, we have developed the multi-scale simulation program of mechanical behaviors for woven composites. A finite element mesh generator of woven composites has been developed, and we have simulated the damage development of woven composites based on damage mechanics. Furthermore, the macroscopic behavior and microscopic stress states are investigated for woven composites by using multi-scale analysis. The numerical technique of finite element modeling and the results of damage development of woven composites are described.

2 Numerical Simulation System for Woven FRP

2.1 Flow of Numerical Simulation System

Figure 1 shows the proposed scheme of the structure analysis of woven fabric composites. The topology of a weave architecture is determined by the input data like a filament diameter, the architecture of strand, etc. The structural model of internal geometry of the fabrics is generated. FE

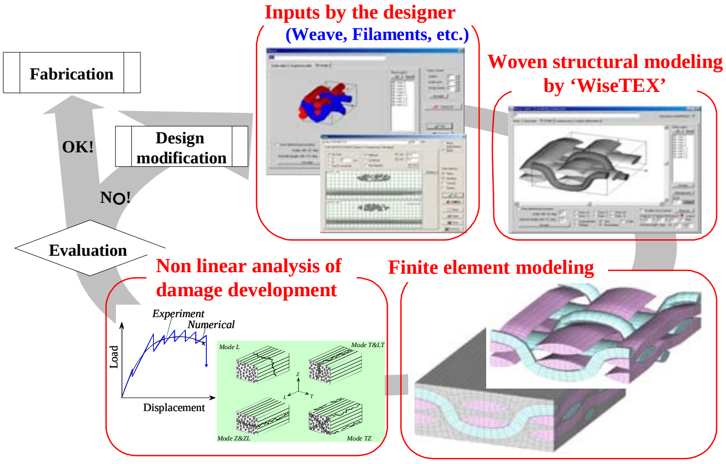
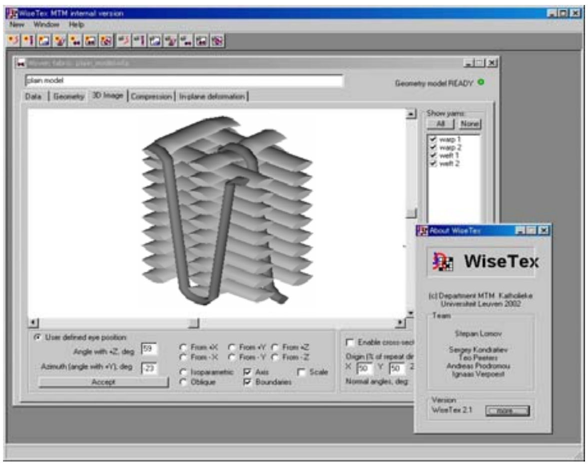


Fig.1 A practical numerical simulation system

model with yarns and matrix by the hexahedron element is generated by the developed numerical modeling program. The deformation and stress distribution can be evaluated by the generated mesh model and multi-scale FEM. The outline of system is shown as below.

2.2 Woven Structural modeling

It is not easy to illustrate the geometry of textiles from the weave diagram or mechanical property of a yarn. In order to solve this problem, Lomov has developed 'WiseTex' program [3][4]. The WiseTex has function to create 3D visual image of woven structure form weave diagram, etc. In calculation of yarns image, the trajectory of the yarn in the stable state is calculated using the bending energy minimum theory. Moreover, not only 2-dimensional textiles such as a plain weave and twill, but 3D woven or knitting can be corresponded. An example of application of the system is shown in Fig.2. A structural image of a 3D fabric can be visualized by using the input information on the arrangement of weave yarns.



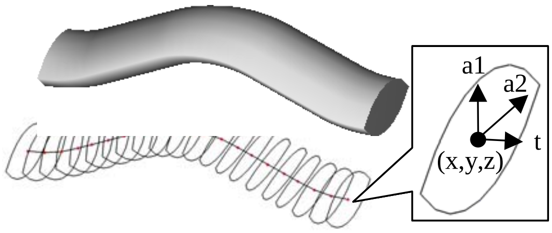
(b) 3D visual image

Fig.2 Geometrical modeling by WiseTex program

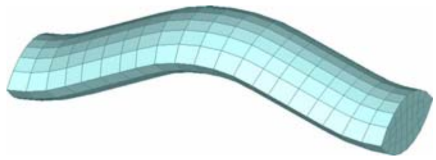
2.3 Finite Element Modeling of Yarns and Resin

A shape of a finite element of a yarn is used as hexahedron, and the element is regularly generated so that an element coordinate system and the direction of a fiber may become equal. The procedure is shown below. Firstly, getting the position and direction of the cross sections form the WiseTex data as shown in Fig.3(a). The mesh of a cross section of the yarn is generated with Delaunay method, and the cross-sectional elements are combined to the neighbor element of another cross section. The procedure is repeated in order to create the hexahedron elements of a yarn in Fig.3(b).

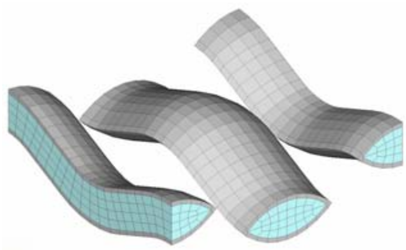
Estimation of damage development of woven fabric composites is very difficult, because matrix cracks and delamination at the crossover parts of fiber bundle may occur leading to complicated



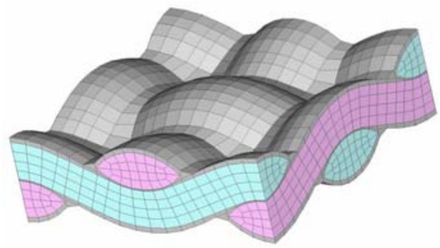
(a) A structural model



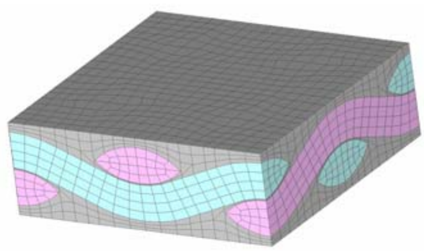
(b) Finite element model a yarn



(c) Generation of matrix parts
to surround a fiber bundle



(d) Connection of weft and warp yarns



(e) Finite model of composites

Fig.3 Procedure of finite element model of woven fabric composites fracture modes in comparison with uni-directional fiber reinforced composites. Therefore, how to generate the finite element of matrix parts is very important. In the paper, finite elements of matrix parts are created by applying the following procedure. After a yarn element was generated in Fig.3(b), the finite elements of matrix parts are generated on the circumference of a yarn in Fig.3(c). Hexahedron elements are generated to connect the warp and weft yarns in Fig.3(d). Finally, finite elements in the upper and the lower parts of matrix are generated, and FE model with yarns and matrix by the hexahedron element can be obtained in Fig.3(e).

Figure 4 shows typical examples of finite element models with several fabric architectures based on the developed program 'MeshTex'. Finite element models of a twill fabric and 3D fabric composites can be obtained easily considering resin parts on the circumference of a yarn and 3 dimensional architecture of a yarn.

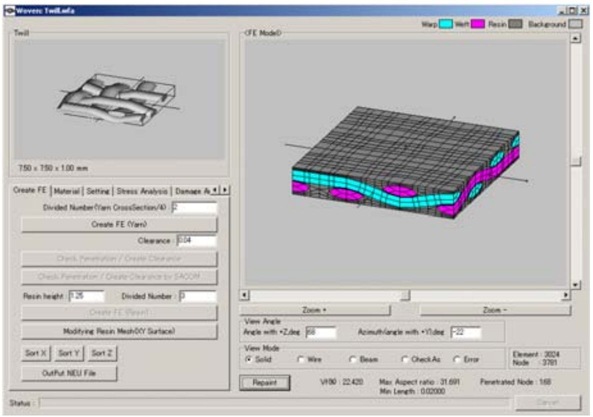


Fig.4 Finite element modeling of twill fabric composites by MeshTex program

3 Multi-scale Analysis based on M^3 Method

3.1 Definition and Constitutive Equation of M^3 Method

To investigate an effect of woven architectures on the mechanical properties of the composites, the macroscopic behavior and microscopic damage states of woven fabric composites yarn are analyzed with the multi-scale analysis of M^3(Macro-Meso-Micro) method[5], which is the finite element method using mesh superposition in 3 scales. Three types of numerical models have been generated. M^3 method has some advantages. The memory of CPU can be reduced and be saved from the modeling procedure. And, the meso-mesh can be superimposed on a macro-mesh without matching of the boundary of each mesh.

Definition of each region in 3scales is shown in Fig.5. The displacements for each model are defined as Eq. (1). The displacement of meso mesh is interpolated from that of macro mesh of meso mesh superimposing parts. The displacement of micro mesh is interpolated from that of meso and macro mesh respectivily. Ω represents the region of each mesh.

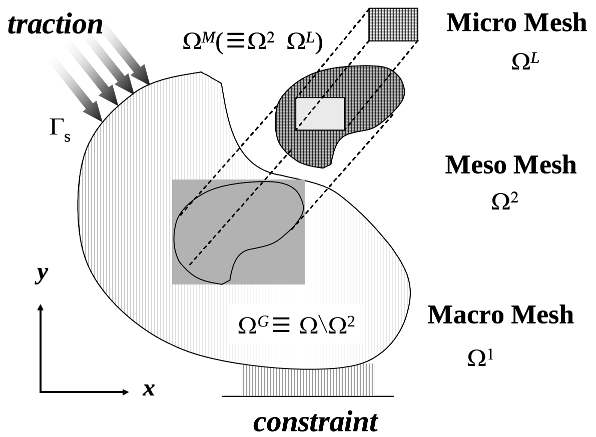


Fig.5 The concept of M-cube method and the definition of each region

$$\{u\}=\begin{cases}\{u^G\} & in\ \Omega^G\\ \{u^G\}+\{u^M\} & in\ \Omega^M\\ \{u^G\}+\{u^M\}+\{u^L\} & in\ \Omega^L\end{cases} \tag{1}$$

$\{u^G\}$, $\{u^M\}$ and $\{u^L\}$ are displacements in the domain Ω^G, Ω^M and Ω^L ,respectively. The suffixes *G*, *M* and *L* show each analysis domain same as displacement domain. The strain vector $\{\boldsymbol{\varepsilon}\}$ can be expressed by strain-displacement matrix $[\boldsymbol{B}]$ and nodal point displacement vector $\{\boldsymbol{d}\}$ as Eq.(2).

$$\begin{aligned}\{\varepsilon\}&=\begin{cases}\{\varepsilon^G\} & in\ \Omega^G\\ \{\varepsilon^G\}+\{\varepsilon^M\} & in\ \Omega^M\\ \{\varepsilon^G\}+\{\varepsilon^M\}+\{\varepsilon^L\} & in\ \Omega^L\end{cases}\\ &=\begin{cases}[B^G]\{d^G\} & in\ \Omega^G\\ [B^G]\{d^G\}+[B^M]\{d^M\} & in\ \Omega^M\\ [B^G]\{d^G\}+[B^M]\{d^M\}+[B^L]\{d^L\} & in\ \Omega^L\end{cases}\end{aligned} \tag{2}$$

We obtain Eq.3 for stress vector by stress - strain matrix $[\boldsymbol{D}]$.

$$\{\sigma\}=\begin{cases}[D^G]\{\varepsilon^G\} & in\,\Omega^G\\ [D^M](\{\varepsilon^G\}+\{\varepsilon^M\}) & in\,\Omega^M\\ [D^L](\{\varepsilon^G\}+\{\varepsilon^M\}+\{\varepsilon^L\}) & in\,\Omega^L\end{cases} \tag{3}$$

From Eq.(1) to Eq.(3), we obtain Eq. (4) as the constitutive equation of M^3 method.

$$\begin{pmatrix}[K^G] & [K^{GM}] & [K^{GL}]\\ [K^{MG}] & [K^M] & [K^{ML}]\\ [K^{LG}] & [K^{LM}] & [K^L]\end{pmatrix}\begin{Bmatrix}\{d^G\}\\ \{d^M\}\\ \{d^L\}\end{Bmatrix}=\begin{Bmatrix}\{F_s^G\}\\ \{0\}\\ \{0\}\end{Bmatrix} \tag{4}$$

Where, $[\boldsymbol{K}^G]$ is the stiffness matrix for macro-region, $[\boldsymbol{K}^{GM}]$ is the one of macro and meso correlation, $[\boldsymbol{K}^{ML}]$ is the one of meso and micro correlation and $[\boldsymbol{K}^{GL}]$ is the one of macro and micro correlation, respectively. $\{\boldsymbol{F}_S{}^G\}$ is the force vector for macro-mesh region.

3.2 Multi-Scale Modeling System

Figure 6 shows the developed simulation system for multi-scale modeling of woven composites based on M^3 method. Three types of multi-scale models can be generated. They are a structural macro model, meso model such as woven structures, and micro model such as filament and resin parts. The mechanical behaviors of each mesh can be estimated with seamless from macro region to micro region at the same time.

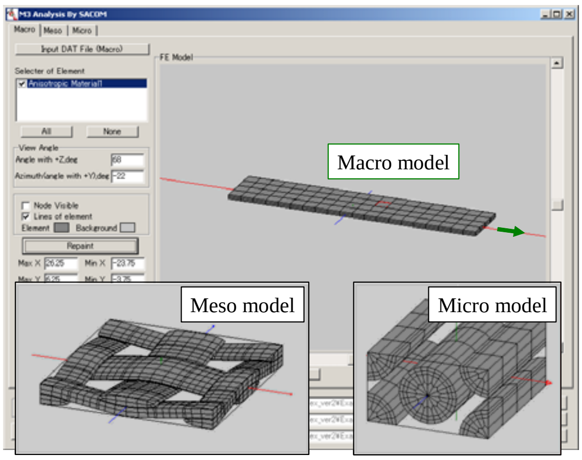


Fig.6 Multi-Scale modeling of woven composites with 3 scales

4 Simulation Method of Damage Development

In the simulation, the modeling of anisotropic damage is very important. Woven fabric composites are treated as heterogeneous bodies with anisotropy for fiber bundles and with isotropy for matrix, respectively. The isotropic damage model is applied for matrix, and anisotropic damage model is applied for the fiber bundle, respectively.

The proposed method is composed of main two parts. The first part is the judgment of the damage occurrence that is judged by Hoffman's failure criterion. The second part is the decision of the damage mode. The damage in fiber bundle consists of four modes as shown in Fig.7[6]. The damage modes for the transverse-crack or the fiber-breakage are based on the damage mechanics. *Mode L* is dominated by fiber breaking, the others are matrix cracking caused by different stress components. The damage mode is judged by the maximum value among the corresponding stress-to-strength ratios in Table 1. The reduction of the stiffness for a damaged element is calculated based on damage tensor defined by each damage mode.

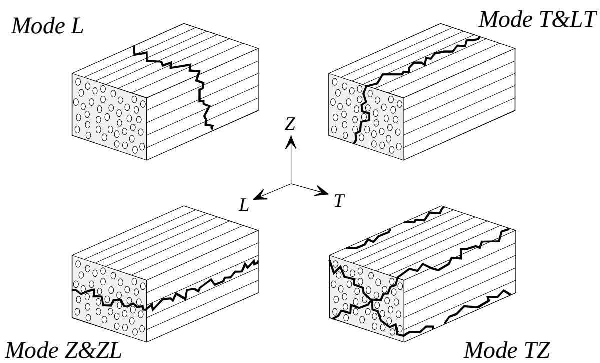


Fig.7 Anisotropic damage mode of fiber bundle

Table 1 Classification of damage mode

Maximum value	Damage mode
$\dfrac{\sigma_L^2}{F_X^t F_X^c}$	Mode L
$\dfrac{\sigma_T^2}{F_Y^t F_Y^c}$ or $\left(\dfrac{\tau_{LT}}{F_{TZ}^s}\right)^2$	Mode T & TL
$\dfrac{\sigma_Z^2}{F_Z^t F_Z^c}$ or $\left(\dfrac{\tau_{ZL}}{F_{ZL}^s}\right)^2$	Mode Z & ZL
$\left(\dfrac{\tau_{TZ}}{F_{TZ}^s}\right)^2$	Mode TZ

5 Numerical Models and Results

5.1 Damage Development of Woven Composites based on M^3 method

Figure 8 shows the macro, meso, and micro meshes generated by 3D 8-node elements. The boundary conditions and the superimposed state of each mesh are also shown. The macro mesh means a tensile testing specimen of GFRP laminates (woven glass fiber / vinylester resin) with three layers. The meso mesh is super imposed in the central layer of the macro mesh, and the micro-mesh is superimposed in the center part of a weft yarn of the meso-mesh.

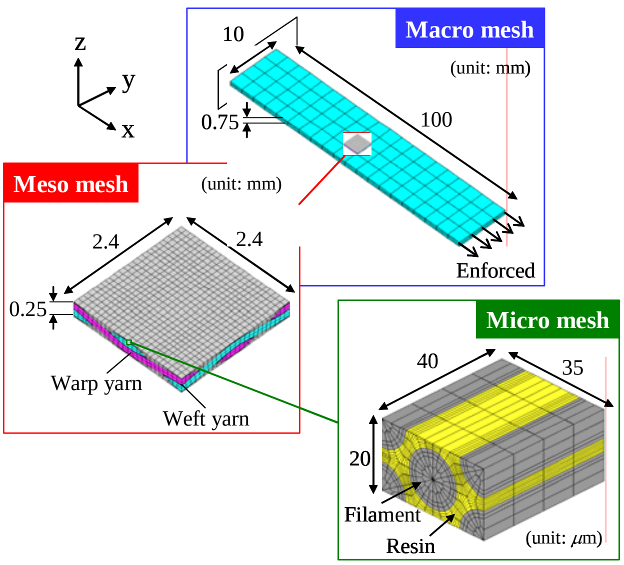


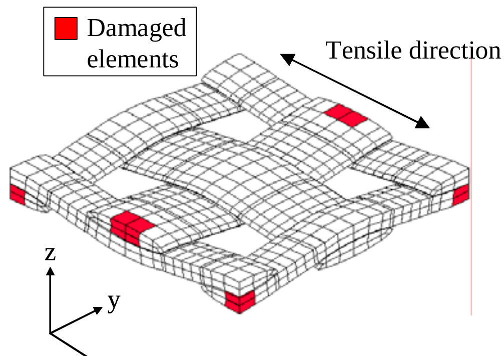
Fig.8 Numerical models for M^3 method

A mechanical behavior of woven laminate under the on-axis tensile loading has been analyzed with the proposed model in Fig.8. The numerical and experimental results of the initial stiffness agree quantitatively well each other. The agreement indicates that the proposed method is acceptable and a useful technique to analyze the micro region.

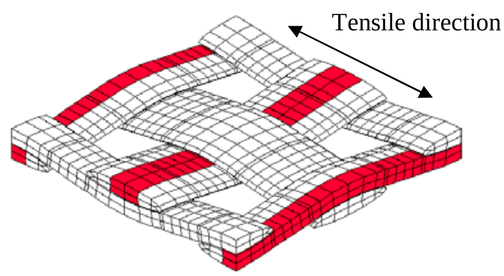
Figure 9 shows the numerical results of damage states of the meso models. To make clear the damage inside the strand, the only strand parts are also illustrated, and the colored parts mean the damaged elements. The initial damage of a transverse crack (Mode T&LT) occurs at the center part of weft strands, and the damages develop gradually with the increase of tensile load. Though it is difficult to detect the damage development insider laminate by the experiments, the proposed simulation will give us the information with accuracy.

Figure 10 shows the numerical results of damages in the micro model illustrated by only resin parts. Initial damages of resin appear on the surrounding parts of filaments. It is revealed that the occurrence of the initial damage and the microscopic damage development are obtained by the proposed numerical method.

Figure 11 shows the numerical and experimental results of S-S curves. The numerical results indicate the mechanical behaviors of the meso model. The numerical and experimental results have same tendency in the elastic region. Furthermore, the non-linear behavior is appeared after 100MPa because of the occurrence of initial damage and reduction of the stiffness for the damaged elements in the numerical results. It is revealed that the non-linear behavior can be estimated with the proposed numerical method.



(a) Strain 0.6%



(b) Strain 0.7%

Fig.9 Damage development for meso-model

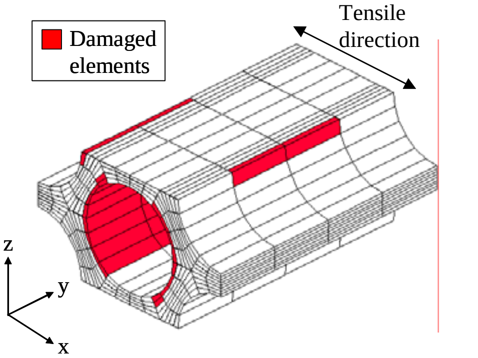


Fig.10 Damage development for micro-model

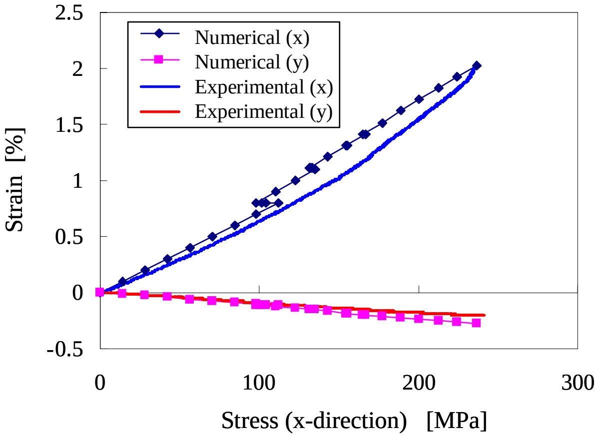


Fig.11 Comparison of S-S curves of experimental and numerical results

5.2 Damage Development of Woven Composites Laminate with Three Layers

Woven fabric laminate consists of a pile of woven layers impregnated with a resin. As it is difficult to control the lay-out of lamina, the relative position of crimped yarns in layers is disordered. We have a few papers about an effect of fabric pile on compressive properties [4]. However, an effect of a disorder on the mechanical properties of woven fabric composites has not been completely investigated. To investigate an effect of the disorder of pile-up on mechanical behaviors under tensile load, the mechanical behaviors have been estimated based on M^3 method. Figure 12 shows the macro, meso, and micro meshes generated by 3D 8-node elements. The shape and the size for a macro and

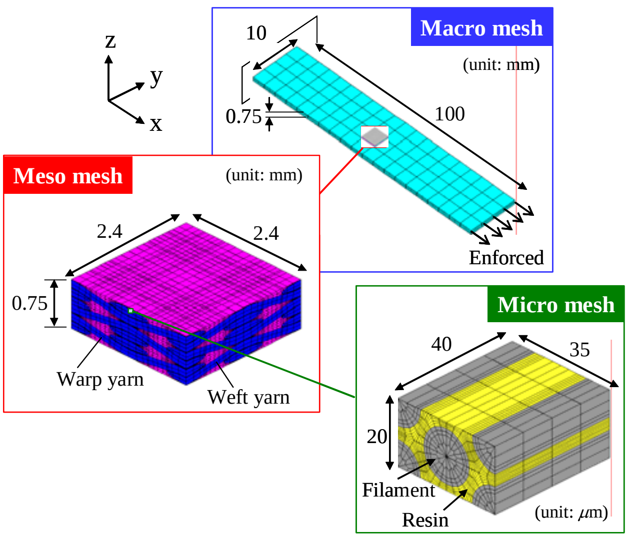


Fig.12 Numerical models for woven laminates with 3 layers

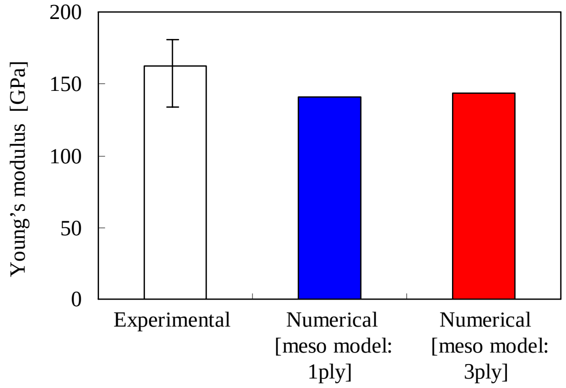
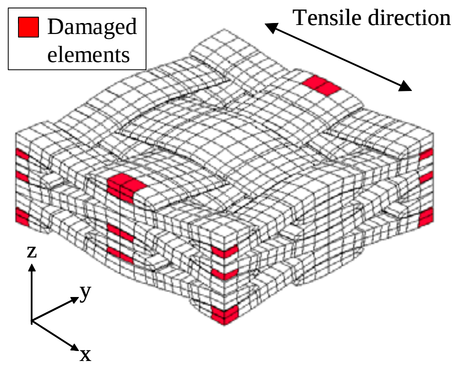
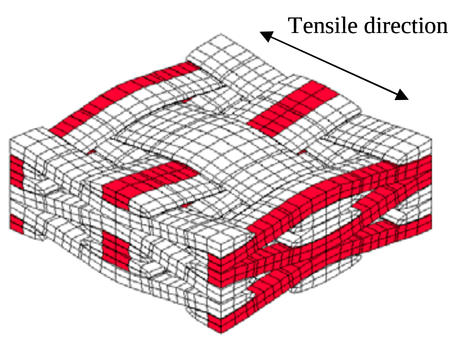


Fig.13 Comparison of elastic modulus



(a) Strain 0.6%



(b) Strain 0.7%

Fig.14 Damage development of meso model

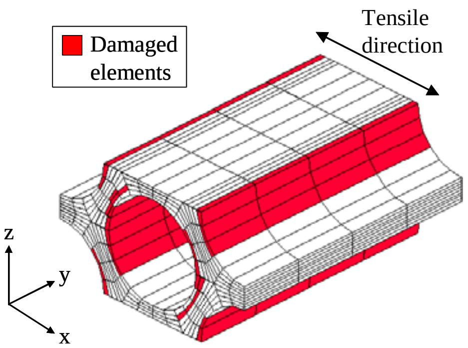


Fig.15 Damage development of micro-model

micro models are same with each model in Fig.8. The meso mesh consists of woven composites laminate with three layers. The position of middle layer is disordered. The meso mesh is super imposed in the central layer of the macro mesh, and the micro-mesh is superimposed in the center part of a weft yarn on outer layer of the meso mesh.

Figure 13 shows the numerical and experimental results of in-plain elastic moduli. On-axial tensile test had been carried out with three specimens of woven composite laminates. The maximum, average and minimum value of elastic moduli are also shown in the figure. The numerical elastic modulus had been estimated with the macro model. From the results, the results of numerical analysis agree with the experiments, however, an effect of the disorder can not be neglected for the estimation of damage development of woven fabric composites. The damage development of meso model is shown in Fig.14. The transverse cracks have developed in the center parts of a weft bundle, and the cracks have propagated to thickness direction. From these results, it is recognized that the mechanical behavior of woven composites can be estimated with the proposed method in case of various structure of meso-scale model. The proposed simulation contributes the design of meso-scale structure which produces high-functional materials.

Figure 15 shows the numerical results of damages in the micro model illustrated by only resin parts. Microscopic damages on the surrounding parts of filament can be estimated like a microscope based on M^3 method.

6 Concluding Remarks

A FE mesh generator and the simulation technique of mechanical behaviors of woven fabric FRP considering damage development was described. FE models of a twill fabric and 3D fabric composites can be obtained easily considering resin parts on the circumference of a yarn and 3 dimensional architecture of a yarn based on MeshTex program.

To investigate an effect of woven architectures on the mechanical properties of the composites, the macroscopic and microscopic behaviors have been analyzed with the multi-scale analysis of M^3 (Macro-Meso-Micro) method. The definition and constitutive equations are described, and the developed simulation system for multi-scale modeling was shown.

Woven fabric composites are treated as heterogeneous bodies with anisotropy, and the anisotropic damage mode was classified based on damage mechanics. And, the simulation method of damage development was also described.

As the above numerical example, the crack evolution for woven GFRP laminate can be simulated by M^3 method based on damage mechanics. The elastic modulus and stress-strain characteristics were also compared with numerical and experimental results. From the results, it is revealed that the non-linear behavior can be estimated with the proposed numerical method. Furthermore, the mechanical behavior of woven composites can be estimated with the proposed method in case of various structure of meso-scale model. The proposed simulation contributes the design of meso-scale structure which produces high-functional materials. And, since the numerical analysis can be carried out with seamless from macro region to micro region at the same time, it has been recognized that M^3 method is a very useful for composites field.

Acknowledgement

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